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**DAM SAFETY INTEREST GROUP (DSIG)**

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# DAM SAFETY PERFORMANCE MONITORING AND DATA MANAGEMENT – BEST PRACTICES


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## ABSTRACT

Dr. Ralph Peck, an eminent dam engineer, stated at the International Commission on Large Dams 20th Congress, Beijing, China, in September 2000 that "Monitoring of every dam is mandatory because dams change with age and may develop defects. There is no substitute for systematic and intelligent surveillance." Over many decades, instruments have been incorporated into dams for various reasons including verifying theoretical assumptions concerning soil mechanics, monitoring response of dams to construction activities, monitoring the ongoing performance of dams, investigating causes of performance, and monitoring the effectiveness of remedial work. According to Dr. Peck and others, every instrument installed in a dam should be designed to answer a specific technical question pertinent to the safe performance of the dam. John Dunnicliff, a world renown expert on instrumentation, echoed this belief and added the requirement that a successful instrumentation program must follow a systematic process from concept to execution. Failure to execute each step of the systematic process can compromise the value of the instrumentation program.

To this end, best practices are needed to obtain the most value from instrumentation programs. These practices can be developed initially by understanding how a specific dam can potentially develop problems or defects. Adequate training, surveillance, monitoring, and management programs can be developed for proper data collection, instrument assessment, data analysis, and conclusions to dam performance assessment.

The objective of this project is to document best practices to develop and implement an effective performance monitoring program for dam surveillance, inspection, instrumentation needs and maintenance, data collection, data management, data analysis, and data interpretation. This includes identifying the responsibilities of management and the key components for managing the overall performance monitoring program along with proper coordination and communications between and among the responsible parties.


**Keywords:**
Dam Safety, Performance Monitoring, Instrumentation, Data Management, Risk Management.

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# EXECUTIVE SUMMARY

This project, *Dam Safety Performance Monitoring and Data Analysis Management – Best Practices,* was originated by CEATI Dam Safety Interest Group (DSIG) in 2009 with the objective of documenting best practices for dam surveillance, inspection, instrumentation, data collection, data analysis, and data management for performance and interpretation as they relate to maintaining the safety of a dam.

A key component of a comprehensive dam safety program is the owner's performance monitoring program that includes policies and procedures to assure the data obtained are accurate and evaluated in a timely manner, anomalies are thoroughly investigated, and appropriate actions are taken in the event the data indicate the dam is behaving in an adverse manner.

Dam safety performance monitoring programs are needed to help dam owners meet their legal, ethical, and moral responsibilities to apply an appropriate standard of care to keep their dams safe. The failure, or adverse performance, of a dam or its appurtenances can have immediate to long-term, direct and indirect consequences and effects that can involve significant risks including human casualties, loss of project benefits, economic damages, and environmental impacts. The consequences of a dam failure can be many times the cost of the facility. Effective performance monitoring provides sound data to help an owner identify, quantify and control these risks.

High quality design, operation, and maintenance of a dam does not guarantee freedom from unexpected events that affect the safety of the dam. There are many historical cases of dam failures and incidents where an early warning sign of failure might have been detected if a good dam safety monitoring program had been in place. A performance monitoring program provides the information needed to develop a better understanding of the on-going performance of a dam so surprising poor performance can be avoided.

The concepts of risk assessment and risk management are introduced as a way to estimate the benefits of a dam safety monitoring program. This approach can give the dam owner approximate numerical estimates of the reduction of risk and show the financial benefits that performance monitoring can produce. It can also point to maintenance and remedial activities that are cost effective risk reduction measures.

Instrumentation and monitoring, combined with vigilant visual observation, can provide early warning for many conditions that contribute to dam failures and incidents. The instrumentation and monitoring must be carefully planned and executed to meet defined objectives. Data must be conscientiously collected, reduced, tabulated, and plotted in a timely manner to determine what it indicates about the safety of the dam. The monitoring team must understand the significance of changes and trends. They should have trigger levels defined for taking action.

A dam's performance may change over time; consequently, the performance monitoring program must change as well. Change can occur through the normal aging process of the components of a dam, or through the development of defects due to something missed in the design or construction of the dam, or with slow changes in internal pore water pressure in earthen components with low permeability.

The owner should ensure that staffing is sufficient and qualified for the project workload, and that all programs necessary for the safety of dam the are established, continued, and realistically funded. Allocation of manpower and funds should give high priority to safety-related functions. Safety-related functions and features must not be sacrificed to reduce costs, improve project justification, or expedite time schedules.

Clear assignment of responsibility for timely collection and review, and follow-up on collected data and reports is needed. This component is subject to each dam owner's available resources for managing the dam inventory. In the case of dam owners having limited or no qualified engineering staff, provisions should be made to secure the professional services of a well qualified engineering consultant. Whether the resources are direct employees, engineers and consultants, or a combination of both, the owner needs to ensure that qualified personnel have the information and resources to conduct effective dam safety performance monitoring and implementation of risk reduction measures, if needed.

A single identifiable, technically qualified individual should be assigned the responsibility for assuring that all management and technical aspects of dam safety performance monitoring are adequately defined and carried out throughout the life of the dam. The position must have continuity of guidance and direction, and the authority and resources to ensure these responsibilities are carried out. These responsibilities include:

- develop and implement dam safety policies and procedures;
- assemble and maintain current all information about the dam;
- indentify the probable failure modes;
- identify what measurements can and should be made;
- design and install appropriate monitoring systems;
- train personnel;
- collect, process, and evaluate visual inspection and monitoring data;
- interpret and report results; and,
- take action when indicated.

When risk reduction measures are indicated, implementation should be prioritized based on significance to dam safety and tracked to completion. Resolution of dam safety corrective and preventative actions should be documented. Follow-up review of the adequacy of the surveillance and monitoring program should be conducted.

Dam owners and senior management have direct responsibility for the safety of a dam. A well executed performance monitoring program is one of the most effective ways to help fulfill this responsibility. Results from this program can also be useful to determine the benefits to risk management of proposed maintenance and remedial programs.

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# 1.0 INTRODUCTION AND OVERVIEW

In 2006, the 116-year-old Ka Loko dam failed resulting in the death of seven people and property damages of more than $100,000,000. Criminal charges were filed against the dam's owner for poor maintenance. In 2005, the Taum Sauk Upper Reservoir Dam failed and caused enormous losses to its owner but fortunately there was no loss of life. In 1976, Teton Dam failed on initial reservoir filling and greatly damaged the reputation of the US Bureau of Reclamation. In 1972, a small dam across Buffalo Creek in West Virginia failed and within one hour took the lives of 125 people living downstream. The resulting wall of water that rushed down Buffalo Creek also destroyed essentially all homes, business and infrastructure in 16 villages.

Failure of a dam can have major consequences to the owner of a dam and to the public.

Dam incidents can include partial dam failure, miss-operation of spillway gates, spillways blocked by debris, and other ancillary feature incidents. Significant impacts can result from such incidents even though the reservoir does not completely drain.

Dams fail because of unknowns about their condition and performance, wrong actions by people, deterioration of materials over time, or loading conditions that exceed those used in the design. Dam safety programs are used to detect these conditions with the aim to intervene and correct the undesirable condition before the dam fails. Dam safety programs repeatedly detect developing problems in time for corrective actions and as a result serve as a highly effective risk management strategy for owners of dams.

> Dam safety programs aim to protect life and property from an uncontrolled release of the dam's contents and thereby manage risk.

The primary objective of a dam safety program is to ensure the integrity and viability of a dam such that it does not present unacceptable risk to the public, property, the environment and the owner. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe functioning is not explicitly determined by its original design and construction.

A dam safety program aims to protect life, property, and the environment by ensuring that a dam is designed, constructed, operated, and maintained as safely and effectively as is reasonably possible. It consists of activities to continually inspect, monitor, evaluate and document the design, construction, operations, maintenance, rehabilitation and emergency preparedness of each dam and coordination with the potentially affected public agencies having responsibility for public safety. It also includes a clear plan that defines responsibilities for each component and communicates the state of the dam safety program to all with responsibility.

Dam safety monitoring is the art of monitoring the performance of structures and other engineering works by combining visual observations and physical measurements of displacements, cracks, stress, pressure, force, fluid flows and vibrations to access the performance of the dam relative to design expectations. Dam safety monitoring is a systematic process to monitor the performance of a dam so that maintenance and remedial action can be taken if unacceptable performance occurs.

> Dam safety monitoring is a systematic process to:
>
> – Monitor the performance of a dam;
> – Perform maintenance and remedial work when required to avoid failure; and,
> – Provide warning for emergency work and initiate emergency action plans.

This report documents best practices for an effective program of dam safety performance monitoring that incorporates: (a) surveillance and inspections; (b) instrumentation; (c) data collection, analysis, evaluation and management; (d) development of remedial/mitigation actions and (e) defining lines of responsibility and reporting; and (f) training.

> Dam Failure – any event that results in the uncontrolled release of stored materials, usually water, from the dam to the downstream area.

Failure of a dam may endanger public safety, property and the environment by a sudden uncontrolled release of enormous volumes of water or other stored materials such as tailings, that can cause death, property damage to roads, railroads, utilities, homes, hospitals, and businesses downstream of the dam, long-term environmental damage, and loss of the dam and its related facilities. Because of the potential for a dam failure to cause loss of life and significant damage to the environment and property, governments have established regulations and agencies to enforce these regulations to help reduce failures. These regulations and their enforcement vary widely and consequently dam safety programs vary considerably.

> Risk for Dam Owners
>
> A dam may expose it's owner to substantial risk.
>
> An effective dam safety performance program can help reduce and manage this risk.

A dam owner may face large consequences if its dam fails and releases large amounts of water, or other materials, in an uncontrolled manner. Ownership of a dam can be in the form of a public agency, a business entity, or an individual. Many dams, particularly older dams of small to intermediate size, are owned by individuals, small private corporations, small municipalities, or small utility companies. Most of these smaller dams were not designed nor supervised during construction by engineers familiar with good practice and safety standards for safe construction and operation of a dam. Whatever the size, hazard potential, or purpose of a dam, the owner has an inherent responsibility to protect the public from incidents that cause dam failure. This responsibility exposes owners of dams to substantial risks. Many times dam owners are not aware of the scope of these risks. A dam safety program is one very beneficial approach for dam owners to greatly reduce the risk of a sudden uncontrolled release of water with the potential to cause great harm.

This report outlines the responsibilities of owners for managing the overall dam safety performance monitoring program, which includes proper coordination and communications between and among key people. It also describes each component of a dam safety performance monitoring program. The object of this report is to provide owners and all members of the dam safety team with information about the key elements of dam safety performance monitoring based on current practice.

A good dam safety performance monitoring program can provide early warnings of unacceptable performance of a dam in time that preventative and remedial actions can be taken to reduce risks to an acceptable level. A good dam safety performance monitoring program should be an important part of any dam owner's risk management program. It should include the means for scheduling maintenance and remedial activities that help reduced risk.

## 1.1 What is Dam Safety Performance Monitoring?

Currently, dam safety programs vary considerably depending on the owner's (a) personnel and economic resources, (b) awareness and understanding of risk, (c) commitment to a dam safety program, (d) specific dam safety regulations from the governing authority, and (e) the dam owner's response to those regulations. Governmental regulations for dam safety usually require the owner to "prove" that the dam is safe and to improve the safety where required. However, merely meeting regulations for dam safety may not be sufficient. Owners may also be required to comply with current standards of practice regardless of the age of the dam. If a dam fails for any reason, including natural disasters, but excluding military or criminal acts, the owner can be liable for the consequences, even when in full compliance with the governing regulations. The owner, and even certain employees, can be found criminally liable if they have not maintained the dam in accordance with applicable standards and practices. Increasingly, the standard of care required of dam owners to prevent harm resulting from dam incidents involves their awareness of and actions regarding 'foreseeability', 'degree of harm', 'preventability', and 'control' for the dam failure and incident. Modern methods of risk management, including an effective performance monitoring program, are vital tools to help identify actions that might be necessary to maintain or improve dam safety.

Dams are man-made facilities that tend to deteriorate over time with a corresponding increase in probability of a failure over time. To ensure that the probability of adverse behavior is minimized, the overall performance of the dam must be properly monitored over its lifetime and a maintenance/repair program consistently executed to remove deficiencies. Depending on the characteristics of the dam, this monitoring can range from simple to expansive. All elements of a safety monitoring program must be done carefully, methodically, and with technical understanding using appropriate expertise. The results must be evaluated promptly to make a determination on whether the dam is performing normally or adversely. If adverse conditions are present, corrective or emergency measures could be needed. A safety management team must be in place to ensure that all elements of a safety monitoring program are being done and to act quickly and effectively to any observation or measurement that indicates an increased risk of failure.

Many existing dams are not well monitored. Instrumentation installed for monitoring during construction and first filling may need to be adjusted for normal operation and for conditions observed during routine monitoring. In such cases, well designed and implemented performance indicators such as systems to monitor deformations, seepage and turbidity combined with periodic visual inspections must be in place to monitor the overall performance of the dam.

Technologies exist to monitor almost any aspect of dam performance and safety. The challenge is to organize and manage the human and financial resources to apply these tools in an effective and efficient safety program and act quickly to implement actions that restore the dam's safety when needed.

Periodic reassessments of the effectiveness of the dam safety monitoring program are necessary during the working life of dam. In addition to deterioration due to normal aging, dams tend to attract or support development. Consequently, a dam's hazard potential in the event of dam failure may change over time. This may result in a need to develop or revise a performance monitoring program.

Several words and phrases are used to define a performance monitoring program. They involve one or more of the phrases: instrumentation program, monitoring program, and surveillance program. This report uses the following definitions:

> **Instrumentation or monitoring program** refers to a systematic set of steps to obtain, process and evaluate measurements from devices installed at a dam to measure aspects of the dam's physical performance in terms of movement, cracking, stresses, water flow, material degradation and erosion.
>
> **Instrumentation** refers to an arrangement of measurement devices installed into a dam, its foundation and its abutments to provide measurements of performance over time to evaluate the structural behavior and performance parameters of the structure. Typical devices used in dams include settlement points, movement points, crack gages, inclinometers, piezometers, strain gages, thermisters or thermocouples, tilt meters, and others.
>
> **Surveillance program** is a systematic program of making close visual observations of the conditions of the components of a dam for indications of unacceptable performance and/or changing conditions, recording those observations and evaluating their significance to the safety of the dam and its related components.
>
> **Performance Monitoring** encompasses metrology, field instrumentation, monitoring, and surveillance to collect, evaluate and report visual observations and data to document the functioning of a dam and related structures over time.
>
> **Performance Monitoring Program** is a systematic process of performance monitoring that includes close visual inspections and instrumentation to document, analyze, evaluate and report the functioning of a dam and its related components over time.

> **Safety program** is a systematic process to gather, evaluate and report data on the functioning of a dam and its related facilities over time; to determine when the functioning of the dam is unacceptable; and to take action to restore the dam to an acceptable performance state.

Proper performance monitoring can indicate when a dam is experiencing distress and indicate what actions can be taken to protect the dam against premature deterioration or failure. A strong performance monitoring program coupled with a responsive maintenance and repair program can allow the dam to continue its life indefinitely. Furthermore, the cost of a proper monitoring and maintenance program is small compared to the cost of major repairs, potential loss of life, and unwarranted and protracted litigation.

Dams that do not have adequate dam safety programs present a higher risk to life and property downstream and to the dam's owner. Lack of an adequate dam safety program was a factor in some notable dam failures and dam safety related incidents including Sayano-Shushenskaya, Taum Sauk, Silver Lake, Ka Loko dams and Buffalo Creek Tailings Dam, as examples.

In an industry survey conducted for this study, a majority of dam owners indicated that spending on dam performance monitoring as a percentage of the estimated replacement value of the facility was generally less than 0.1 percent per year. The costs associated with potential loss of life, downstream property and environmental damage, and litigation resulting from a dam failure can be orders of magnitude higher than this amount. These points indicate that greater investment in performance monitoring can be a prudent risk reduction strategy. Effective and technically sound performance monitoring programs and rapid response with appropriate remedial programs can reduce risk by 10 times or more in many situations (Marr, 2007).

Traditionally some monitoring programs focused on dam structures as individual components. The Taum Sauk Dam failure and the Sayano-Shushenskaya incidents illustrate the need to look at dams from an overall systems perspective and not just as a collection of individual components. (Regan, 2010). What this means is that dam failures and safety incidents are seldom due to a single, easily identifiable cause. Failures are generally the result of a sequence of multiple actions that combine in ways to create uncontrolled release of water. Managing the risk associated with dam failures requires consideration of all factors that can possibly create a failure mode.

Making decisions on how risk can be best managed requires an overall systems assessment of the dam, including:

1. Knowledge of the current state of the risk at the dam based on the owner's performance monitoring program;
2. The potential for adverse interactions among the numerous components and subsystems at the project, for example seepage control system, dam operations systems, debris blockage of spillways, remote operational control, and organizational interactions;
3. The contributions of the various system failure modes to the risk;
4. Possible risk management alternatives;
5. The risk reduction each alternative would achieve at the specific site; and,
6. The associated cost for each risk reduction alternative.

Due to the individuality of each dam, a wide range of owner-management configurations and the differences between regulatory governance models for each project, there is no one answer to drive risk as low as reasonably practicable (ALARP) at a given dam. In each case, a performance monitoring program coupled with remedial actions when required are necessary for enhancing dam safety. A systematic approach to dam safety provides an opportunity to identify the best means and methods of instrumentation and monitoring which will help manage risks in a cost effective and timely manner.

## 1.2 Scope

This report describes current practices and guidelines for dam safety performance monitoring programs. The concepts presented in this document are not meant to be prescriptive. The elements discussed do provide an overview of important considerations which should be taken into account when reviewing an existing dam safety performance monitoring program or when developing a new program. Each dam owner must take into consideration their organizational structure, technical capability of staff, regulatory environment, and specific characteristics of their dam inventory in developing and maintaining their own dam safety performance monitoring program. ***Appendix E*** provides some sample checklists to aid a dam owner in developing its own monitoring program tailored to the conditions of each project.

***Section 2*** discusses how dams fail and the value of incorporating potential failure mode analysis in the dam safety performance monitoring program. Key concepts in this section are:

- Causes and rates of dam failures
- Hazard classification system (Low, Medium and High Hazard Potential)
- Performance states for dams (Normal, Caution, Alert)

***Section 3*** presents the reasons for and benefits of dam safety performance monitoring, and discusses the important role of performance monitoring as a risk management tool. Key concepts in this section are:

- Reasons to monitor performance of a dam
- Calculation procedure to estimate risk of a dam failure
- Estimating probability of failure

***Section 4*** presents key elements of a successful dam safety monitoring program, including the role of top management. Key concepts in this section are:

- Potential failure mode analysis
- Components of a dam safety program
- Organizational charts showing responsibilities and reporting requirements
- Contingency planning and emergency preparedness

***Section 5*** provides the components of a model surveillance, monitoring, and evaluation program. Key concepts in this section are:

- Training of personnel
- Visual surveillance
- Overview of instruments used for monitoring
- Instrument types for different failure modes
- Monitoring components for hazard potential and performance state
- Data collection and management systems

***Section 6*** outlines a systematic approach for procuring, installing, and operating performance monitoring systems. Key concepts in this section are:

- Ten elements of a systematic approach to obtain an effective monitoring program
- Definitions of Threshold Value and Limit Value
- Guidelines for repairing, replacing, removing and adding instruments to existing dam

***Section 7*** presents important guidelines for summarizing performance and evaluating monitoring data. Key concepts in this section are:

- Data reduction and presentation
- Data evaluation and interpretation
- Performance monitoring action states
- Threshold and Limit Values for instruments
- Developing monitoring summaries, conclusions and recommendations

***Section 8*** summarizes typical dam safety performance monitoring and data management programs employed by owners who responded to an industry survey. Key concepts in this section are:

- Supporting documentation
- Typical monitoring programs for dams with low, medium and high hazard potential

***Section 9*** summarizes and concludes this study. This Section addresses the responsibilities of Owners and summarizes the important elements of an effective dam safety monitoring and surveillance plan. Key concepts in this section are:

- Failure of a dam can cause great consequences, thus a dam can pose a high risk
- A dam's owner is responsible for its dam safety program
- The dam owner has a legal, moral and ethical responsibility to operate and maintain its dam in a safe condition
- Information from a performance monitoring program helps plan maintenance, remedial work and emergency action plans to reduce the risk of a dam failure
- A dam safety program must be coordinated with the owner's organization and participating members trained in their responsibilities and reporting requirements
- Performance monitoring programs need to change with technological advancement and with the changes in the dam and its surrounding environment over time to provide the best value as a risk reduction tool.

***References*** presents a listing of sources cited in this document.

***Glossary of Terms*** defines the common terms used for dams and the abbreviations used in this document.

***Appendix A*** provides an extensive bibliography on use of instrumentation in dams. An expanded bibliography was also develop and provided to CEATI as an electronic file.

***Appendix B*** summarizes the more commonly used instruments and some newer technology for dam performance monitoring.

***Appendix C*** provides some examples of dams with issues affecting performance monitoring systems.

***Appendix D*** provides a guidance tool to assess potential failure modes for a dam as an aid to develop a dam safety performance monitoring system.

***Appendix E*** presents a sampling of various dam safety forms which can be adapted to an Owner's dam.

Owners and chief executives for companies that own dams and impoundments are encouraged to read at a minimum Sections 1-4 and 9 as they have the ultimate responsibility for dam safety.

## 2.0 UNDERSTANDING HOW DAMS FAIL

A Dam is defined in this document as a structure that impounds fluids, usually water, and fluid bearing materials behind a barrier. Types of dams include water storage reservoirs, locks, weirs, mine tailings dams, and levees. Names of types of dams include Afterbay, Ambursen, Arch, Buttress, Cofferdam, Crib, Diversion, Double Curvature Arch, Earth, Embankment, Gravity, Hollow Gravity, Hydraulic Fill, Impoundments, Industrial Waste, Masonry, Mine Tailings, Multiple Arch, Overflow, Regulating, Rockfill, Roller-Compacted Concrete, Rubble, Saddle and Tailings. Fluid bearing materials include tailings, slurries, and industrial wastes.

Dams are built for many purposes including power supply, transportation, water supply, flood control, recreation, industrial and agricultural uses, fire protection, low flow augmentation, storage of slurries, storage of tailings and storage of industrial wastes. Dams can be made of concrete, timber cribs filled with rocks, stone blocks, steel sheet piling, or they can be formed from embankments of earth, rock fill or solid waste products such as tailings.

Dam failure as used in this document is defined as the uncontrolled release of water or other stored materials from a dam. Once stored materials start spilling from a dam, they tend to destroy more of the dam, expand the area of flow, and increase the rate of spillage. Consequently <u>any</u> uncontrolled release from a dam is considered a hazard and defined as failure. Note that consequences are not a part of this definition.

The public perception is that dams do not fail and those that do are typically small dams that fail by overtopping caused by large storms. While many dams have storage conditions such that failures have few or no repercussions, many dams have conditions that failure can cause significant flooding and other consequences downstream. Most large dams were historically viewed as having a low probability of failure. The historical record supports this view with an average annual probability of failure of $10^{-4}$ for a typical dam that is well designed, well constructed, and well maintained. (Baecher, et.al., 1979.

In reality, dams do fail, many times with catastrophic consequences to life, property, environment and assets. Because there are hundreds of thousands of dams in the world and many failures that were not included in Baecher, et. al., there is a high probability of failure of several dams each year. A comprehensive dam safety performance monitoring program has the objective of making sure that a specific dam does not become another failure statistic.

The consequences of a dam failure can vary from none to major. For example a minor overtopping that is remedied quickly has low consequences. Without immediate attention, the dam may further erode, leading to a complete breach and major consequences in many ways. Some potential consequences include the following:

- loss of life;
- damage to homes, businesses, transportation networks, lifelines, utilities, schools, industrial facilities and other improvements;
- damage to the environment;
- threat to other dams located downstream that can result in cascade failures;
- loss of stored materials;
- loss of use of the dam;

- loss of economic benefit from the dam;
- loss of the capital investment to the dam's owner;
- fines to the owner;
- criminal charges to owner or designer;
- lawsuits and other litigation;
- destruction of the owner's business; and
- damage to reputation of owner, design engineer and regulator.

Some examples of dams that failed with big consequences are presented in ***Table 2.1*** below.

**Table 2-1 Dam Failures and Causes** (Adapted from ASDSO, www.damsafety.org)

| Dam | Country | Type | Built | Failed | Fatalities | Probable Cause of Failure |
|---|---|---|---|---|---|---|
| Situ Gintung | Indonesia | Earthfill | 1933 | 2009 | 100+ | Overtopping; inadequate spillway |
| Ka Loko | USA (Hawaii) | Earthfill | Unknown | 2006 | 7 | Overtopping; blocked spillway; poor maintenance |
| Taum Sauk Upper Reservoir | USA (Missouri) | Earthfill | 1963 | 2005 | 0 | Overtopping; instrumentation failure |
| Silver Lake | USA (Michigan) | Earthfill | 1945 | 2003 | N/A | Design flaws |
| Machhu II | India | Masonry-earthfill | 1972 | 1979 | 1,300 | Overtopping |
| Teton | USA (Idaho) | Earthfill | 1975 | 1976 | 11 | Piping in core and foundation |
| Banqiao | China | Earthfill | 1952 | 1975 | 26,000 | Overtopping; inadequate spillway |
| Buffalo Creek | USA (W. Virginia) | Tailings (non-engineered) | 1960 | 1972 | 125 | Overtopping |
| Van Norman (San Fernando) | USA | Earthfill | 1930 | 1971 | N/A | Seismic liquefaction |
| Vajont (Vaiont) | Italy | Concrete thin-arch | 1960 | 1963 | 2,600 | Partial failure. Reservoir slope landslide |
| Malpasset | France | Concrete thin arch | 1954 | 1959 | 421 | Abutment failure |
| Alla Sella Zerbino | Italy | Concrete gravity | 1923 | 1935 | 100 | Structural collapse |
| South Fork (Johnstown) | USA (Pennsylvania) | Earthfill | 1839 | 1889 | 2,209 | Overtopping; spillway inadequacy and debris blockage |

Summary descriptions of the incidents at the Buffalo Creek Dam, the Taum Sauk Upper Reservoir Dam Failures and the Ka Loko Dam failures are given to demonstrate the significant risks associated with dam failures that resulted in big consequences.

**Photo 2.1 - Buffalo Creek Dam After Failure**

The Buffalo Creek Flood involved a small dam that failed on February 26, 1972, when the Pittston Coal Company's coal slurry impoundment Dam #3, located on a hillside in Logan County, West Virginia, USA, burst four days after having been declared satisfactory by a federal mine inspector. The resulting flood unleashed about 132,000,000 gallons (500,000 cubic meters) of black waste water, cresting over 30 feet (9.1 meters) high, upon the residents of 16 coal mining hamlets in Buffalo Creek Hollow. Out of a population of 5,000 people, 125 were killed, 1,121 were injured, and over 4,000 were left homeless. 507 houses were destroyed, in addition to 44 mobile homes and 30 businesses.

Dam #3, constructed of coarse mining refuse dumped into the Middle Fork of Buffalo Creek starting in 1968, failed following heavy rains. The water from Dam #3 then overwhelmed Dams #2 and #1. Dam #3 had been built on top of coal slurry sediment that had been collected behind Dams #1 and #2, instead of on solid bedrock. Dam #3 was approximately 260 feet (79.2 meters) above the town of Saunders when it failed. This un-engineered dam had no dam safety program.

**Photo 2.2 - Taum Sauk Upper Reservoir Dam**

On December 14, 2005, the northwest corner of the embankment dam for the Taum Sauk Pumped Storage Project's Upper Reservoir breached over a width of about 700 feet (213 meters), causing a catastrophic, uncontrolled, rapid release of water down the west slope of Proffit Mountain and into the East Fork of the Black River. The reservoir, located about 100 miles (160 kilometers) south of St. Louis, Missouri, was reported to have drained in about ½ hour. Approximately 4,300 acre-feet (5,300,000 cubic meters) of storage was released. The breach flow passed through a State park and campground area and into the lower reservoir. Upon leaving the Lower Reservoir area the high flows proceeded downstream of the Black River to the Town of Lesterville, MO. The incremental rise in the river level was about 2 feet (0.61 meters) which remained within the river banks. Due to the time of the failure, the campground downstream of the dam was not occupied and there was no loss of life. However, there were substantial environmental and economic impacts associated with this event. Following investigation and analysis, it was determined that substandard construction and instrumentation problems were significant factors in the failure. It was also determined that the foundation was not properly prepared and that the embankment rockfill deviated from the design specifications. Design requirements for rockfill dams were also evolving at the time Taum Sauk was originally constructed. As a result of this failure, the Owner has completely rebuilt the reservoir dam and revised the surveillance and monitoring program.

**Photo 2.3 - Ka Loko Dam**

Ka Loko Dam failed by breaching. This earthfill dam was built in 1890 to provide water for sugarcane farms. It was raised by 12 feet (4.2 meters) in 1911 to approximately 40 feet (13.9 meters) in height. It stored 350-400 MG (1200 acre-ft). The spillway was reportedly filled in and the height possibly raised in recent years. At last inspection it was classified as a Low Hazard Potential Dam. It was privately owned. It breached at 5 AM on March 4, 2006 following a period of heavy rains. The resulting uncontrolled release of water killed seven people and caused more than $100,000,000 (US) in property damage. The owner was indicted on seven counts of manslaughter but was later acquitted. This failure is attributable in part to an inadequate dam safety program and poor maintenance.

According to the National Inventory of Dams maintained by the US Army Corps of Engineers (USACE), there are approximately 85,000 inventoried dams in the US. This number does not include ash ponds, tailings dames or lock and dam systems.

***Figure 2.1*** tabulates numbers of dam by types as collected by the National Performance of Dams Program (NPDP) at Stanford University which maintained a data base of dams for 2000-2007 based on archived data and reported incidents. The NPDP data base contains approximately 77,000 dams. The number is less than the NID value because NPDP stopped adding dams after 2007 and the NID register more dams as state inventories became more comprehensive. Nevertheless, we can use the numbers in Figure 2.1 to conclude that more than 92% of the inventoried dams are earth and rockfill dams. Only about 3% are concrete dams. The remaining 5% are other types including timber cribs and masonry types. It is sobering to think that these various "other" types total about 4,000 dams and that about 1/3 of the total number of dams are classified as having significant or high hazard classifications.

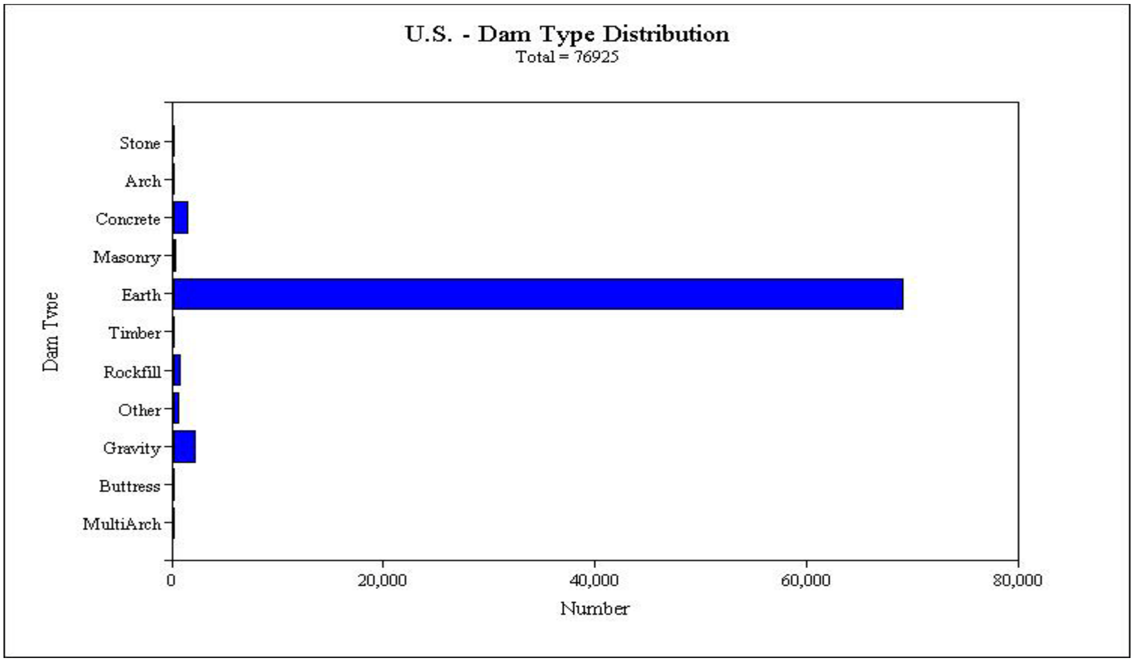


**Figure 2-1 U.S. Dam Types**

(From U.S. National Performance of Dams Program)

Figure 2.3 shows the number of US dam failures during each year from 2000 to 2007. The total number of failures in this eight year period was 91. Considering the total number of dams in the database of 76,927, the average annual rate of failure of this population of dams was about $1.5*10^{-4}$.

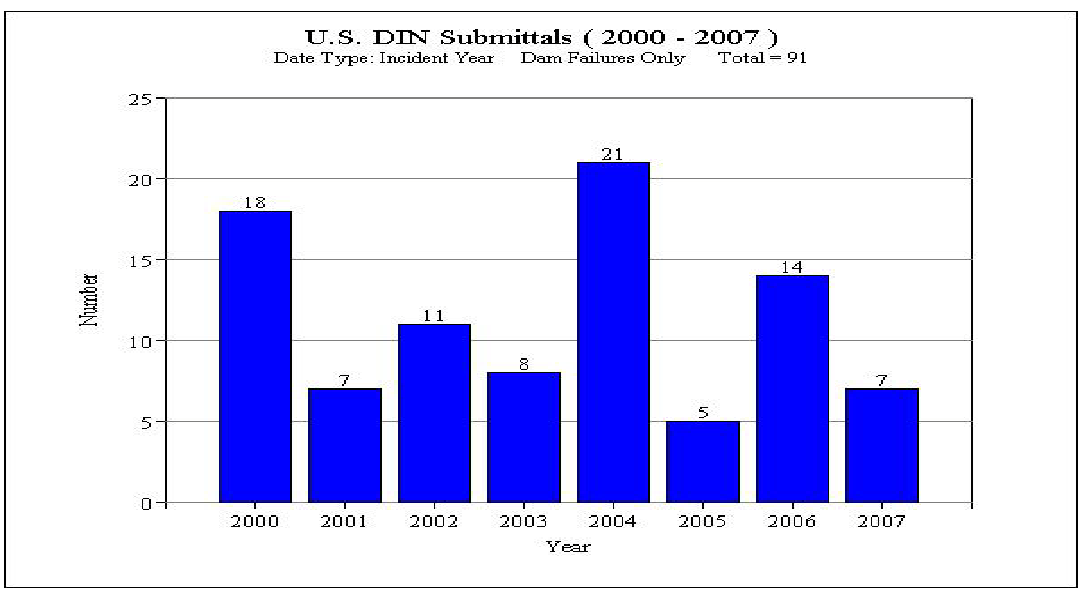


**Figure 2-2 U.S. Dam Failures**

(From U.S. National Performance of Dams Program where DIN = Dam incident Notification)

The reported incidents may be the result of a combination of excessive loads, design errors, construction deficiencies, unknown or different conditions, deterioration, operational errors or intentional action. They can also result from a combination of unanticipated systems interactions such as the performance of dam gates and other hydraulic features and control systems. Since the structural failure of a gate at Folsom Dam in 1995, there has been considerable focus given to the operability and reliability of hydraulic systems at dams during normal operations as well as during periods of high flow.

International dam incident data suggests that roughly one out of every 100 dams that have been built, have failed sometime in their life. If we assume that the average age of these dams is similar to the US, which is 50 years, this failure rate corresponds to an annual failure rate of any dam of $2*10^{-4}$. Roughly half of the failures of embankment dams having storage volumes that could cause significant flooding downstream, were due to piping, where "piping" is defined as a continuous process where flowing water removes soil particles from the downstream part of the dam until it collapses. Most concrete dam failures were associated with foundation failures. In contrast, dam failure statistics indicated that only a small percentage of dam failures result from stresses being too high in concrete dams or sliding instability of embankment dams. The points of this section are to demonstrate that dams do fail, describe the various ways that dams can fail, show that the average annual probability of failure of any dam is on the order of $1\text{-}2*10^{-4}$ and indicate that the consequences of a dam failure can be large.

## 2.1 Definition of Hazard

Dam failures and incidents of most concern involve unintended or uncontrolled releases or surges of impounded water. It may also involve a total collapse of the dam but that is not always the case. Damaged spillways, overtopping of a dam or other problems may result in a hazardous situation being created. In some cases, it is an unintended consequence of the dam's operations.

For the purpose of this document we are focused on events that lead to the uncontrolled release of quantities of water or other retained fluids in amounts that could lead to harm downstream and/or significant damage to the dam or related components.

During the last 40 to 50 years, the general understanding of how dams fail has progressed sufficiently to provide guidance for dam engineers and builders to help prevent similar failures. Lessons learned were codified and design practices standardized. However, dams continue to fail. Forensic examinations of recent dam failures often reveal that failures were not due to a single flaw but rather were due to a complex linking of dam condition, operational circumstances, flaws or errors that combined to result in failure, or unknowns that were not detected until after the failure. This linkage of "conditions" and "other factors" is one possible description of a "failure mode."

Various regulatory agencies have established a hazard potential rating system based on the consequences of a dam failure. As an example, ***Table 2.2*** presents the hazard potential classification system for dams, which was developed by the U. S. Army Corps of Engineers National Inventory of Dams (2011). The Interagency Committee on Dam Safety (2004) provides background materials, which supports these designations.

**Table 2-2 Federal Guidelines for Dam Safety Hazard Potential Classification Systems for Dams**

| Hazard Potential Classification | Loss of Human Life | Economic, Environmental, Lifeline Losses |
|---|---|---|
| Low | None expected | Low and generally limited to owner |
| Significant | No probable loss of life | Yes |
| High | Probable that one or more lives lost | Yes (but not necessary for this classification) |

Loss of human life potential is based upon inundation mapping of the area downstream of the project. Analysis of loss of life potential should take into account the population at risk, time of flood wave travel and wave height, and warning time. Indirect threats to life caused by the interruption of lifeline services due to dam failure or operation, i.e. direct loss of critical medical facilities, should also be considered. Economic, environmental, and lifeline impacts should be evaluated based on the incremental flood wave produced by dam failure, beyond which would normally be expected for the magnitude of the flood event which the failure occurs.

Typical dam hazard potential classifications can vary with regulatory jurisdiction; Hazard potential classification can be described more generally than as follows.

***Low Hazard Potential*** dams are located in areas where failure will damage nothing more than isolated buildings, undeveloped lands, or town or county roads and/or will cause no substantial economic loss or substantial environmental damage. Loss of human life is not expected. Economic, environmental, and lifeline impacts are considered to be low and generally limited to the owner.

**Significant *Hazard Potential*** dams are located in areas where failure may damage isolated homes, main highways and minor railroads, interrupt the use of relatively important public utilities and/or will cause substantial economic loss or substantial environmental damage.

***High Hazard Potential*** dams are located in areas where failure may cause loss of human life, substantial damage to homes, industrial or commercial buildings, important public utilities, main highways or railroads and/or will cause extensive economic or environmental losses.

In addition to its hazard potential, a dam may exist in different performance states. Many dams operate in very safe and well defined conditions. Others may have problems that require more attention and response. Three performance states are used in this document to help define the scope of a dam safety monitoring program.

***Normal* –** performance is within the design parameters with no anomalous behavior and no indicators of undesirable performance and is expected to remain in this state for the near future.

***Caution* –** performance is outside the range expected in the design, or anomalous behavior not anticipated in the design is occurring, or an indicator of undesirable performance is occurring at an increasing rate.

***Alert* –** performance is in a range where safety of the dam is in question, or performance is deteriorating and not controllable.

Various agencies use different definitions for performance states. For instance, USACE uses five (Urgent and Compelling, Urgent, High Priority, Priority and Normal). Others may find that too many options can create opportunities for confusion and disagreement. The National Dam Safety Review Board of Canada uses four (Satisfactory, Fair, Poor and Unsatisfactory). We are recommending that the above three performance states be used because they imply an action. However, an Owner might choose to call them by different names. Examples include:

- ***Normal*** = Green, Safe, Satisfactory, Okay
- ***Caution*** = Yellow, Alert, Review, Fair, Poor
- ***Alert*** = Red, Action, Response, Unsatisfactory

It is highly recommended that definitions of hazard potential and performance state be established and adopted by the dam owner. These definitions should be understood and consistently used by all parties associated with dam safety for that particular project.

## 2.2 Potential Failure Modes

A potential failure mode is any means by which any component of a dam may fail to perform its intended function. Understanding potential failure modes for dams is the basis of a good dam safety program (Regan et al., 2008; USSD, 2002). The dam owner needs to know the general behavior characteristics for various types of dams and identify all potential failure modes under static loading, normal operating water level, flood, and earthquake events including all external loading conditions for water retaining structures. Only then can the owner assess those potential failure modes of enough significance to warrant continued awareness and attention to visual observation, monitoring, and remediation, as appropriate. Understanding the general behavior characteristics of dams requires knowledge of how dams work and how they may fail.

The causes of dam failures and incidents have been catalogued (ASCE 1975 and 1988, National Research Council 1983, ICOLD 1992 and NPDP, 2006).

In some cases, failure resulted from an unintended consequence of normal operations. This was the case in 1976 when an increase in discharge by the Army Corps of Engineers from Mud Mountain Dam coincided with the removal of flashboards at the Puget Power & Light diversion dam downstream. This resulted in a much higher than normal surge of water coursing down the White River which overwhelmed and killed two children. (State of Washington, Department of Ecology, 1994).

Dam failures may be caused by structural deficiencies in the dam itself. These may come from poor initial design or construction, lack of maintenance and repair, the gradual weakening of the dam through the normal aging processes, or the development of an unanticipated or undetected failure condition. However, they can also be caused by other factors including, but not limited to, debris blocking the spillway, flooding, earthquakes, volcanic lava flows, landslides, improper operation, vandalism, or terrorism.

Dam failures can result from any one or a combination of the following conditions:

- prolonged periods of rainfall and flooding, which cause most failures;
- inadequate spillway capacity, resulting in overtopping of the embankment;
- internal erosion caused by loss of soil from the interior of the dam or its foundation;

- animal burrow impacts on earthen dams;
- external erosion due to lack of maintenance;
- improper maintenance, including failure to remove trees, repair internal seepage problems, or maintain gates, valves, and other operational components;
- improper design or use of construction materials;
- failure of upstream dams in the same drainage basin;
- landslides into reservoirs, which cause surges that result in substantial erosion or overtopping;
- destructive acts of terrorists; and,
- earthquakes, which typically cause longitudinal cracks at the tops of the embankments, leading to structural failure.

Further discussion on how to integrate Potential Failure Mode thinking into a Performance Monitoring Program is presented in ***Section 4***.

## 2.3 Embankment Dams & Abutments

The principal causes of embankment dam failures and incidents are:

- overtopping from inadequate spillway capacity, spillway blockage, or excessive settlement resulting in erosion of the embankment;
- erosion of embankments from failure of spillways, failure or deformation of outlet conduits causing leakage and piping, and failure of riprap;
- embankment leakage and piping along outlet conduits, abutment interfaces, contacts with concrete structures, or concentrated piping in the embankment itself;
- foundation leakage and piping in pervious strata, soluble lenses, and rock discontinuities;
- sliding of embankment slopes due to overly steep slopes, seepage forces, rapid drawdown, heavy prolonged rainfall, or erosion;
- sliding along weak seams in foundations;
- cracking due to differential settlements; and,
- liquefaction from seismic loading.

Earth embankments particularly may be damaged by distortions at critical points. Differential settlement may be severe at steep abutments and at structural interfaces where effective compaction is difficult to achieve. At these locations, deformation of the fill may open dangerous paths of seepage. Many failures along outlet conduits have occurred from this reason. Liquefaction of foundation soils resulting from strong earthquake motions can be a concerning factor depending on construction practices in place during construction.

Although properly constructed embankments are able to accommodate substantial movement, they have relatively poor resistance to overflow; so their freeboard and associated spillway capacity must be determined conservatively.

## 2.4 Concrete Dams & Appurtenant Structures

In contrast, most concrete dams can withstand overtopping for at least several hours. The key factor to their safety may be the resistance of the foundation to scouring by spilling water. The common causes of concrete dam failures and incidents can be summarized as:

- overtopping from inadequate spillway capacity or spillway blockage resulting in erosion of the foundation at the toe of the dam or washout of an abutment or adjacent embankment structure;
- foundation or abutment leakage and piping in pervious strata, soluble lenses, and rock discontinuities;
- sliding along weak discontinuities in foundations; and,
- dissolution of limestone rock foundations over time.

Arch dams carry large loads. Their integrity depends inherently on the strength of the abutments and the foundation. Failure may be caused by rock deterioration or by shearing under water pressures. Weakening of arch support also may be triggered by foundation erosion.

Gravity dams are noted for durability. Because of their large masses, they can survive considerable weathering and site deficiencies. However, some have failed where foundation elements were susceptible to sliding. A few buttressed dams also have shown this tendency.

ICOLD Bulletin 79 (1991) reported that several concrete gravity dams have experienced problems with Alkali-Aggregate Reaction (AAR). Damage to concrete caused by AAR takes a variety of forms, the most common being surface cracking and, sometimes, exudations of gel at the exposed face. Such damage has been reported in many countries, particularly in those with hot-wet climates. The time the damage first appears varies from a few months to several decades after construction. Cracks usually grow wider with time and site repairs are often found to be ineffectual. The AAR problem has been known to cause significant impacts on electro-mechanical power generation equipment. AAR problems can also cause operational problems with spillway gates and generating equipment.

Concrete deterioration per se may have different causes, AAR being only one among many. Some other causes are swelling due to expansion of the cement (from free lime) or swelling clay in the aggregate, external factors such as cycles of freezing and thawing or the attack on concrete by water in some forms such as extremely pure water, acidic water, and sulfate-rich water. In many cases, there may be a combination of causes, so that when there is an AAR reaction in the concrete for example, the effects of other factors are aggravated or accelerated.

## 2.5 Dam Life Phases

USSD (2008) describes the life of a dam as having several distinct phases. Performance monitoring needs vary depending on which phase the dam is in. Dam life phases can be categorized as:

1. Design phase;
2. Construction phase;
3. First reservoir filling phase;
4. Long-term (or normal operations) phase;
5. Loads exceed design conditions; and
6. Periods of unexpected performance.

Field investigation work typically provides the information for basic characterizing of the geology and materials at and around the dam site. Instrumentation used in the design phase helps establish baseline conditions for design and may also is used during construction and first filling to monitor and evaluate changes in baseline conditions. Typical monitoring during this phase might include monitoring to establish existing ground water conditions and movement of any potentially unstable areas. Instrumentation may be used in the design phase to provide information on key performance parameters for the dam. For example, slopes with weak zones might be instrumented to verify design strength for the weak materials. This instrumentation might be incorporated into the long-term monitoring phase as well.

Issues that come up during the construction phase of a new dam, or during the modification of an existing dam, involve confirmation of design parameters, changes in groundwater and stability conditions on site and at adjacent sites, worker safety, and construction quality control. This information can become especially important if design modifications are required as a result of unexpected performance. This is the phase where most of the instrumentation used is dams is installed. These instruments may be used to monitor performance during construction, first filling, steady state operation of the dam, and extreme loading .

> ***"Analysis of more than 1,100 dam failures and safety incidents indicates that about a third occurred during construction or within 5 years of completion. There is still a significant probability of failure later in a dam's life with approximately half of the failures occurring after 10 years of operation."***
>
> Adapted from Patrick J. Regan, FERC, 2008

The first filling phase is one time in the life of the dam when visual surveillance and instrumentation monitoring are imperative. As the reservoir is filled, the seepage resistance of the dam, foundation, abutments, and reservoir rim is being tested for the first time. Full reservoir load also tests the structural strength and integrity of the dam. During this time, instrumentation typically is used to:

- provide an early indication of unusual or unexpected performance,
- provide confirmation of satisfactory performance of the design and construction,
- provide information and data so that actual performance of the dam under reservoir load is better understood,
- identify elements that need further examination.

A filling plan with staged fill and hold points is generally required so that monitoring data can be collected and evaluated at each stage. When performing major repairs or modifications that requires reservoir dewatering, a refilling plan should be developed.

Performance monitoring during the long-term (normal operations) phase has a similar role to the first filling phase. At this point in the life of the dam, a significant body of information has most likely been developed. This can be used to identify the dam safety issues of current concern. These issues may be significantly different that those existing prior to initial filling. Therefore, a new assessment of the areas of concern and the information that should be provided by the monitoring program may be appropriate. Additional instrumentation may be warranted for areas with unexpected performance. Some instrumentation may be retired if it no longer serves a purpose. This might be the case for slope inclinometers used to monitor horizontal movements of the dam's slopes and its foundation for stability during construction.

> *"Because the monitoring needs for a particular dam change over time, it is important to reevaluate the monitoring program on a regular basis."*
>
> *USSD, 2009*

Some dams will show unexpected performance. The visual and instrumentation monitoring associated with this phase should focus on defining the developing problem and on providing a means of confirming that the problem has been successfully addressed by the implemented remedial actions.

## 2.6 Other Factors Influencing Potential Failure in Dams

An examination of dam failures and safety related incidents shows that most were not caused by a single, easily analyzed, component failure but rather by interactions between various components, operational considerations, and lack of appropriate organizational response. In order to reduce the risk associated with a dam to a level that is as low as reasonably practicable, we must do our best, within the limits of our current knowledge and understanding, to recognize potential failure modes before they begin to develop and to monitor those failure modes over time. To achieve this goal, dam owners must find an effective way to integrate operations, engineering, and dam safety performance monitoring into a comprehensive dam safety program.

Performance monitoring and record keeping are essential to making well-informed decisions regarding the condition of the dam. Ideally, dam information would be readily available and organized for a straightforward and timely assessment of the condition of the dam. Within the context of dam safety, information collected from instruments, physical observations, photographs, design drawings, stability calculations, field explorations, and operational and maintenance history should be combined into a single readily accessible folder to allow the engineer, policy maker, and dam safety official to make informed decisions relating to the condition and/or operation of a dam. Collecting data and filing it is not a replacement for sound engineering judgment and experience. Performance monitoring documentation is a tool to help track information and its change over time and to support sound engineering judgment and informed decision making.

As the systems that control our dams get more complex and more automated, and more are remotely operated, the opportunities increase for undetected incidents that can lead to dam failure. Understanding factors relating to dam safety, such as owner risk awareness, management responsibility, personnel training, and system and sub-system interactions, become increasingly important.

# 3.0 WHY MONITOR PERFORMANCE?

A high quality design, operation, and maintenance program for a dam does not guarantee freedom from unexpected events that affect the safety of the dam. There are many historical cases of dam failures and incidents where an early warning sign of failure might have been detected if a good dam safety monitoring program had been in place. A performance monitoring program provides the information that is needed to develop a better understanding of the on-going performance of a dam. Knowing that the dam is performing as expected is reassuring to dam owners. The ability to detect an unexpected change in this performance is critical because the dam owner is directly responsible for the consequences of a dam failure (ASCE, 2000).

> *"Monitoring of every dam is mandatory because dams change with age and may develop defects. There is no substitute for systematic and intelligent surveillance"*
>
> *Peck, 2000*

As stated in ***Section 1***, owners have an inherent responsibility to exercise an appropriate standard of care to maintain their dams as safe as reasonably practicable. They must understand the entire process of how their dam performs throughout its entire life based on a thorough knowledge of the design, construction and prior performance of the dam. To ensure good performance, the performance of the dam must be monitored throughout its life and remedial work undertaken whenever the performance monitoring program indicates such work is required. Performance monitoring can range from simple to comprehensive depending on the nature and size of the risks. This section discusses the reasons for and benefits of dam performance monitoring.

## 3.1 Reasons for Performance Monitoring

Dams and their appurtenant structures are significant engineering facilities. They store water and occasionally other fluids and waste products that if released in an uncontrolled fashion can cause great harm downstream. In planning and designing these facilities, there are many technical issues that need to be addressed, including the hydrology of the watershed, geologic, geotechnical and structural characterization of the dam and appurtenant structure site, dam type and construction materials, analysis and design tools, construction processes and monitoring, advances in the state-of-the-practice and dam engineering knowledge. None of these issues are completely deterministic. All involve uncertainties, meaning that there are gaps in the knowledge base associated with each that must be addressed for the entire life of the dam facility. Performance monitoring provides an effective means to help manage these issues and their uncertainties. The interested reader might also consult other references that focus on identifying and quantifying uncertainties in dam design and performance (Bowles, 1988, 1997, 2003; Hartford and Baecher, 1994; Chauhan and Bowles, 2003, USACE, 2010).

> There is some chance that any dam can fail.
>
> The consequences of a dam failure can be catastrophic and exceed many times the value of the dam.
>
> A person with management responsibility for a dam can be held personally liable for the consequences of a dam failure.
>
> Failure of a dam that causes loss of life can lead to criminal charges against the owner of the dam.

Risk and uncertainty analysis of dam safety assist the dam owner in evaluating the needs for dam safety improvement, selecting and prioritizing remedial and corrective actions, and improving the operation, maintenance, and surveillance procedures. The USACE, USBR, FERC, and U.S. Department of Homeland Security, including FEMA, are actively using risk based assessment and design methodologies to improve the safety of dams and levees. The use of risk assessment in dam safety management is also advocated by ICOLD (1988). The USACE is currently developing risk based design procedures for dams and levees so we can expect more application of risk management techniques in the future.

Owners will not pay for very conservative designs to minimize the potential effects of the many uncertainties in a dam; nor will society accept the potential risks from large uncertainties. Usually designers cannot justify, and owners will not accept, the expense of investigations and studies required to remove all uncertainty about the conditions and parameters that affect dam design. Thus, all dams exist with multiple sources of unknowns and uncertainties.

Where the consequence of these unknowns and uncertainties might threaten the success of a project, a performance monitoring program is implemented to monitor the actual functioning of the dam. The observations and measurements are used to identify potential undesirable outcomes, including failure, and make plans to take preemptive action early. Generally, the lowest overall cost to a project to address the potential impacts from unknown and uncertain conditions is to monitor the dam's performance to determine the need for remedial work and then complete that work as early as possible. An effective performance monitoring program is vital to this approach.

Since there are numerous uncertainties from various disparate sources, there will always be a finite probability that a dam will fail. Lumb (1968) illustrated this issue with the figure reproduced in ***Figure 3-1***. It shows two important points: (1) failure can occur anytime during the life of a dam, and (2) the probability of failure is higher during the early phase when it is constructed and first put into operation, drops to a steady value over the service life, and climbs again at the dam approaches the end of its working life. Thus, performance monitoring is useful over the life of a dam to determine whether any condition is developing that might lead to a failure of the dam.

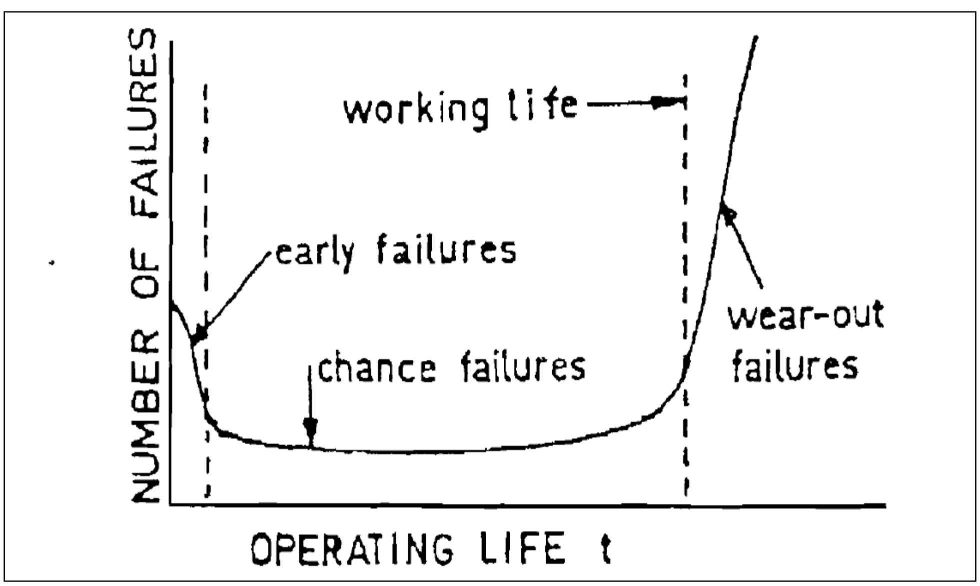


**Figure 3-1 Failure Rates of Dam**

One useful tool that has been widely used to address some of these potential performance issues, particularly during construction and the early life of a facility, is the "Observational Method" (Peck, 1969). Peck's method uses available information to make reasoned assumptions in the design about uncertainties, then implements an observational program during construction to measure how the design is performing, and prepares to take remedial measures if the measurements show performance that is different from that considered in the design and unacceptable. Today, the consequences of a dam failure can be so large that we need to broaden Peck's original Observational Method to consider the larger risks that dams may pose to the public as well as to their owners.

A comprehensive program of dam safety performance monitoring builds on Lumb's observations and extends Peck's Observational Method into a broad-based approach to risk management. However, it must be done carefully and methodically, and the results must be assessed promptly to make the critical decision of whether a dam is performing adversely in a way that corrective or emergency actions are needed. In concept, these principles are simple and easy to understand issues. In practice, they may be difficult to quantify or substantiate.

***Table 3.1*** summarizes the principle technical reasons to implement a performance monitoring program for a project. Dunnicliff (1988, 1993) discusses some of these points. Marr (2007) developed and described the full list given in ***Table 3.1*** for civil engineering applications. Some of these reasons may not apply to a specific dam.

**Table 3-1 Reasons to Monitor Dam Performance**

| Reason | Description |
|---|---|
| 1 | Indicate impending failure. |
| 2 | Provide a warning of unacceptable performance. |
| 3 | Reveal unknowns. |
| 4 | Evaluate critical design assumptions. |
| 5 | Assess contractor's means and methods of construction. |
| 6 | Minimize damage to existing structures during construction. |
| 7 | Control construction to avoid performance problems. |
| 8 | Control operations to avoid performance problems. |
| 9 | Devise remedial measures to fix problems. |
| 10 | Improve performance to meet desired goals. |
| 11 | Advance state-of-knowledge. |
| 12 | Show change in performance over time to predict future conditions. |
| 13 | Document performance for assessing and allocating damages. |
| 14 | Be a good neighbor and inform stakeholders. |
| 15 | Comply with regulatory and/or governance guidelines. |
| 16 | Reduce litigation associated with claims and failure. |
| 17 | Show that dam is performing well. |

**Adapted from Marr (2007)**

Performance monitoring programs may save lives by giving advanced warning in time for people to get to a safe area (Dunnicliff and Green, 1988). A good monitoring program may reveal an unknown condition early enough that changes can be made that greatly reduce the risk of failure.

Effective monitoring can save money and reduce risk by decreasing the likelihood of an unexpected failure that delays or destroys the project, if preventative and remedial measures are not put into place before the failure occurs.

### 3.1.1 Reasons to Monitor During Construction and First Filling Phases

As shown in ***Figure 3.1***, dams have a higher rate of failure during the construction and first filling phases. Several of the reasons listed in ***Table 3.1*** to monitor performance may apply during these stages. It is during this time that assumptions used in the design may prove to be wrong, or that construction means and methods need to be changed. First filling is especially important because it provides "stress testing" of the dam under full loading for the first time (ICOLD, 1988). Instruments to measure movements and internal pore water pressures can show which elements of the dam may be underperforming. Warnings of unexpected performance during construction and first filling may allow corrective actions to be taken to remove the problem with little impact to the project cost and schedule. This approach is very effective risk management.

Performance monitoring can show the impacts of defective materials or unexpected conditions on dam performance. A seam of weak material, a zone of high compressibility, or a pocket of high pore water pressure may go undetected in the exploration work and not be considered in the design, but may show up in the construction if performance is being monitored. Construction generally produces homogeneous materials but there may be off-spec materials, soft spots, weak seams, or sources of water that go undetected during construction. These hard-to-detect details may become the primary cause of undesirable performance during construction or after the dam is put into operation.

Performance monitoring may be used to determine whether the contractor's means and methods meet the specified performance requirements. Some facilities must be instrumented to meet the requirements of specific regulations. For example, in the U.S., the Federal Energy Regulatory Agency (FERC) requires a performance monitoring program on most dams under its authority. (FERC Guidelines, www.ferc.gov)

Data from a good monitoring program may help prove the existence or absence of a differing site condition claim by the Contractor and lead to an equitable arrangement between the Contractor and the Owner. Results from a performance monitoring program have the potential to save significant money and management time in reducing the frequency of litigation, its duration, and the size of the claim.

Data from an instrumentation program can help maintain the various parties' confidence in the performance of the work and free them to focus on other issues. Some of the most effective monitoring programs boil the results down to a green-yellow-red light scenario with the objective to keep all performance measures within the green zone.

### 3.1.2 Reasons to Monitor During the Operating Life Phase

***Figure 3.1*** shows that the probability of failure is lower during the operating phase of the dam. Baecher, et.al. (1979) used the history of dam performance to conclude that the average annual failure rate of a modern, engineered dam is about $10^{-4}$ per year. They also indicated that about half of the recorded failures were experienced during construction and first-filling and the rest over the operating life of the dam. Older dams and those will little to no engineering are expected to have a higher failure rate. Dams fail during their operating life due to time related processes that change the condition or properties of the materials use to construct the dam or the occurrence of loads that exceed those for which the dam was designed. Examples include time for water to flow through the core and enter the downstream shell to create stability problems, development of internal erosion and piping over time, loss of soil or rock strength over time due to increased presence of water, external changes such as erosion that degrade the dam's characteristics, and deterioration of metal and concrete materials by corrosion. Many of these may occur slowly over time starting with first filling but the manifestations are below ground beyond detection by visual inspection. Also, the storm runoff into the reservoir may increase due to development upstream or the effects of climate change so that the spillway no longer has adequate capacity, or more hydraulic load than the dam has ever experienced develops.

Most of the reasons given in ***Table 3.1*** to monitor performance also apply to the operating phase of the dam, except numbers 5, 7 and 13. Probably the most important reason to monitor performance during this phase is the last one – show that everything is OK. The public increasingly wants to know the condition of any facility that might impact their lives. The consequences of adverse performance increase over time as resources become more strained and downstream development raises the number of people and facilities that might be impacted by a failure. The public and government are increasing their expectations for the dam's management team to take direct responsibility for the consequences of any failure.

Other significant factors for performance monitoring during the operational life of a dam include demonstrating that the dam is operating as expected, showing the change in performance over time to predict when a green condition might become a yellow or red condition, and using the instrumentation data to help control the operation of the dam.

### 3.1.3 Reasons to Monitor During the Extended Life Phase

***Figure 3.1*** shows that the probability of failure increases as the dam approaches and extends beyond its working life. This is mainly caused by the deterioration of materials used to construct the dam over time and the probability that the experienced loads will exceed those for which that dam was designed. Design requirements for storms and earthquakes are tending to increase over time as more historical information on extreme events becomes available. Development upstream of dams is increasing runoff that must safely pass through the spillway. Climate change is increasing the severity of storms in some locations. Soils may become weaker, more compressible and more permeable over time. Concrete may deteriorate, water stops may fail, and metals may corrode away. All of the reasons to monitor performance given in ***Table 3.1*** apply during this phase except perhaps 5, 7, 8, 13 and 16.

Performance monitoring during this phase has significant positive benefits. It can show that the dam continues to function well and can remain in service beyond its original design life. It can show which elements require remedial work or replacement to extend the operational life of the dam (ASCE, 2000). It can reduce risk by indicating poor performance in time to complete remedial measures before failure occurs, or move people and assets out of harm's way.

The original instrumentation placed in the dam during construction or operation may have deteriorated and no longer functions, especially if there is not an effective maintenance program in place to maintain the various devices. As a dam approaches the end of its working life, a detailed review should be undertaken of the dam's performance and the status of the monitoring program to determine what needs to be done to upgrade the performance monitoring system for the dam to safely operate beyond its original design life. At conception, owners usually have a design life or service life in mind. For instance, tailings dams properly closed out are anticipated to work forever. Two important points to consider are that a dam will wear out if not maintained and that dams need more review, as they get older.

## 3.2 Quantifying Benefits of Performance Monitoring

Most professionals responsible for maintaining the dam safety-monitoring program have considerable difficulty justifying the expense necessary to execute an effective monitoring program. Over time, almost every dam safety program faces cuts in its budget and resources. This is the natural tendency for management personnel who look at a history of great performance and do not comprehend that this is no reliable indicator of future performance. *Section 3.1* described the engineering reasons for monitoring performance of a dam. These are the talking points in engineer-to-engineer exchanges. They are the language used in proposals and publications; but they are not the language of business. Business professionals can read and comprehend the discussion in the previous section but they have trouble translating the words into perceived benefits that add value and justify the expense.

This section provides an approach to quantify these benefits. While the suggested method is not precise, it is generally sufficient to decide how much of a dam safety performance monitoring program is worthwhile for many situations. The suggested method is based on concepts of decision theory and risk analysis that are increasingly used by the USACE, USBR and FERC.

Risk analysis and decision theory provide a framework for managers to make decisions when faced with incomplete and uncertain information. They use estimates of uncertainty and probabilistic analyses to quantify potential outcomes. Decisions are based on the desirable outcomes with the highest likelihood of success or lowest chance of failure. Most graduate level business programs teach decision theory as a recognized decision making tool.

Risk analysis embodies a wide range of scientific theory and engineering analyses to identify potential sources of risk, determine the probability of occurrence for each source, and estimate the consequences from each source of risk. Total risk is the summation of the probability of each source of risk occurring times the consequences of that occurrence.

*RISK = (PROBABILITY OF FAILURE) X (CONSEQUENCES OF FAILURE)*

Risk can be decreased by actions that reduce the probability of a source of risk occurring or reduce the consequence of such event if it occurs. Performance monitoring for dam safety is one very effective tool to help reduce the probability and consequences of failure, thereby reducing risk.

As an example, consider two dams of similar construction in a similar setting. Both dams might have the same probability of failure. However, Dam A is located 10 miles upstream of a major city sited within the flood plain of the river and Dam B outlets directly to the ocean 10 miles away and has a floodplain with no improvements and no people. Clearly, Dam A poses a much higher risk than Dam B even though they have a similar probability of failure. Dam B could have an even higher probability of failure than Dam A; yet pose less overall risk. Common sense tells us that a larger monitoring program that helps lower risk is justifiable for Dam A. However, risk is in the wallet of its recipient. While failure of Dam B might present much less societal risk, its risk of failure might still be unbearable to its stakeholders who would suffer from the physical loss of the facility and its economic benefits. To them a monitoring program that reduces their risk by an order of magnitude might be very desirable. For management to come to these conclusions without considerations of risk is very difficult.

Risk analysis provides input for decisions when important factors are uncertain. A manager may choose a course that minimizes risk, or the manager may choose a course in which the benefits achieved by lowering risk outweigh the costs of achieving that reduction. Both approaches require a quantification of risk.

In its simplest form, the approach to help quantify the benefits of instrumentation by reducing estimated risk is as follows:

1. Determine all ways by which the dam can fail or experience undesirable performance. These are called Potential Failure Modes (PFMs).
2. Estimate the probability of occurrence of each of these events during the period of interest.
3. Define the consequences of each event and estimate the potential cost of each consequence.
4. Calculate risk as the probability of occurrence of each event times the consequence of the event if it occurs.
5. Estimate the reduction in probability of occurrence of each event with an effective performance monitoring program.
6. Estimate the cost of each consequence with an effective performance monitoring program in place.
7. Calculate the reduced risk with the performance monitoring program in place.
8. Determine the expected reduction in risk produced by using a performance monitoring program by subtracting the reduced risk with monitoring from the original risk estimate.
9. Estimate the full cost of a performance monitoring program to achieve the reductions in risk estimated in prior steps.
10. As long as the cost of the performance monitoring program is a fraction of the estimated reduction in risk then the monitoring program is worthwhile.

A dam safety performance-monitoring program can be used to help reduce probabilities of failure, minimize damages and avoid delays. Each of these elements can be assigned a cost. Consequences may include added construction costs, damages to downstream facilities, delays, litigation, loss of use, loss of facility, loss of life, damage to the environment, etc.

## 3.3 Example Demonstrating How to Use Risk Calculations to Develop a Performance Monitoring Program

It is easiest to illustrate how to use risk assessment to determine the value of a performance monitoring program with an example. ***Figure 3.2*** shows one section of an earthen dam. This dam is a composite of situations at various earth dams and does not represent a specific dam that is in existence. The dam is constructed on sedimentary rocks that include limestone in a seismically active region. The dam was constructed in the 1930s using a method called hydraulic filling that was common during that time. The core was placed by hydraulically transporting fine grained silts and clays from a nearby borrow area and allowing them to settle into place.

This produces a core of low density with the potential for horizontal lenses of silt that have higher permeability. Excessive seepage can occur through cores of this type and create higher than desired pore pressures in the downstream shell. A core of this type may also lose most of its shear strength when subjected to significant earthquake shaking. The upstream and downstream shells were place by end dumping from rail cars with no compaction, but the upstream embankment is more porous and denser. The material is a non-plastic mixture of gravel, sand and silt with cobbles and boulders. Its density varies from loose to dense. The material might be susceptible to strength loss during a significant earthquake. The transition zones were created by hydraulically sluicing the fines out of the end dumped glacial till into the core of the dam. The low level outlet has become inoperable. Over the last few years, springs have appeared at some locations along the downstream toe and left groin and portions of the crest on the left side have settled up to ¾ of an inch.

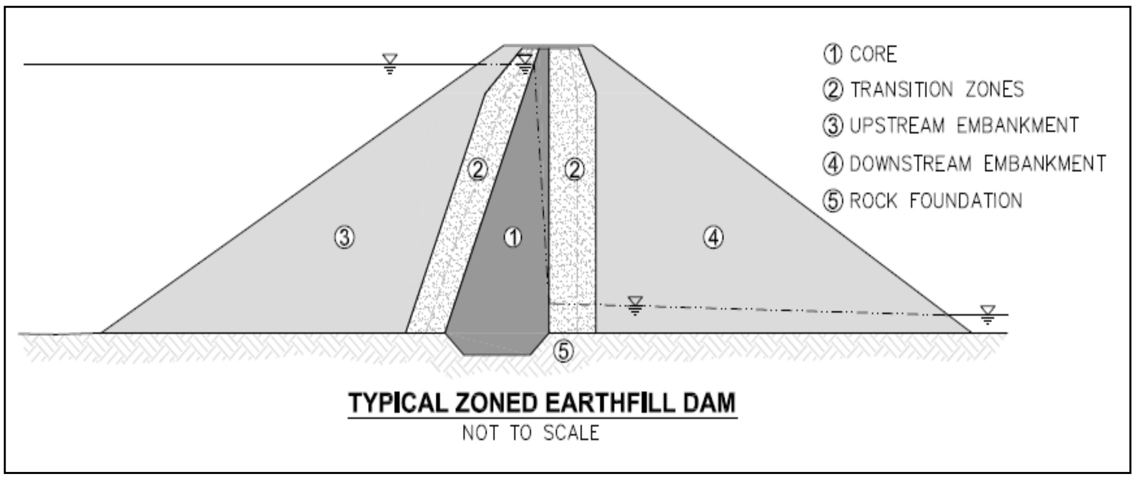


**Figure 3-2 Section Through Earthen Dam**

The dam was built and the reservoir filled without major problems. Since the dam was built, many homes and some industry were built downstream of the dam within the flood plain.

The gradual appearance of seepage and wet areas along the downstream toe prompted the Owner to assemble a Review Team to evaluate the condition of the dam.

After becoming familiar with the information on the dam, the Review Team prepared a list of potential failure modes for the dam. They identified about 20 modes. ***Table 3.2*** summarizes those with the greatest potential to create a breach of the dam resulting in uncontrolled release of water.

**Table 3-2 Potential Failure Modes that Create Uncontrolled Released of Water**

| Potential Failure Mode | Potential Consequences | Likelihood of Occurrence | Possible Mitigation Measures |
|---|---|---|---|
| Major slide triggered by earthquake | Uncontrolled release of water and total breach | 5% in 50 years(0.1% annually) if high pore pressures in downstream embankment; otherwise 0.5% in 50 years (0.01% annually)[1] | Major remedial work to drain and flatten downstream embankment ($20M) |
| Cracking of dam caused by dissolution of limestone in the foundation that causes the observed settlement and leads to seepage through a crack in the core, internal erosion and piping, then breach and loss of containment | Uncontrolled release of water and total breach | 0.2% per year[2] | Grout the foundation to fill voids and slow seepage ($30M) |
| Slide along base of embankment caused by high pore pressures in downstream foundation from excessive seepage through solution cavities in limestone | Uncontrolled release of water and total breach | 1% per year if pore pressures are high; very low if no excess pore pressures from under seepage[3] | Install a grout curtain and add relief drains along downstream toe ($13M) |
| Piping though embankment-foundation contact caused by high pore pressures | Uncontrolled release of water. | 1% per year if high pore pressures in foundation; 0.01% per year if no excess pore pressures from under seepage[4] | Install a grout curtain for cutoff and add relief drains along downstream toe ($8M) |
| Overtopping by excessive inflows | Uncontrolled release of water and total breach | 5% in 100 years (0.05% annually)[5] | Re-evaluate probability maximum flood and check adequacy of the spillway |

Notes:

1. Based on USGS design earthquake and assumption that 50% chance that dam will fail if that earthquake occurs.
2. Based on expanded fault tree analysis shown in Figures 3.3 and 3.4 by subject matter expert in dam design.
3. Based on quantified judgment of subject matter expert in stability analysis of dams.
4. Based on quantified judgment of subject matter expert in piping of dams.
5. Based on storm runoff models.

For the sake of this example, assume that the consequences of a complete breach of the dam are as follows:

- 100 lives lost if no time for warning; 1 life lost if time for warning and evacuation
- $500,000,000 downstream property loss
- $28,000,000 environmental cleanup due to metals in sediments in reservoir
- $10,000,000 litigation expenses
- $50,000,000 value of the dam which becomes a total loss
- $22,000,000 per year current value of lost revenue from power generation.
- Loss of reputations – not quantifiable

The above information is sufficient to look at the potential risks resulting from a total breach of the dam. ***Table 3.3*** summarizes results for the risk assessment for the events that lead to an uncontrolled release of water and assuming no timely warning can be issued. The annual potential financial risk is $14M per year with a potential life loss risk of two per year. Note that this dam classifies as a High Hazard Dam due to the potential for loss of life. For these approximate calculations, results are typically rounded to one or two significant digits because of the impreciseness of the data. If a timely warning could be made, the potential life loss risk would reduce to nearly zero but the potential financial consequence would remain the same.

The owners plan to continue using the dam for at least 25 years. The present value of the $14M annual financial risk over 25 years at a 7% discount rate is $163M, not including a significant potential for loss of life. One approach would be to perform all the mitigation steps listed in ***Table 3-2*** but the cost is large and the benefit uncertain due to incomplete information about the current state of the dam and its future performance. This is a prime candidate for employing a performance monitoring program to better define the condition of the dam and provide information with which to make decisions to reduce the risk created by the dam.

**Table 3-3 Potential Risks for Existing Conditions and Available Information**

| Risk Event | Annual Probability of Occurrence | Potential Financial Consequence | Potential Annual Financial Risk | Potential Life Loss | Potential Annual Life Loss Risk |
|---|---|---|---|---|---|
| Earthquake | 0.055 | $ 610,000,000 | $ 336,000 | 100 | 0.055 |
| Cracking | 0.002 | $ 610,000,000 | $ 1,220,000 | 100 | 0.2 |
| Slide | 0.01 | $ 610,000,000 | $ 6,100,000 | 100 | 1 |
| Piping | 0.01 | $ 610,000,000 | $ 6,100,000 | 100 | 1 |
| Overtopping | 0.0005 | $ 610,000,000 | $ 305,000 | 100 | 0.05 |
| Total | 0.0231 | | $ 14,000,000 | | 2.3 |

***Table 3.4*** summarizes the results for the condition where a performance monitoring program is operated to better define the flow of water through the dam and its foundation. The review team thinks there is a good chance that a performance monitoring program will show that pore pressures in the downstream embankment are not high. This would reduced the estimated probability of failure from an earthquake, from sliding and from piping by a factor of 5. A performance monitoring program would also provide sufficient warning to evacuate people and reduce the expected life loss to much less than 1. A performance monitoring program would also reduce the

probability of failure by cracking to 1/10th. With an effective performance monitoring program, and some remedial work the annual potential financial risk is reduced to $1M, per year a 14-fold reduction with a potential life loss risk of zero.

To determine actual existing conditions, one could install instrumentation into the dam to measure pore pressures in the downstream embankment and underlying foundation. Additional instrumentation might be warranted to determine what is causing the settlement of the crest of the left side of the dam. If the instrumentation shows high pore pressures do exist, then mitigation measures such as those described in ***Table 3.2*** could be taken to lower those values and reduce the risk. Until those measures are implemented one might use instrumentation to provide a warning of a developing failure so that people could be evacuated from the flood zone. In any case, the potential consequences of a dam breach are such that a long-term performance-monitoring program is justifiable to ensure that one or more of the identified failure modes does not develop. The alternative is to undertake expensive remedial work without the facts or to do nothing and accept the risk.

This example shows that performance monitoring can provide information to take action to help lower risk. It shows that potential financial risk can be lowered by about 14 times if the data gathered from the performance monitoring system shows the dam to be performing as envisioned by the original design. It shows that performance monitoring can significantly reduce potential life loss by providing advanced warnings and indicating where mitigation measures will be most effective at reducing potential risk.

**Table 3-4 Potential Risks for Better Conditions with Additional Information**

| Risk Event | Annual Probability of Occurrence | Potential Financial Consequence | Potential Annual Financial Risk | Potential Life Loss | Potential Annual Life Loss Risk |
|---|---|---|---|---|---|
| Earthquake | 0.0001 | $ 610,000,000 | $ 61,000 | 100 | 0.01 |
| Cracking | 5.00E-05 | $ 610,000,000 | $ 31,000 | 100 | 0.005 |
| Slide | 0.001 | $ 610,000,000 | $ 610,000 | 100 | 0.1 |
| Piping | 0.0001 | $ 610,000,000 | $ 61,000 | 100 | 0.01 |
| Overtopping | 0.0005 | $ 610,000,000 | $ 310,000 | 100 | 0.05 |
| Total | 0.00175 | | $ 1,070,000 | | 0.175 |

## 3.4 Probability of Failure

The last section used estimates of probability of failure for each potential failure mode to calculate the potential financial consequence and potential life loss risks. Because information about dams is often uncertain and incomplete, those responsible for dam safety have considerable difficulty determining probability of failure for a particular failure mode. Because each dam is unique, it is not possible to use historical measurements of dam failure to determine the probability of failure of a specific dam for a specific failure mode. As a result, probabilities of failure must often be estimated.

There are three approaches to determine probability of failure for a particular failure mode:

1. Extrapolation of historical data
2. Analysis using event and fault trees of subcomponents
3. Quantifying human judgment.

The historical record of dam failures is of limited value. Records of dam failures are maintained (ICOLD, ASDSO, and others) and numerous papers have been published that analyze these failures. A common value quoted for rate of dam failures is that one in ten thousand modern dams will fail each year (Baecher, et.al., 1980). About one-third of these failures occur by overtopping or spillway inadequacies, another one-third by piping or seepage, and the remaining one-third from a variety of causes. These statistics do not include most of the estimated one million dams in the world nor do they consider the many failures that go unreported because such information is not available. The historical record for dam failures is too poorly defined to be of much value in addressing the probability of failure of a specific dam.

> ***"Perhaps the main advantage of using statistical methods is that the element of judgment is expressed as a numerical probability, and so forms a consistent and rational basis for comparisons of all kinds of data."***
> *Lumb (1968)*

Detailed probabilistic analyses are possible for some failure modes. This approach is widely used in manufactured systems where each element of the system can be identified and component failure rates measured. Event trees and fault trees are used to evaluate probabilities of failure of discrete elements for different load levels. See Hartford and Baecher (1994) for more information on these tools applied to dams. Many facilities of similar design and construction provide actual failure rates that can be used to refine the analysis. Event trees and fault trees can be used in dam safety to examine probability of failure caused by extreme loads such as floods and earthquakes. In this case, frequencies of occurrence of loads of different magnitudes can be determined from the historical record. The probability of failure of the structure can be determined for each magnitude. These are combined by analysis to obtain an overall annual probability of failure from extreme loads. Some parts of event trees developed for dams still require judgment to estimate probabilities. Detailed probabilistic analyses require considerable effort, time and money. They are typically not used to show the potential value of a performance monitoring system except for some high hazard dams where the risks are high and the costs to reduce those risks are high as well.

Quantified judgment is increasingly used to establish probabilities of failure for each failure mode of a dam for the purpose of making decisions. So called "subject matter experts" with some knowledge of probability and considerable expertise in a particular area are used to develop approximate estimates of probabilities of failure.

***Figure 3.3*** event tree looks at one potential failure mode – loss of containment as a result of a crack developing through the core of the dam. Earth dams are designed with filters downstream of the core to prevent flow of soil particles out of the core. Earth dams are also designed with drains to safely remove water that flows through the core and the dam's foundation. The event tree lays out the step by step pathways that the dam might fail due to a crack through its core. Each step of each pathway is assigned a probability of occurrence based on expert assessment of the materials and conditions of the dam. The event tree also includes steps where monitoring detects the developing failure mode in time for preventative measures to be applied to avoid failure. For each pathway that leads to the dam failing, the probabilities of each step are multiplied together to arrive at the probability that failure occurs along that pathway. There are six pathways that lead to failure. The probabilities of failure of these pathways are added together to obtain the estimated probability of failure due to cracking of the dam's core of 0.00005 or 0.005% per year. This example event tree for the failure of an earthen dam by cracking was developed by Whitman (1984) in his Terzaghi lecture and is used here as an illustration.

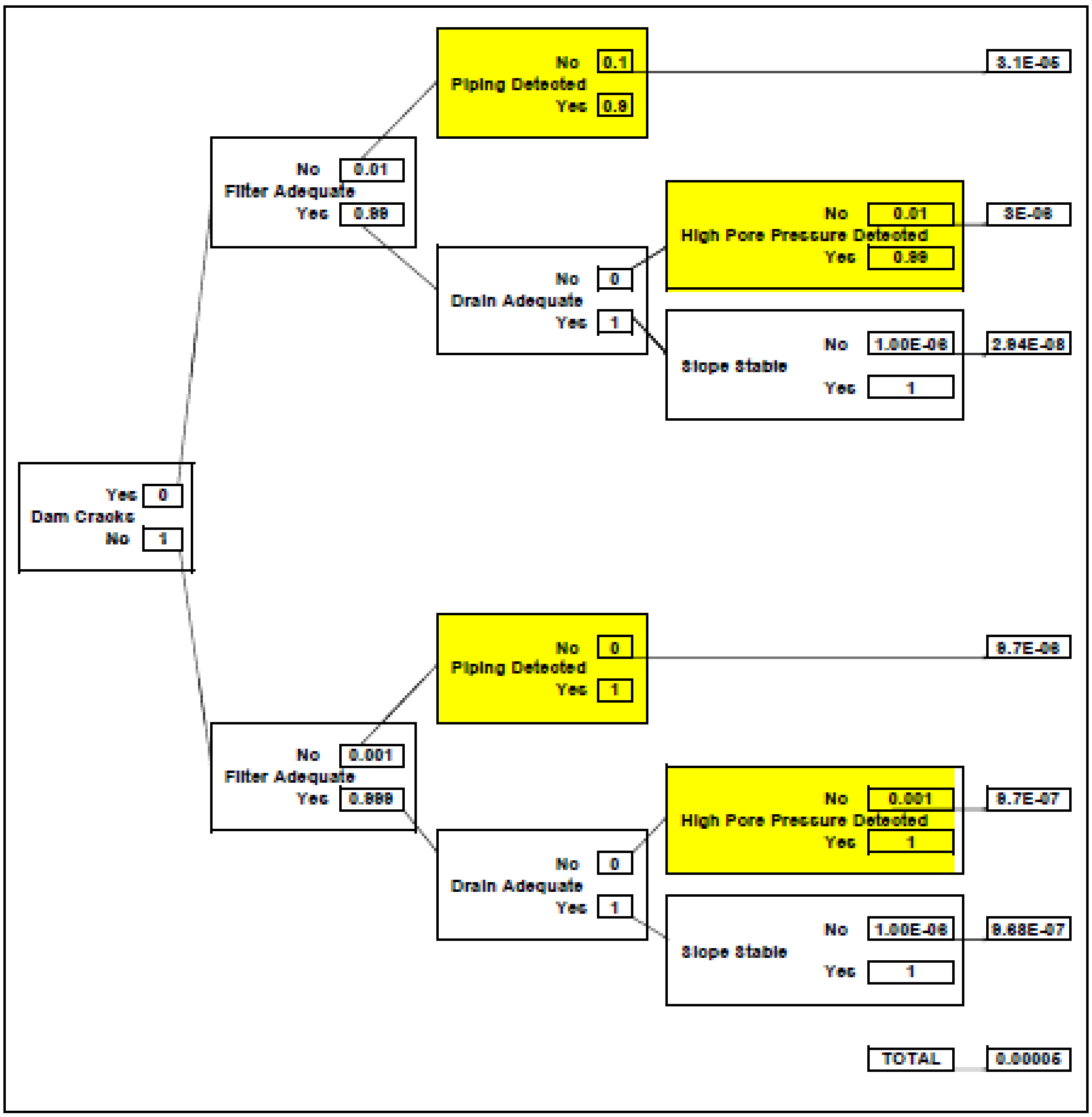


Figure 3-3 Event Tree for Failure mode of Cracking of the Dam with an Effective Performance Monitoring Program

***Figure 3.4*** shows the same event tree but with the probabilities for monitoring success reduced to 10%, i.e. the monitoring program is poor or not very effective. The probability is not reduced all the way to zero because some possibility remains that someone will observe a problem with the dam and action will be taken before the failure develops. The result is an estimated probability of failure due to cracking of the dam's core of 0.002 or 0.2% per year. Without the monitoring program this is a 40-fold increase, or stated another way, an effective performance monitoring program is estimated to reduce the probability of failure of this dam by cracking by 40-fold, a very significant reduction in risk.

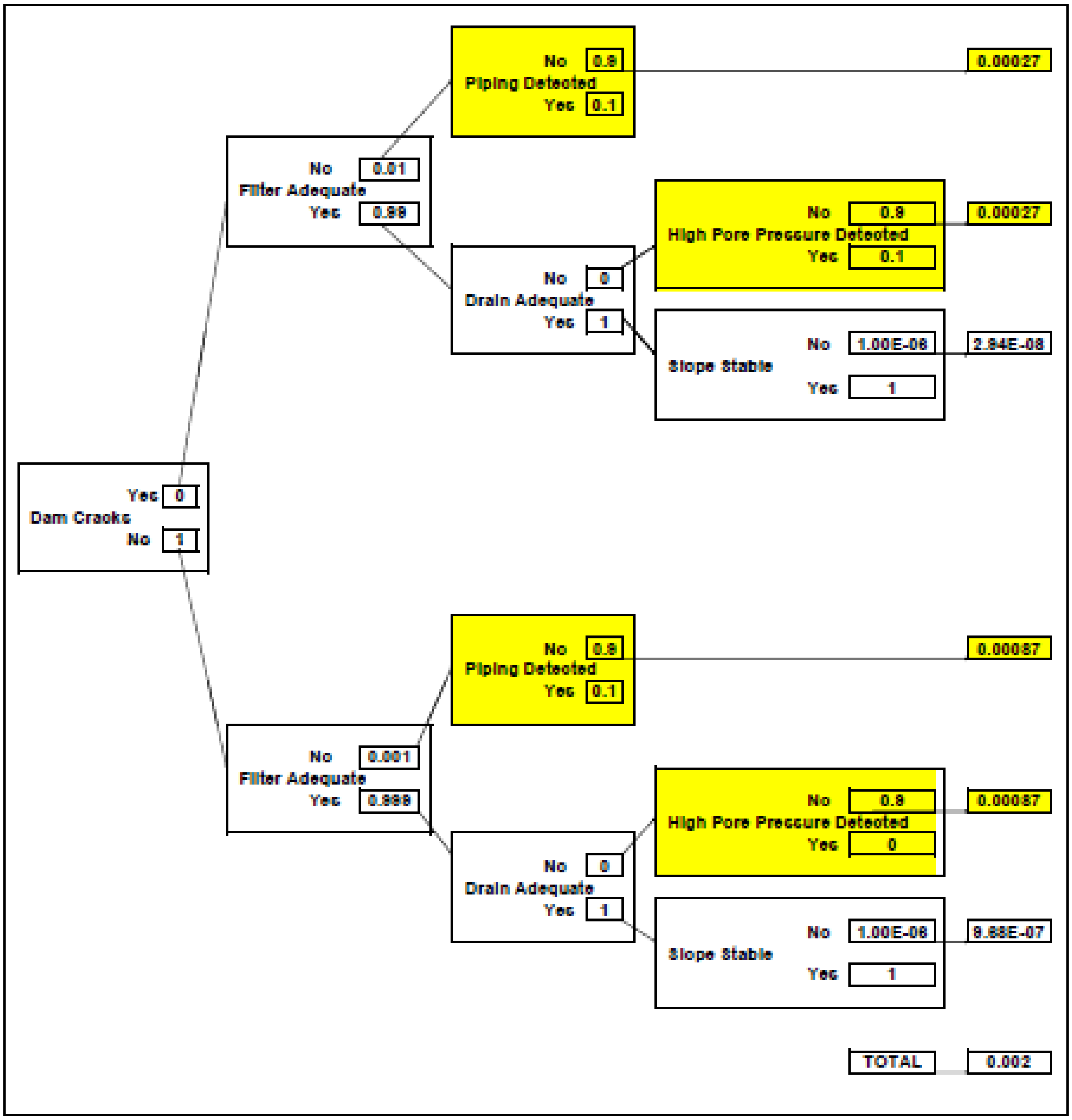


Figure 3-4 Event Tree for Failure of Cracking of the Dam with Monitoring Program Effectiveness Reduced by 90%

In a risk based evaluation one seeks to identify all significant undesirable outcomes and to estimate the likelihood of their occurrence using available information and expert opinion. This is using what is called "subjective probability" or "degree of belief" approach. See Vick(2002) for an excellent explanation of these concepts applied to dams. Many engineers are reluctant to provide quantified estimated of their judgment although they use engineering judgment all the time. Risk workshops managed by a skilled risk facilitator are often used to focus the evaluations and coach quantified estimates out of the subject matter experts.

Some people are willing to use subjective words to describe their judgment about a particular failure mode. ***Table 3.5*** provides a list of some of these subjective words and what they might mean in a quantified sense for dam safety. The values in ***Table 3.5*** are described in Marr (2007) based on publications in other fields and represent his interpretation of what numerical probabilities to assign to subjective adjectives in the context of developing performance monitoring programs. These values are intended only to provide a tool to aid in making approximate assessments of risk. Decisions based on these values should take into account their approximate nature. The results in ***Table 3.5*** apply to people's use of words to describe probabilities and are not a scientific application of the rules of probability. For example, scientifically there is never a zero probability for an uncertain condition. But, people including subject matter experts will state that a particular event is impossible. To come to a reasonable, useful solution, a probability of less than 0.0001 is assigned to these words. In reality it becomes time consuming and expensive to quantify probabilities less than 0.0001 with much precision. The exception to this is when the failure mode under consideration can be broken into smaller components where each component has conditional probability of failure greater than $10^{-4}$. Then the combination of the conditional probabilities can become less than $10^{-4}$. This might be the case for an earthquake having an annual probability of occurrence of 0.0005 and the probability of causing a stability failure of 0.01. Then the annual probability of a stability failure from an earthquake at the dam would be 0.0005 x 0.01 or 0.000005, a very small number.

***Table 3.5*** is meant to provide an approximate tool to help estimate relative risks. Should critical decisions come to depend on any specific numbers given in ***Table 3.5***, a more detailed assessment should be carried out to refine the estimate of probability of occurrence beyond that deduced from an adjective.

**Table 3-5 Verbal Descriptors of Probability**

| Words used by people to indicate Likelihood | Probability of Occurrence | Simplified Probability for Risk Assessment |
|---|---|---|
| Zero, none, impossible | <0.0001 | 0.01% |
| Virtually impossible, very unlikely | 0.00011 to 0.001 | 0.1% |
| Unlikely, improbable, barely possible | 0.0011 to 0.01 | 1% |
| Small, limited, marginal | 0.011 to 0.1 | 10% |
| Moderate, considerable, somewhat unlikely | 0.11 to 0.5 | 50% |
| Likely, probable | 0.51 to 0.9 | 90% |
| Highly likely, very probable | >0.9 | 100% |

Scott (2011) recently published a table of verbal descriptors of probability similar to that of ***Table 3.5*** which is used by the USACE. It is reproduced in ***Table 3.6***. While there are many similarities, in the two tables probably indicating some commonality in sources of information, there are also some differences, especially in the low values of probability. These differences show that subjective estimates of probability are not precise and must be used with considerable care when the values directly impact decisions.

**Table 3-6 Verbal Descriptors of Probability from Scott (2011)**

| Verbal Descriptor | Suggested Probability | Approximate Probability Range (from Regan et. al.) |
|---|---|---|
| **Virtually Impossible,** due to known physical conditions or processes that can be described and specified with high confidence | 0.001 | 0-0.05 |
| **Very Unlikely,** although the possibility cannot be ruled out | 0.01 | 0.01-0.15 |
| **Unlikely,** considerably more unlikely than not. | 0.1 | 0.05-0.25 |
| **Neutral,** with no reason to believe that one outcome is more or less likely than the other (when given two outcomes) | 0.5 | 0.4-0.6 |
| **Likely,** considerably more likely than not | 0.9 | 0.6-0.92 |
| **Very Likely,** but not completely certain | 0.99 | 0.75-0.99 |
| **Virtually Certain,** due to known physical processed and conditions that can be described and specified with high confidence | 0.999 | 0.9-0.995 |

# 4.0 KEY ELEMENTS OF AN EFFECTIVE DAM SAFETY PERFORMANCE MONITORING PROGRAM

Every dam owner should carry out, or participate in, a dam safety program for each dam under its charge. A dam safety program should be developed based on the type of dam, its condition, and its hazard potential. Each dam safety program should have a performance monitoring program.

Each dam safety performance monitoring program should include an element based on visual inspections of the dam and its surroundings. Visual inspections should be conducted on a regular basis by persons qualified by training and experience. Visual inspection can detect many indications of undesirable performance but they can't reveal conditions below the surface and they don't provide quantitative information that can be used to determine trends with time. Visual observations often have to be supplemented with physical measurements using instruments. Every dam should have at least one instrument; that is a gauge to measure the depth of water passing through the spillway.

All safety inspections should incorporate failure modes and consequence analyses as part of the evaluation process (FERC, 2005). The evaluation should consider "sunny day" conditions, i.e. normal operating conditions, and "extreme loading conditions", i.e. maximum credible flood, maximum credible earthquake and other significant loads. A comprehensive dam safety inspection and monitoring program integrates periodic reviews and discussions of all available information including historic records and photographs, engineering analysis, previous inspection reports, current instrumentation data, and risk reduction opportunities. By taking into account the contents of this section, an effective dam safety performance monitoring program can be adapted to meet the needs and resources of all dam owners. Where internal resources are not available to effectively carry out elements of the dam safety performance monitoring program, provision should be made for the professional services of engineers, consultants, and specialty contractors to supplement the dam safety performance monitoring program.

Some argue that small dams do not require a dam safety program. We believe that any dam with the potential to harm people, property or the environment should have a dam safety program. The only way to know whether a dam can cause harm is to do a safety assessment.

## 4.1 General Considerations

All dams should be assigned a hazard potential classification according to the potential impacts of a dam failure. The factors used to assess a hazard potential classification are:

- the type of dam, its height of the dam and the maximum impoundment capacity;
- the potential for loss of human life;
- the economic loss which could result from failure of the dam;
- the environmental damage which could result from a failure of the dam;
- the physical characteristics of the dam site including the foundation and abutments and flood discharge capacity;
- the physical condition of the dam and its history of performance;
- the sensitivity of the dam's probability of failure to incremental change;
- the location of developed areas, occupied buildings or other land improvements in the area which could be affected by a failure of the dam;
- other site specific characteristics which could lead to unacceptable outcomes.

Design of an effective dam safety performance monitoring program requires an understanding of potential failure modes for the specific type of dam and site conditions under consideration. (Regan et. al, 2008). A potential failure mode for a dam is a process consisting of five phases (condition, initiation, continuation, progression, and reservoir release) as shown in ***Figure 4-1.***

The role of a dam safety program is to identify and prevent a potential failure mode from progressing towards the uncontrolled release of water.

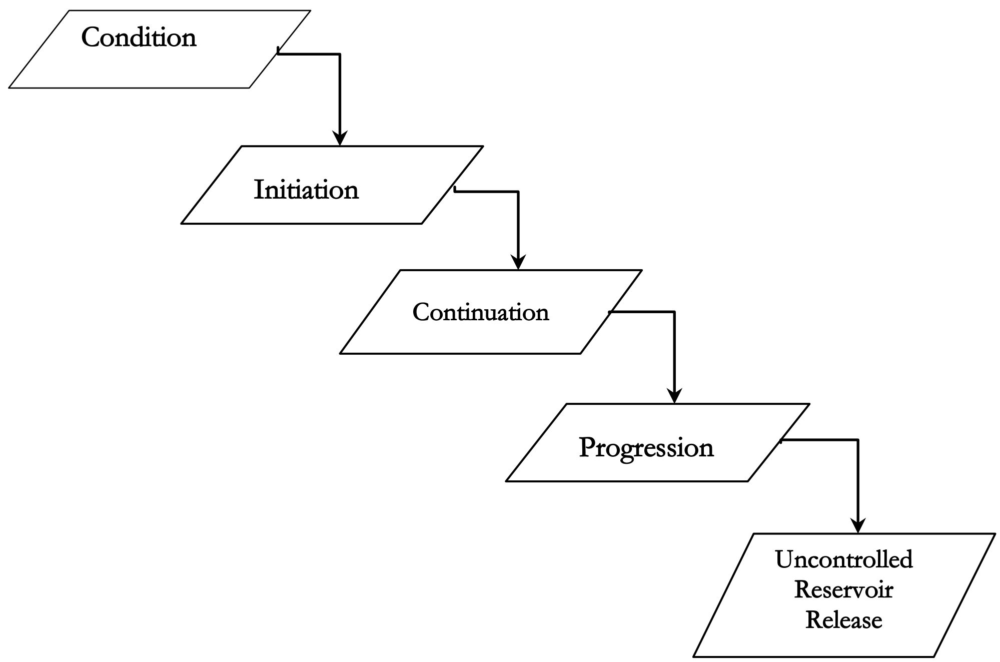


**Figure 4-1 Potential failure Mode Process**

The dam safety performance monitoring program should be developed in conjunction with an initial failure modes analysis or review of an existing failure modes analysis. The process should take into consideration several factors including, but not limited to the questions contained in ***Table 4.1***

**Table 4-1 Integrating the Potential Failure Mode Analysis**

| **Considerations for Development of an Effective Dam Safety Program** |
|---|
| At what point can the potential failure mode process be detected? |
| Can the potential failure mode be detected visually before an actual dam failure occurs? |
| Is the potential failure mode something that can be detected with instrumentation? |
| How quickly will the potential failure mode develop once detected? |
| Is there someone at the dam who has been trained in what to look for and can that person detect the potential failure mode? |
| What actions will be taken if there is an indication that a potential failure mode is initiating, continuing, or progressing? |
| Will there be time to take effective action once the potential failure mode is detected? |
| What, if any, instrumentation is appropriate to detect the potential failure mode and where will it be placed? |

| Considerations for Development of an Effective Dam Safety Program |
|---|
| What specific visual observations are useful to detect the potential failure mode and how often do the visual observations need to be performed? |
| How often does the surveillance and instrumentation data need to be collected and evaluated? |
| How will the surveillance and instrumentation data be collected and evaluated? |
| How is the staff responsible for taking the readings and evaluating the data trained to detect possible dam safety problems? |

Adapted from FERC Engineering Guidelines, Chapter 14, Section C (2010)

It is important to fully understand the complete process of each potential failure mode. This will help establish the right mix of visual surveillance and instrumentation to be selected and the frequency with which these activities should occur. The goal is to provide the greatest opportunity to detect the potential failure mode early in the process as shown in ***Figure 4.1***. This makes it possible to maximize the time available to take action to prevent the complete failure of the dam and/or to warn the population downstream of the dam. Early detection also makes possible early intervention to correct the problem at usually less cost.

Instrumentation and monitoring, combined with vigilant visual observation, can provide early warning of many conditions that contribute to dam failures and incidents. For example, settlement of an embankment crest may increase the likelihood of overtopping; increased seepage or turbidity could indicate active piping; settlement of an embankment crest or bulging of embankment slopes could indicate sliding or deformation; inelastic movement of concrete structures could indicate sliding, differential settlement, or degradation of the concrete. Conversely, lack of normally expected natural phenomena may also indicate potential problems. For example, lack of seepage in a drainage system could indicate that drainage collection system is not functioning as intended such that flow discharges from another location in an uncontrolled manner.

Instrumentation and monitoring must be carefully planned and executed to meet defined objectives. Every instrument in a dam should have a specific purpose. If it does not have a specific purpose, it should not be installed. If an existing instrument no longer has a purpose, it should be properly removed. Instrumentation for long-term monitoring should be rugged and easy to maintain and it should be capable of being verified or re-calibrated.

Installation of instruments or accumulation of instrument data by itself does not improve dam safety or protect the public. Instruments must be carefully selected, located, and installed (Dunnicliff, 1981). Data must be conscientiously collected, meticulously reduced, tabulated, and plotted. The reduced data must be judiciously evaluated in a timely manner with respect to what it indicates about the safety of the dam (USSD, 2002). The monitoring team must understand the significance of changes. They should have trigger levels defined for taking action. A poorly planned and executed program will produce unreliable data that the dam owner will waste time and money collecting and interpreting, often resulting in disillusionment and a diminished quality of the program.

Visual observation of all fluid retention structures should be made in conjunction with instrumentation monitoring to adequately assess the safety of a dam. Visual observation, also called surveillance, can detect indications of poor performance such as offsets, misalignment, bulges, depressions, seepage, leakage, and cracking. More importantly, visual observation can detect variations or spatial patterns of change of these features.

Most visual observation provides qualitative rather than quantitative information, while instruments provide detailed quantitative information. Visual observations can only reveal conditions manifested at the surfaces of the structures. Visual observations usually cannot identify the source of a problem that develops within the structure. For many failure modes, visual observations may come too late to implement an effective mitigation program. *Section 5* provides more guidance on visual surveillance.

Instrumentation placed within the dam can help identify the source and cause of a problem and give precise quantitative data day and night that shows the rate of progression. Visual observation and instrumentation data are natural complements and when used together they provide the primary means for engineers to evaluate the safety of an existing dam.

Though only a small percentage of dams develop problems, the highly indeterminate nature of each dam makes it impossible to predict which dam will develop problems. The many unknowns about the properties of the materials, and the infinite number of possible variations in conditions that could affect the safety of a dam or appurtenant structures can never be fully revealed. Therefore, it is prudent that any dam that may affect the public safety has a performance monitoring program to monitor its vital signs.

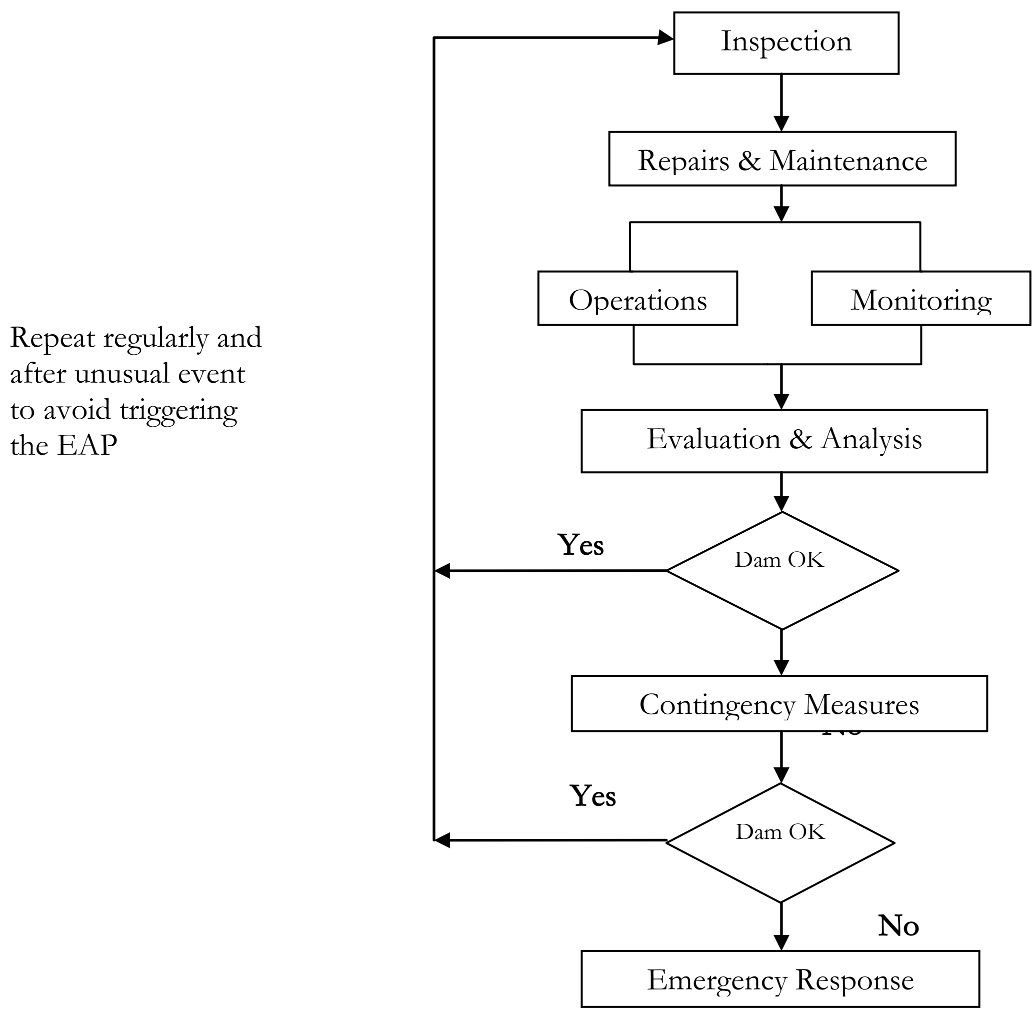


**Figure 4-2 Procedural Guidance for Dam Safety Programs**

*Figure 4-2* presents a procedural guideline for an effective dam safety program.

A dam's performance will change over time; consequently, the performance monitoring program must change as well. Change can occur through the normal aging process of the components of a dam, or through the development of defects due to something missed in the design or construction of the dam, or with slow changes in pore pressure in earthen components having low permeability.

A key component of a comprehensive dam safety program is the owner's performance monitoring plan that includes policies and procedures to assure the data obtained are accurate and evaluated in a timely manner, anomalies are thoroughly investigated and appropriate actions are take in the event the data indicates the dam is behaving in an unacceptable manner.

Steps critical to this effort include:

- Indentifying potential failure modes (PFM);
- Evaluating existing inspection protocols and instrumentation arrays for effectiveness in monitoring identified PFM.
- Installing appropriate surveillance and/or monitoring systems to detect the development of the identified PFM;
- Indentifying action levels for all instruments;
- Developing and implementing policies and procedures for obtaining data in a timely and accurate manner;
- Developing and implementing policies and procedures to assure the data are evaluated in a timely manner; and,
- Developing an emergency action plan (EAP) that addresses the steps to be taken in the event an action level is exceeded.

The design function for a dam can never be considered finished as long as the dam remains in place. Involvement of knowledgeable design professionals should continue throughout construction and operation of the project (Kollgaard and Chadwick, 1988). The responsibility for project operation should be assigned to a single staff member of the operating organization. He/she should also handle the operating organization requirements for coordination with the design organization, including reporting changed conditions discovered by operators. Participation of the operating organization personnel with engineering personnel in the periodic inspection

A good Dam Safety Program demonstrates the following:

1. Clear understanding and exercising of responsibilities at all levels of the organization.
2. Regulatory compliance.
3. Conformance with risk criteria and standard good practices, including for example
    a. Public safety requirements
    b. Design criteria
    c. Inspections and monitoring
    d. Periodic reviews
    e. Emergency preparedness
    f. Change management
4. Systematic management to address non-conformance and reassess changing hazards
5. Progress of risk reduction towards established objectives
6. Dynamic organization with learning and continual improvement, evidenced in
    a. Training of staff/competency
    b. Planning for succession
    c. Education of stakeholders
    d. Learning from incidents (own and others)
    e. Improving collective knowledge (R&D, industry groups)
    f. Improving methods and tools.
7. Financial responsibility

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program is highly desirable. Continuing liaison should be maintained among the personnel concerned with the various stages of project development and operation so that each concerned discipline and organizational unit knows and understands the relevant activities of the others. This coordination must be given constant attention to be sure proper action is taken. (FEMA 1993)

## 4.2 People

Dam owners can be classified into two general categories: Public corporations or public benefit agencies; and, private individual owners, municipal governments, associations, or small business entities. Regardless of the owner's business configuration, the responsibility for developing and maintaining an effective dam safety program rests with the legal owner of the dam. Many dams are owned by smaller entities of limited financial resources but that does not relieve the owners of their responsibility to maintain a safe dam, a part of which is to carry out a dam safety performance monitoring program with a component of periodic visual inspections and prompt action to correct any deficiency that puts human life at risk.

According to federal guidelines for dam safety (FEMA 93), a single identifiable, technically qualified administrative head should be assigned the responsibility for assuring that all management and technical safety aspects of dam engineering are adequately considered throughout the development and operation of the project. The position must have continuity of guidance and direction, and the authority and resources to ensure these responsibilities are carried out.

The dam owner should ensure that organization staffing is sufficient and qualified for the project workload, and that all programs necessary for the safety of dam are established, continued, and realistically funded. Allocation of manpower and funds should give high priority to safety-related functions. Safety-related functions and features must not be sacrificed to reduce costs, improve project justification, or expedite time schedules.

Clear assignment of responsibility for timely collection and review and follow-up on collected data and reports is needed. This component is subject to each dam owner's available resources for managing its dam inventory. In the case of dam owners having limited or no qualified engineering staff, provision should be made to secure the professional services of a well qualified engineering consultant. Whether the resources are direct employees, engineers and consultants, or a combination of the both employees and consultants, the owner needs to ensure that qualified personnel have the information and resources to conduct effective dam safety performance monitoring in a timely manner.

***Figure 4-3*** shows a organizational framework for the assignment of dam safety responsibilities with in a corporate structure. Generic titles are used to describe the principal management roles in a typical large organization. The arrows show the flow paths of responsibility from the Chief executive Officer to the people inspecting the dam and collecting data. A key point of ***Figure 4-3*** is that the top executive officers of the corporation have the overall responsibility for dam safety.

***Figure 4-4*** shows an organizational framework of responsibilities for a Municipalities, Associations, Small Business, and Private Individuals. In many cases the organizational framework is limited such that the owner of the dam essentially performs all of the dam safety functions and has the sole responsibility for dam safety. The Owner of a dam with intermediate to high hazard potential is strongly urged to retain a consulting engineer familiar with dam safety to provide periodic review and advice regarding the safety of the dam.

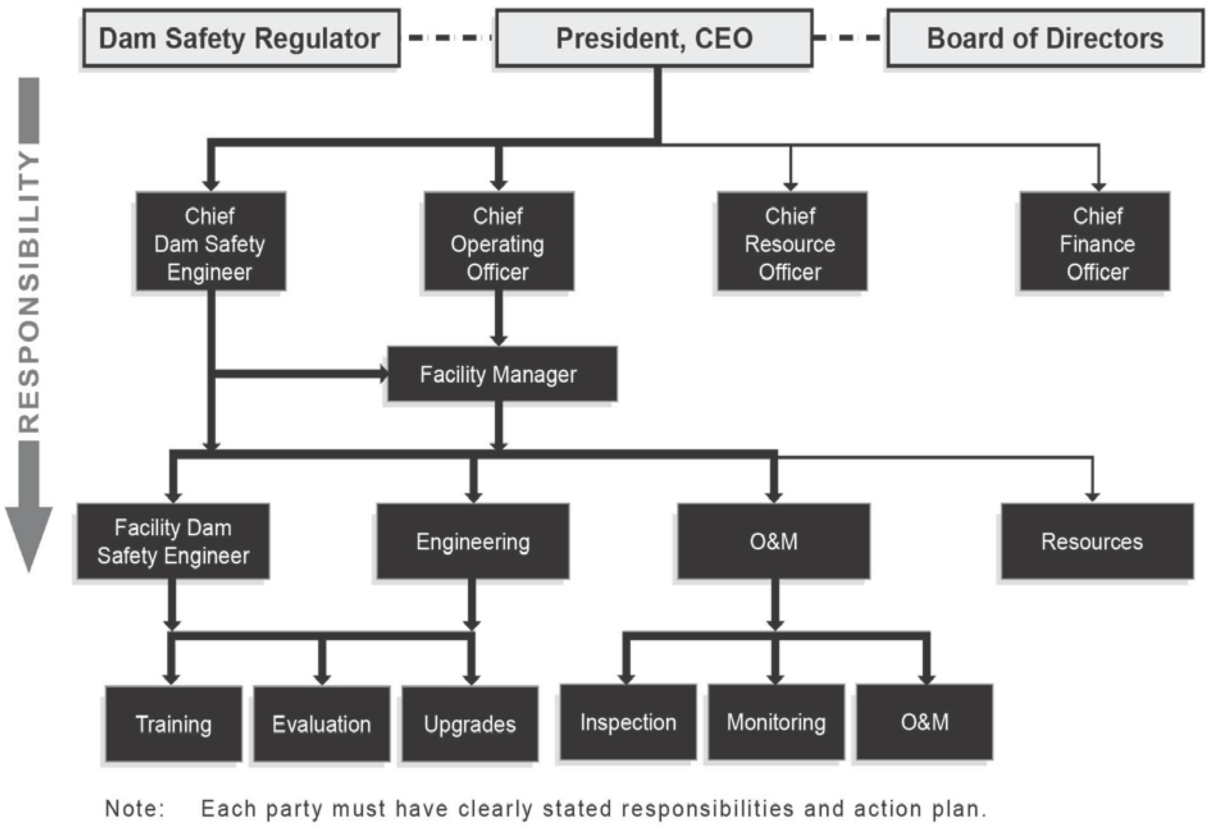


Figure 4-3 Responsibility Flow Chart for Public Corporations, Public Benefit Agencies, or Private Companies

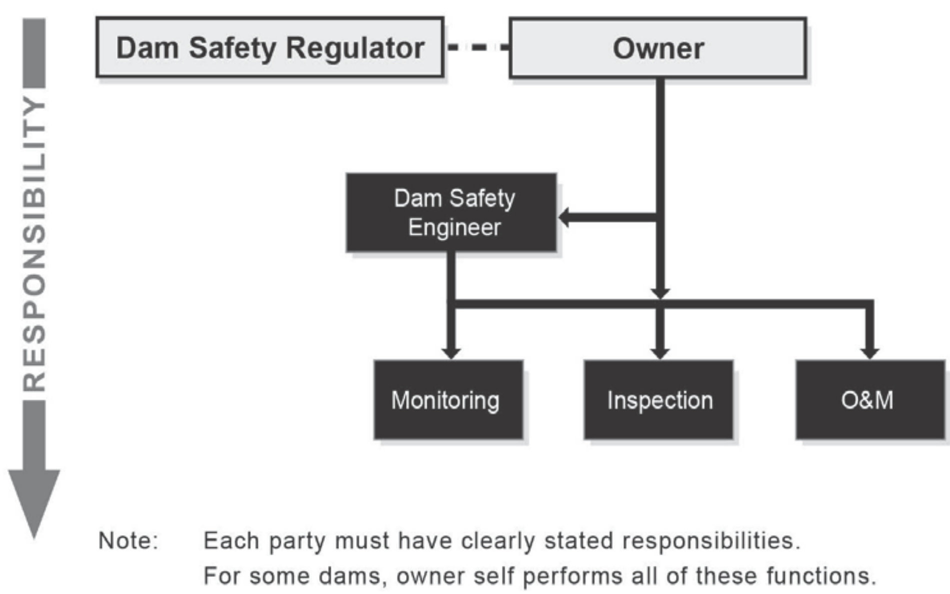


Figure 4-4 Responsibility Flow Chart for Municipalities, Associations, Small Business, Individuals

Historical information typically resides with individuals who have a long association with the owner's dam inventory. This information can be lost when these individuals leave the organization or when consultants are replaced. Traditionally, the fact that staff turnover may be lower than other industries helps to compound this problem because all historical information is lost when that long-term employee leaves. This loss usually occurs even when the information has been documented since the process of locating the information is often too onerous. Rigorous documentation of the dam safety program and its results are invaluable should a problem develop in the future. Quality assurance procedures should be in place for record keeping. Hand over procedures should be in place when key personnel are changed.

The dam owner needs to understand the emerging "pressure points" in their dam safety program knowledge areas that will be significantly impacted as a result of future retirements, attrition and/or business model evolution. Owners need to make decisions relating to knowledge preservation, retention and transfer today in order to position the dam safety program for tomorrow.

In all cases, owners need to identify the people who are authorized decision makers, who are provided with clear lines of communication and responsibility, and who are authorized to initiate operational risk reduction actions to protect the dam from failure, declare an emergency situation, and implement the emergency action plan.

***Figure 4.5*** shows a possible communications flow chart for reporting dam safety problems and concerns within a corporate organizational type structure. Essentially, the communications lines are the reverse of the normal responsibility paths of communications within the organization as shown in ***Figure 4.3***. In the case where normal communications flow paths break down, for whatever reason, suggested alternate communications paths for reporting dam safety problems and concerns are shown in ***Figure 4.7.***

Similarly, ***Figure 4.6*** shows a general communications flow chart for reporting dam safety problems and concerns by municipalities, associations, small business, or individuals. As shown in ***Figure 4.8***, the dam safety engineer responsible for inspections, conditions assessments, and evaluations has a responsibility to report adverse dam safety findings directly to the regulatory agency if the owner is unresponsive to problems and concerns.

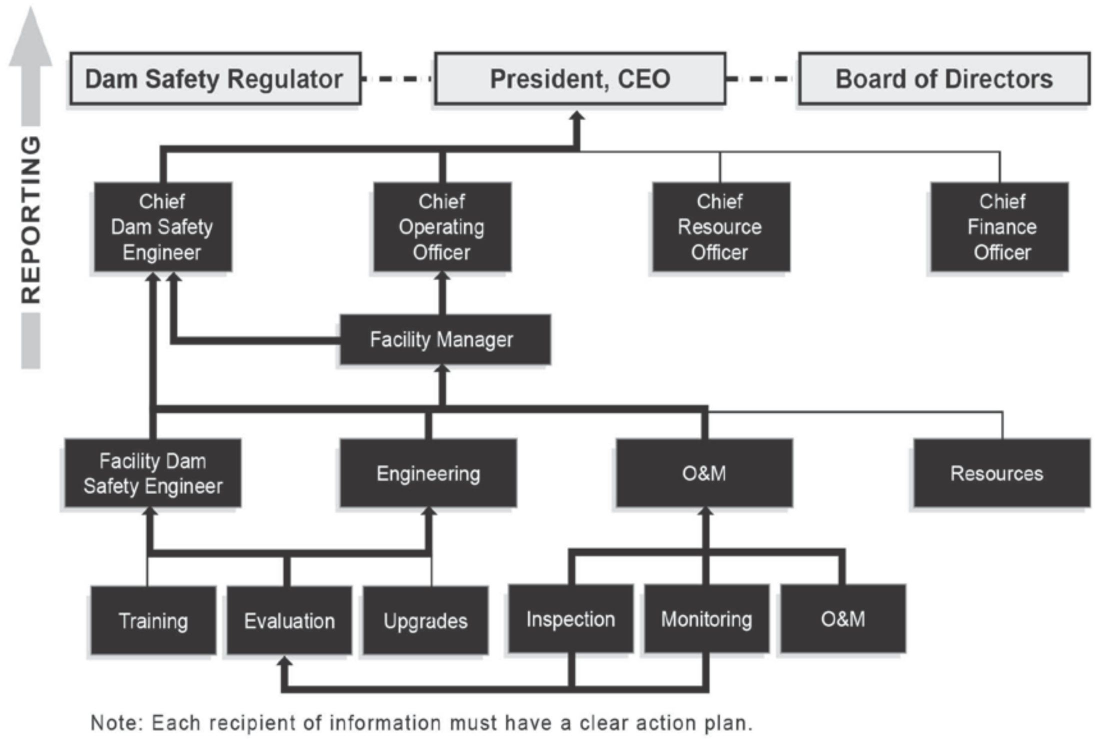


Figure 4-5 Reporting Flow Chart for Dams Owned by Public Corporations, Public Benefit Agencies, or Private Companies

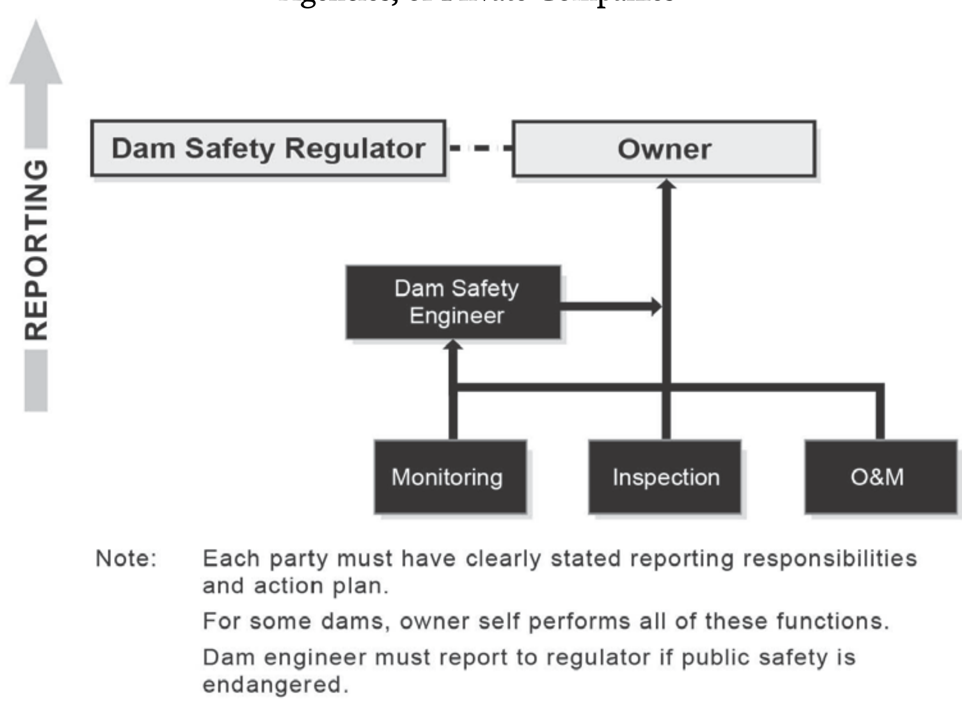


Figure 4-6 Reporting Flow Chart for Dams Owned by Municipalities, Associations, Small Business, or Individuals

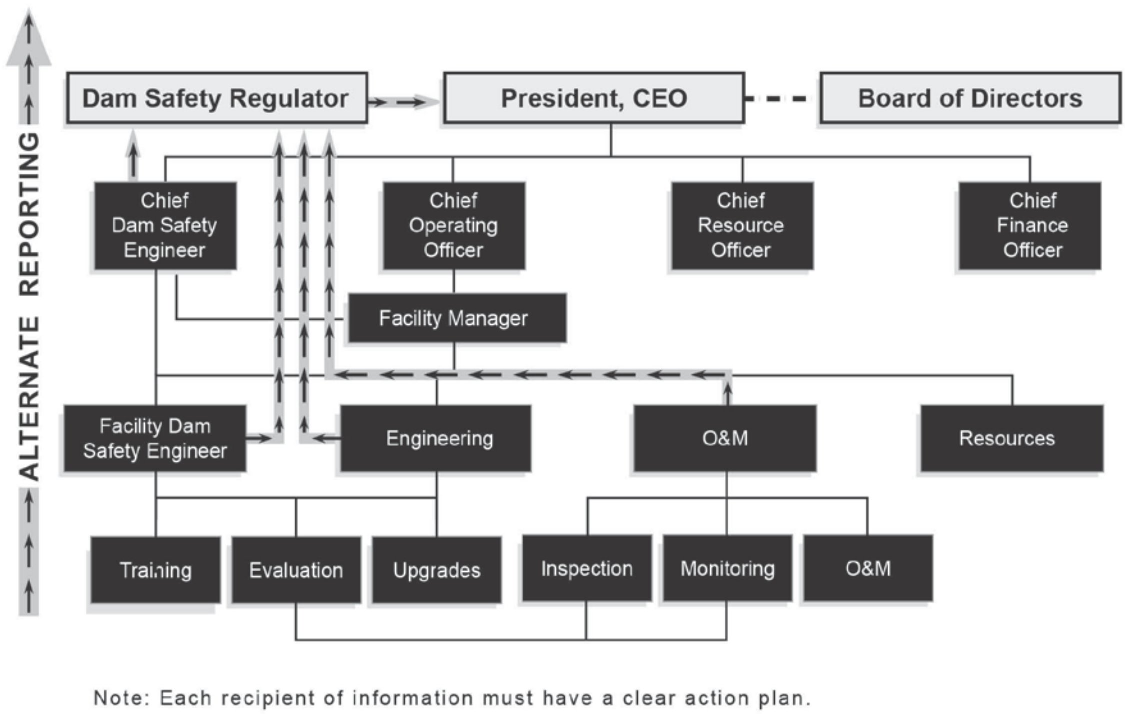


Figure 4-7 Alternate Reporting Flow Chart for Public Corporations, Public Benefit Corporations, or Private Companies.

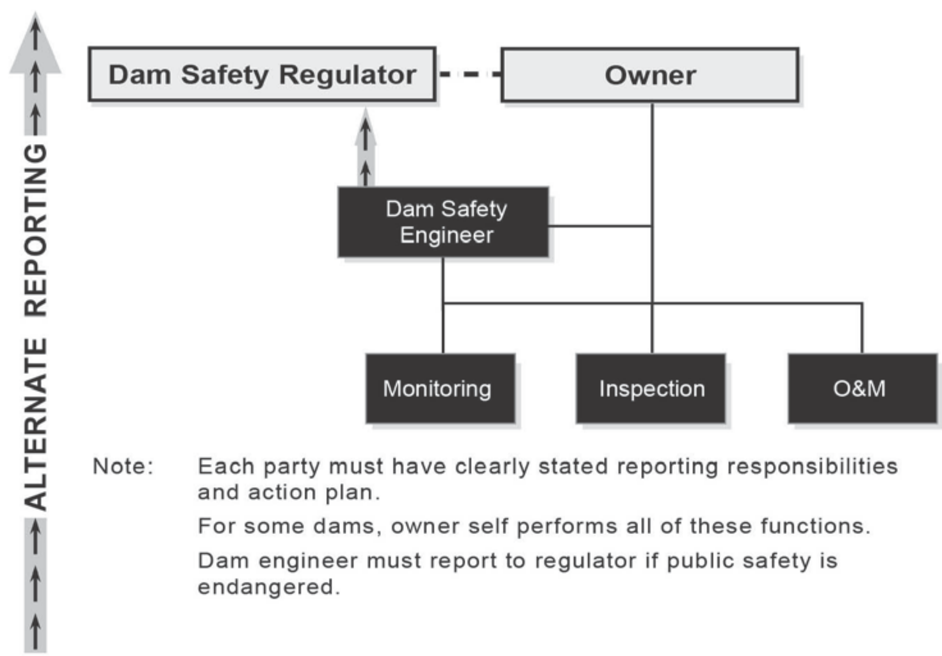


Figure 4-8 Alternate Reporting Flow Chart for Municipalities, Associations, Small Business, or Individuals

## 4.3 Training

A well trained operation and maintenance staff is an important component of the dam safety program (ASCE, 2000; Davidson et al., 1991). Owners should provide internal training for all technical staff associated with engineering, construction, operations, maintenance, monitoring and inspection of dams. Technical personnel concerned with all phases of project development and operation should be given periodic refresher training in the elements of the dam safety program. See ***Section 5.1*** for more information about training in support of the Dam Safety Performance Monitoring Program.

## 4.4 Technology

Geotechnical and structural instrumentation form an essential part of safety and performance monitoring of dams. The engineering practice of geotechnical instrumentation involves a combination of the capabilities of measuring instruments and the capabilities of people. Dam owners have access to a wide variety of good instruments, including many with automatic data acquisition. ***Section 5*** and ***Appendix B*** provides information on the types of instruments used in dams. To be of most value, they must be maintained by qualified technicians, and data must be retrieved on schedule and evaluated promptly. Increasingly instrumentation systems for dam safety are automated to provide more frequent readings at less cost. ***Section 5.6*** gives more information on this subject.

The need for automated performance monitoring systems is increasing as the personnel resources available for dam safety monitoring becomes more limited. A properly designed and implemented automated acquisition system can improve the quantity and quality of the data and the dam owner's ability to detect a developing unsafe condition and do so quickly. ***Section 5*** provides more information on automated data collection from instruments.

As performance monitoring systems become more dependent on technology there is an increasing need for the performance monitoring program to include consideration of the following needs:

- Additional technical support for power supplies, communications, and instrument maintenance, will be required from technicians to maintain Automated Data Acquisition System equipment.
- Instrumentation testing (calibration), maintenance, and repair or replacement of non-functioning instrumentation should be given a high priority and properly budgeted.
- Provision for upgrades in the sensor and data acquisition technology as improvements occur that provide better performance, higher reliability and or lower operating costs.
- Procedures should be established to screen and disseminate information on technical advances relating to dam design, construction, and operation.
- Programs for continuing professional training should be orientated toward keeping the technical staff abreast of improved technology.

Technological developments are rapidly changing the way performance monitoring information is collected, stored and viewed. Today's data acquisition systems and communications systems allow data from instruments to be stored directly into data bases that are accessible by the Internet. Increasingly all data are becoming digital and evaluation and reporting of data occur by computer. A growing trend is to use GIS (Geographic Information System) software to archive and display background information and monitoring data. The main advantage of a GIS-based approach to data management is the ability to spatially and temporally, retrieve, and correlate dam information organized on one map. Instrumentation data, geologic data, and photographs taken during inspections can be stored in a GIS data base to allow the user to visually correlate these elements on a map. By compiling the information in a GIS standardized format the data can be integrated with other similar datasets and shared amongst the dam owner's staff and management, consultants, and regulatory agency as required. This approach was applied to San Gabriel Dam, an earth and rock fill dam in southern California, owned by the Los Angeles County Department of Public Works. San Gabriel Dam's data may also be displayed in Google Earth or Adobe Acrobat allowing others who are not familiar with GIS software to view it. (Wang and Ferris, 2010)

## 4.5 Organization Structure

At the 28th Annual USSD Conference in Portland in 2008, authors P. Regan and D. Boyer, suggested that the dam safety profession has moved beyond the point where all dams were viewed as either safe or unsafe. It is recognized that all dams have some probability of failure and given the consequences of dam failure, some risk. It is also recognized that most dam failures and incidents are caused by three forces of engineering analysis – static, flood, and seismic stability – as well as other factors including piping, overtopping by floods less than the design flood, failure of control systems, and deficiencies or weaknesses in an owner's dam safety program.

In today's world, the dam owner, whether an individual or a corporate entity, must have ***responsibility awareness*** and ***risk management awareness*** factored into both their operations and engineering managers. The dam safety program must inform management of their responsibility, risk exposure and liability. In recent years, there have been examples of dam failures where management was aware of deficiencies but underestimated the risks and liabilities.

The prime responsibility for operational integrity and safety should rest with the individuals responsible for the dam and the activities that give rise to the risks associated with its operation. Effective leadership and management for operational integrity and safety should be established and sustained by all dam owners, primarily for protection of the public, but also for effective risk management.

## 4.6 Contingency Planning

All dams are unique and have specific vulnerabilities and potential failure modes that require expert judgment to assess. Prevention of loss of life is paramount over all other social, economic, environmental, and operational considerations. Consequently, all dam owners should have site specific contingency plans for implementation of risk reduction measures when monitoring indicates that the dam is not performing to the required level. A contingency plan is a formulated set of actions with assigned responsibilities to respond to an undesirable event in ways that minimize negative consequences.

General consequences associated with each potential failure mode should be identified. Structural and non-structural risk reduction measures should be considered to reduce the probability of failure and/or the consequences associated with the failure mode. For instance, reservoir pool restrictions and modification of the reservoir regulation plan are usually options to lower risk.

Examples of non-structural risk reduction measures include but are not limited to:

- Reduce operating pool levels and/or durations.
- Pre-position emergency contracts for rapid supply of materials, equipment, and labor.
- Improve or increase inspection and monitoring to detect evidence of worsening conditions.
- Update Emergency Action Plan and inundation mapping to include specific failure mode(s).
- Develop explicit procedures, communications systems, and training of skilled team members for prompt and effective emergency response in the event of the detection of worsening or catastrophic conditions.
- Indentify instrumentation and monitoring action levels and threshold readings that would initiate urgent monitoring response.
- Install early warning systems.
- Perform preventive and corrective maintenance such as cleaning drains, improving spillway gate reliability where non-functioning components would exacerbated the existing conditions in an emergency.

Examples of structural risk reduction measures include but are not limited to:

- Isolate problem area (i.e. cofferdam around project feature).
- Improve seepage collection system.
- Lower spillway crest to aid in prevention of failure.
- Increase spillway capacity.
- Breach or lower saddle dikes along the reservoir perimeter.
- Strengthen weak areas (i.e. upstream or downstream blanket to cut off or slow seepage; install tie-backs or anchors; install buttress.)
- Construct downstream dike to reduce head differential.
- Construct downstream berm.
- Modify outlet discharge capability such as by installing temporary siphon(s).
- Increase erosion protection where necessary.
- Construct shallow cutoff trench to slow seepage.
- Target grout program specifically for suspected problem area(s) to slow seepage.
- Remove significant flow restrictions.

## 4.7 Emergency Preparedness

Although most dam owners have a high level of confidence in the structures they own and are certain their dams will not fail, history has shown that dams do fail. Dams are also subject to operational incidents that have the potential to cause unplanned water releases. Sometimes these failures and incidents cause loss of life, injuries, and extensive property damage. A dam owner should prepare for this possibility by developing an emergency action plan which provides a systematic means to: identify emergency conditions threatening a dam; expedite effective response actions to prevent failure; and, reduce loss of life, environmental damage, and property damage should failure occur.

An Emergency Action Plan (EAP) is a formal document that identifies potential emergency conditions at a dam and specifies preplanned actions to be followed to minimize property damage and loss of life. The EAP specifies actions the dam owner should take to moderate or alleviate the problems at the dam. It contains procedures and information to assist the dam owner in issuing early warning and notification messages to responsible downstream emergency management authorities of the emergency situation. It also contains inundation maps to show the emergency management authorities of the critical areas for action in case of an emergency.

The plan should be in the detail warranted by the size, location, and hazard potential of the dam and reservoir. It should evaluate downstream inundation hazards resulting from floods or dam failure, and upstream conditions that might result from major land displacements or increased flood flows, including the effects from failure of upstream dams.

Emergency Action Plan in the Event of Dam Failure should be developed in cooperation with those emergency management agencies responsible for public safety in the area(s) potentially affected by a dam failure. In the event of an emergency condition involving the stability of a dam, the owner must establish a clear procedure to promptly and efficiently make all notifications necessary to warn and evacuate people in the potential flood inundation area.

Every EAP must be tailored to site-specific conditions. EAPs generally contain six basic elements:

- ✓ Notification Flowchart
- ✓ Emergency Detection, Evaluation, and Classification
- ✓ Responsibilities
- ✓ Preparedness
- ✓ Inundation Maps
- ✓ Appendices

The FERC Engineering Guidelines, Chapter 6, October 2007, provides recommendations for the components of an EAP. Even if not required by regulations a simple EAP that gives call numbers for emergency response teams and anyone that might be endangered by a dam break can safe a life.

### 4.8 Documentation

It is incumbent on the owner to maintain continuity of information on the performance history of the dam through accurate and complete documentation that is maintained and kept current over the life of the project.

Throughout project development (planning, site investigation, design, construction, initial reservoir filling, and operation), all data, computations, and engineering and management decisions should be documented. Documentation should cover investigation and design, construction plans and construction history, operation and maintenance history, damage and repairs and improvements, and periodic inspections during construction and operation. It should include, but not be limited to, memoranda, engineering reports, criteria, computations, drawings, and records of all major decisions pertaining to the safety of the dam.

One copy of all documents concerning dam safety should be assembled in a single project file. The file should be kept up to date and should be maintained as a permanent archival reference. A second file of the materials should always be easily accessible to responsible personnel for reference in future reviews and inspections, and in dealing with problems, repairs, etc. Both files should be continuously updated with records on problems, repairs, operation, instrumentation, and inspection for the life of the project. Information such as foundation reports and as-built drawings and maps should also be permanently retained.

Periodic photos that are dated and annotated can be invaluable to assessing changes in the level of safety of a dam. They are especially useful to capture the performance of the dam at peak storm events. A photo of the spillway at its peak discharge during a storm provides very valuable information on maximum water level reached during the storm. The authors recommend that owners collect a representative set of photos each year at the time of maximum reservoir level.

As obvious as it seems, a copy of all these documents should be maintained at a separate location. There have been instances where the only copy of historical records were lost in the failure.

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## 5.0 MODEL SURVEILLANCE, MONITORING AND EVALUATION PROGRAM FOR DAM SAFETY

Performance monitoring programs for dam safety must be carried out at regular intervals by qualified inspectors who know what to look for and how to interpret what they are seeing. An effective dam safety performance monitoring program should consist of the following elements:

- clearly defined objectives of the monitoring program with a means to assess accomplishment of those objectives.
- distinct, defined duties and responsibilities for each participant in the monitoring program.
- up-to-date written description of each component of the monitoring program and its purpose.
- definition and outline of the reporting protocol and chain of delivery for observations, conclusions and recommendations from the monitoring program.
- written Standard Operating Procedures for carrying out the monitoring program.
- definition, outline and requirements of each type of report.
- formalized training program for those who will participate in the monitoring program.
- an up-to-date monitoring schedule that is revised when necessary to account for changes in the condition of the dam.
- written processes for data analysis, evaluation and interpretation.
- means to define and initiate the appropriate response action for unacceptable or unexpected performance from the monitoring program.
- defined chain of communication and reporting process for distributing results of the monitoring program whenever a decrease in the level of safety of the dam of the dam is indicated.

### 5.1 Training of Personnel

Training of inspection, monitoring, operating and maintenance personnel is an essential part of any dam safety program. The training messages are different for each of these functions. Therefore the training program should be different for each.

Technically qualified operating personnel should be trained in problem detection and evaluation, and application of appropriate interim risk reduction measures. This is essential for proper evaluation of developing situations at all levels of responsibility, which must be based on observations made by operating personnel at the project. The training should cover the problems that experience has shown are most likely to occur with the type of dam and facilities, and include the kinds of monitoring best suited to early detection of those problems. Such training will permit action when time is a critical factor. A sufficient number of personnel should be trained to ensure adequate coverage of all tasks at all times. If a dam is operated by remote control, training must include procedures for dispatching trained personnel to the site at any indication of distress.

Personnel involved in inspections should be trained for the requirements of these duties. The training should cover the types of information needed to prepare for the inspection, critical features that should be observed, inspection techniques, and preparation of inspection reports. In addition to dam safety training, those involved in the dam safety program should also participate in emergency action plan training exercises and periodic reviews. Based on the role of the individual within the dam safety program, periodic training could take the form of in-house brown bag or tailgate briefings, classroom lectures, or formal courses on special topics related to dam safety. There are some excellent guidelines, technical memorandum, and training materials available from professional societies and agencies including:

Association of Dam Safety Officials (ASDSO): www.damsafety.org
United States Society on Dams (USSD): www.ussdams.org
International Committee on Large Dams (ICOLD): www.icold-cigb.net
Canadian Dam Association (CDA): www.cda.ca
U. S. Army Corps of Engineers (USACE): www.usace.army.mil/library/publications
U. S. Bureau of Reclamation (USBR): www.usbr.gov/library/
U.S. Federal Emergency Management Agency (FEMA):
www.fema.gov/plan/damfailure/publications.shtm
American Society of Civil Engineers (ASCE): www.asce.org
Federal Energy Regulatory Commission (FERC): www.ferc.gov

Visual inspections are many times made by staff in operations, maintenance, trained inspectors or dam safety engineers. It is important to recognize what each of these specialties can and cannot do. ***Table 5.1*** provides a generalization of the roles each functional level. The key message of ***Table 5.1*** is that Operations and Maintenance personnel play an important role in visual inspections of dam safety but cannot substitute for the special capabilities of trained dam inspectors and dam safety engineers.

**Table 5-1 Capabilities of Staff Specialities in Visual Inspection**

| Activity | Operations | Maintenance | Trained Inspectors | Dam Safety Engineers |
|---|---|---|---|---|
| Detect visual changes of reservoir level, spillway overflow, change in operational patterns | X | X | X | X |
| Detect visual changes in vegetation, cracking, deformation, springs, boils, whirlpools, sinkholes, soft spots, damaged slope protection, malfunctioning drains, poor maintenance, spillway blockage, general deterioration | | X | X | X |
| Differential movement, change in alignment, ASR, unstable slopes, changes in seepage patterns, piping, malfunctioning equipment and instruments, weathering effects | | | X | X |
| Interpretation of importance of visual observations on safety of dam, recognition of emerging failure modes | | | | X |

When developing dam safety training and emergency action plan training exercises, provisions should also be made to involve the owner's management team with periodic briefings regarding the "health" of the dam. Emphasis should be given to developing "risk awareness" and "risk management awareness" for engineering and operation managers.

The training program should consist of two levels. Level I is an introductory level where new staff are trained to understand the important features of the dam, potential failure modes, the elements essential to the safety of the dam, the dam safety program, the location and contents of the written dam safety program, their specific duties in the dam safety program and methods to carry out those duties, report the results and take action when indicated. ***Table 5.2*** provides the outline of a recommended introductory training program. Level II is an annual review of the safety program, changes in the condition and operation of the dam for the past year and the coming year, a review of the performance of the safety team, and a discussion of methods to improve and enhance the safety program. ***Table 5.3*** gives an outline for an annual training program. Contents of the training program may differ for the various functional levels in the organization as indicated in ***Tables 5.2*** and ***5.3***. Each organization should develop its own training program that addresses the unique aspects of its management structure and its dam facilities.

Table 5-2 Introductory (Level I) Training Program for Dam Safety

| Training Element | Owner/Trustee/ Board of Directors | Management, Safety, Security | Operators | Maintenance | Inspectors | Engineer |
|---|---|---|---|---|---|---|
| Introduction to the dam, the main elements and their function | Y | Y | Y | Y | Y | Y |
| Review Potential Failure Modes | Y | Y | Y | Y | Y | Y |
| Dam safety program | Y | Y | Y | Y | Y | Y |
| Chain of responsibilities for dam safety | Y | Y | Y | Y | Y | Y |
| Role of each group in dam safety | Y | Y | Y | Y | Y | Y |
| Record keeping and reporting | --- | Y | Y | Y | Y | Y |
| Visual inspections – Level I | Y | Y | Y | Y | Y | Y |
| Visual inspections – Level II | --- | --- | ---- | ---- | Y | Y |
| Monitoring program | Y | --- | --- | --- | --- | Y |
| Reading instruments/checking data | --- | --- | --- | Y | Y | Y |
| Data Evaluation/Reporting | --- | --- | --- | --- | --- | Y |

**Table 5-3 Annual (Level II) Training Program for Dam Safety**

| Training Element | Owner/Trustee/Board of Directors | Management, Safety, Security | Operators | Maintenance | Inspectors | Engineers |
|---|---|---|---|---|---|---|
| Review of main elements of dam and their function | Y | Y | Y | Y | Y | Y |
| Review potential failure modes | Y | Y | Y | Y | Y | Y |
| Review of dam safety program | Y | Y | Y | Y | Y | Y |
| Chain of responsibilities for dam safety | Y | Y | Y | Y | Y | Y |
| Review of Role of each group in dam safety | Y | Y | Y | Y | Y | Y |
| Review of Record keeping and reporting procedures and performance over past year | ---- | Y | Y | Y | Y | Y |
| Review of dam performance over past year and expected performance/changes in upcoming year. | Y | Y | Y | Y | Y | Y |
| Review of dam safety program performance for prior year, evaluation of what can be improved | Y | Y | Y | Y | Y | Y |
| Review and evaluation of Visual inspection procedures – Level I | ---- | Y | Y | Y | Y | Y |
| Review and evaluation of Visual inspection procedures – Level II | ---- | --- | ---- | ---- | Y | Y |
| Review and evaluation of Performance Monitoring program | Y | Y | --- | --- | --- | Y |

The level of training provided for each targeted functional category will vary based on roles and responsibilities within the owner's organization. For example, in some organizations, operations and maintenance personnel collect and record instrumentation data and perform routine visual inspections. In this situation, these personnel should be provided refresher training on the specific instruments and visual inspection techniques for that dam.

For individual dam owners and small organization owners with limited full time dam safety staff, consideration should be given to retaining a qualified professional engineer to provide periodic training and evaluation of the adequacy of the existing dam safety program.

## 5.2 Visual Surveillance

Visual surveillance represents one of the most important elements of a dam safety program. It can give the first warning that something is going wrong with the dam. Good visual inspections provide important information on unexpected performance of the dam.

The human eye connected to a trained brain that is applying critical thinking skills is the most powerful monitoring tool available. This combination can recognize pattern changes very efficiently so that changes in surface appearances of the dam and elements around the dam can be quickly identified. This combination can interpret the observed pattern changes to determine whether they are related to dam safety or not.

As an example, a person on the crest of the dam might observe an area along the dam abutment contact where the vegetation color differs. This pattern difference may be significant for dam safety, or it may not. The cause might be due to differences in the vegetation type, or the development of a wet spot due to seepage through the dam or the abutment. A trained individual will inspect further to better determine the cause of the color difference.

***Figures 5.1 – 5.19*** provide examples of some of the indicators of poor performance of a dam that can be identified by visual inspection. Most of the photographs show advanced stages of deterioration. Visual inspections should be designed to recognize indicators of these and other failure modes at the earliest possible time.

**Figure 5-1 Sinkhole which developed over Spillway Conduit (FEMA, 2005)**

**Figure 5-2 A failure due to internal erosion often leaves a tunnel-shaped void along the conduit (FEMA, 2005)**

***Tables 5.4 to 5.13*** summarize typical elements that a trained dam safety inspector should consider in a visual inspection of the important components of a dam. Each table focuses on a specific element of the dam to help an inspector focus on things to look for when inspecting that element. This results in some performance indicators being listed multiple times across the tables; however, the pursuit of thoroughness in the inspection outweighs shortening the tables. Some elements in the tables do not apply to all dams. These tables should be used as a guide and tailored to a specific dam. Some dams may have important features that are not covered in these tables. Those features should be added to a site-specific set of tables. The right column in each table provides a scale to suggest the level of importance of each element to overall immediate dam safety. The levels of importance are tied to the performance states, Normal, Caution and Alert, described in ***Section 2.1***. ***Section 7.5*** discusses the actions to be taken when the Caution and Alert performance states are identified.

These tables are only a guide to help the Dam Safety team develop their own ranking system. We recommend that the dam safety team work with the dam designers to modify these tables to each dam. Others have provided ranking systems for visual deficiencies in dams that may be helpful (Lambe et al,1981)

**Table 5-4 Some Elements to look for in a Visual Inspection of Crest of Earth/Rockfill Dam**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Unexpected settlement | Decreasing freeboard means less flood protection | Alert if settlement is accelerating for no known reason; or different than past patterns; otherwise Caution |
| Differential movement horizontally or vertically | Dam not performing uniformly; cracks could be developing | Alert if rate of movement is accelerating or different than past patterns for no known reason; otherwise Caution |
| Cracking in transverse direction | Cracks extending to below water level in dam can initiate a breach | Alert if more than 0.5 inches wide and increasing daily; otherwise Caution if not deeper than half of the freeboard or 5 ft; whichever is less and not increasing. |
| Cracking in longitudinal direction | Cracks running parallel to axis of dam may indicate shear strains occurring in the upstream or downstream slope or within the foundation | Alert if more than 0.5 inches wide with differential settlement across the crack and increasing daily; otherwise Caution |
| Structure is unexpectedly moving differently than adjacent components | Might indicate loss soil at depth, undermining of the structure, or slippage of soil or rock. | Alert if recent and increasing daily. Caution if long-term at constant rate without immediate threat. |
| Misalignment along length of crest | May indicate portions of dam shifting horizontally more than others. | Alert if recent and increasing; Normal if long-term at constant rate without immediate threat |
| Depression in surface | May indicate erosion of soil out of core of dam | Alert if recent and growing daily; Caution if continual increase over time; Normal if no change in recent years. |
| Sinkhole | Indicates soil or rock is being removed from the dam in an uncontrolled manner. | Alert if below the phreatic surface and increasing; otherwise Caution |
| Flattened grass, scrape marks, water-borne debris, erosion rills | May indicate recent overtopping event | Alert if reservoir is full and more rain is expected; otherwise Caution and should prompt a review of design for overtopping. |
| Poor maintenance (Holes, trees, shrubs, burrowing animals, deteriorating concrete elements) | May provide pathways for surface water to flow into the dam and create voids. | Caution if effects might extend below the phreatic surface in the dam; otherwise Caution to be corrected by maintenance. |

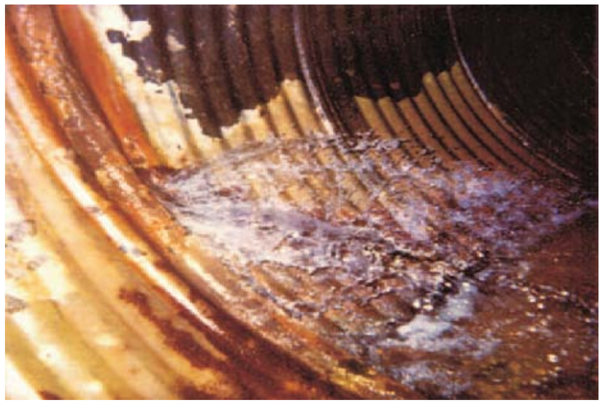

Figure 5-3 Figure of an Embankment Dam
due to the discontinuity represented by the conduit
(FEMA, 2005)

Figure 5-4 Leakage through a defective joint in a
corrugated metal pipe outlet works conduit
(FEMA, 2005)

**Table 5-5 Some Elements to look for in a Visual Inspection of Upstream Slope of Earth/Rockfill Dam**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Unexpected settlement | May indicate shearing in soil below the surface, loss of soil by erosion or consolidation of slope or foundation | Alert if settlement is accelerating for no known reason; or different than past patterns; otherwise Caution |
| Differential movement horizontally or vertically | Dam not performing uniformly; cracks could be developing | Alert if rate of movement is accelerating or different than past patterns for no known reason; otherwise Caution |
| Cracking in transverse direction | Cracks extending to below water level in dam can initiate a breach | Alert if more than 0.5 inches wide and increasing daily; otherwise Caution if not deeper than half of the freeboard or 5 ft; whichever is less and not increasing. |
| Cracking in longitudinal direction | Cracks running parallel to axis of dam may indicate shear strains occurring in the upstream slope or within the foundation | Alert if more than 0.5 inches wide with differential settlement across the crack and increasing daily; otherwise Caution |
| Depression in surface | May indicate erosion of soil from interior of embankment or its foundation. | Alert if recent and growing daily; Caution if continual increase over time; Normal if no change in recent years and above high water level. |
| Sinkhole | Indicates an open channel has developed within dam or foundation through which soil and water can be lost. | Alert if below the normal water level and increasing; otherwise Caution |
| Damaged slope protection | May expose slope to accelerated erosion by wave attack. | Alert if erosion benches have developed to point that shear slide might develop in the slope; otherwise Caution. |
| Whirlpool in surface of water near slope, or evidence of rapid inflow of water into the dam. | May indicate presence of hole in dam through which water is escaping uncontrollably | Alert and must be investigated immediately. |
| Poor maintenance (Holes, trees, shrubs, burrowing animals, deteriorating concrete elements, degraded slope protection) | May provide pathways for water to enter dam at faster rate than it was designed to handle, or for accelerated erosion of upstream slope. | Alert if effects might extend below the phreatic surface in the dam; otherwise Caution to be corrected with maintenance.. |


Figure 5-5  Shallow Slide
(Rizzo Photo, 2007)


Figure 5-6  Embankment Sinkholes
(Rizzo Photo, 2007)

**Table 5-6 Some Elements to look for A visual Inspection of Downstream Slope of Earth/Rockfill Dam**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Unexpected settlement | May indicate shearing in soil below the surface, loss of soil by erosion or consolidation of slope or foundation | Alert if settlement is accelerating for no known reason; or different than past patterns; otherwise Caution |
| Differential movement horizontally or vertically | Dam not performing uniformly; cracks could be developing | Alert if rate of movement is accelerating or different than past patterns for no known reason; otherwise Caution |
| Cracking in transverse direction | May provide a point of weakness through which water can concentrate and erode away soil leading to uncontrolled release of water. | Alert if more than 0.5 inches wide and increasing daily; otherwise Caution if not deeper than half of the freeboard or 5 ft; whichever is less and not increasing. |
| Cracking in longitudinal direction | Cracks running parallel to axis of dam may indicate shear strains occurring in the downstream slope or within the foundation | Alert if more than 0.5 inches wide with differential settlement across the crack and increasing daily; otherwise Caution |
| Depression in surface | May indicate erosion of soil from interior of embankment or its foundation. | Alert if recent and growing daily; Caution if continual increase over time; Normal if no change in recent years and above high water level. |
| Sinkhole | Indicates an open channel has developed within dam or foundation through which soil and water can be lost. | High if increasing in size; otherwise Caution. |
| Damaged slope protection | May expose slope to accelerated erosion by surface water runoff. | Alert if erosion rills and channels have developed to point that shear slides may develop; otherwise Caution. |
| Seeps, wet spots, soft areas | Indicates water flowing from the dam in ways that it was not designed to do; potential for loss of soil. | Alert if escaping water is turbid or if condition has recently worsened; otherwise Caution. |
| Flattened grass, scrape marks, water-borne debris, erosion rills | May indicate recent overtopping event | Alert if reservoir is full and more rain is expected; otherwise Caution and should prompt a review of design for overtopping. |
| Isolated locations with lush vegetation | May indicate presence of seepage through dam in way it was not designed. | Caution if recent. |
| Poor maintenance (Holes, trees, shrubs, burrowing animals, deteriorating concrete, degraded slope protection) | May provide preferential paths for water to seep uncontrollably out of dam and carry away soil (piping). | Alert if muddy seepage is occurring at the location of any of these defects. Caution if effects might extend below the phreatic surface in the dam; Caution if trees are dead and rotting away. |

Figure 5-7 Embankment Seepage
(Rizzo Photo, 2007)

Figure 5-8 Embankment Seepage
(Rizzo Photo, 2007)

Figure 5-9 Embankment Seepage Advanced
(Rizzo Photo, 2007)

**Table 5-7 Some Elements to look for in a Visual Inspection at Abutments, Toe of Dam and Downstream**

| Performance Indicators | Why significant | Importance |
|---|---|---|
| Movement downstream or heave | May indicate shear slide developing in downstream slope or foundation of dam. | Alert if rate of movement is accelerating or different than past patterns; otherwise Caution |
| Seeps, wet spots, boils | Indicates water flowing from the dam foundation in ways that it was not designed to do; potential for loss of soil. | Alert if escaping water is turbid or if condition has recently worsened; otherwise Caution |
| Soft spots, blisters, spongy areas | Indicates excess pore pressure at depth that is pushing the surface layer of soil upward. | Alert because water may break through and remove soil at any time resulting in erosion or loss of stability. |
| Isolated locations with lush vegetation | May indicate presence of seepage through dam in way it was not designed. | Caution if recent. |
| Flattened grass, scrape marks, water-borne debris, erosion rills | May indicate recent overtopping event | Alert if reservoir is full and more rain is expected; otherwise Caution and should prompt a review of design for overtopping. |
| Poor maintenance (Holes, trees, shrubs, burrowing animals, deteriorating concrete, degraded toe protection) | May provide preferential paths for water to seep uncontrollably out of dam and carry away soil. | Caution if seepage is occurring at the location of any of these defects or if trees are dead and rotting away. |

**Figure 5-10 Embankment Sand Boil, Early State Piping (Rizzo photo, 2007)**

**Figure 5-11 Embankment Animal Borrow (Rizzo Photo, 2007)**

Table 5-8 Some Elements to look for in a Visual Inspection of Concrete Spillway

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Differential movement of concrete segments | May indicate erosion of underlying materials that could undermine the spillway | Alert if effects are recent and getting larger; Caution if continued movement will affect future safe operation. |
| Scour of concrete surface | Can lead to failure of the spillway liner and result in a breach | Alert if effects are recent and at faster rate than previous performance with possibility of failure in next event; otherwise Caution. |
| Cracks in concrete | May allow water to get below liner and erode away its foundation or uplift a segment of the spillway. | Alert if recent or increasing and creates possibility of failure in next event; otherwise Caution. |
| Blockage | Reduces discharge capacity of spillway. May give way suddenly under large pressure and damage something. | Alert if it will cause further accumulation of debris or higher backup of water behind the dam; otherwise Caution. |
| Alkali-silica reaction (ASR) or other mass concrete deterioration | Degrades strength of concrete and exposes rebar to corrosion. | Caution. |
| Poor maintenance (spalling concrete, exposed rebar, vegetation growing through joints and cracks) | May provide preferential paths for water to seep below spillway and erode away its foundation or uplift a segment of the spillway. | Alert if water is discharging in an uncontrolled manner or structural capacity of the element is in question; otherwise Caution. |

Figure 5-12 Upstream Debris on Dam Outlet (Rizzo Photo, 2007)

Table 5-9 Some Elements to look for in a Visual Inspection for Earthen Spillway

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Differential movement down slope or horizontal cracks perpendicular to axis of spillway | May indicate unstable conditions and potential shear slide | Alert if recent and movement is continuing to increase daily; otherwise Caution. |
| Vertical cracks that extend through the protective cover | May provide pathways for water erode the spillway liner at much faster rate. | Alert if underlying soil is erosive; otherwise Caution to be corrected by maintenance. |
| Damaged spillway cover | Allow higher rate of erosion such that spillway might fail and cause uncontrolled release of water | Alert if during the flood season for the dam; otherwise Caution. |
| Flattened grass, water-borne debris, erosion rills | May indicate recent overtopping event | Alert if reservoir is full and more rain is expected; should prompt a review of design for overtopping; otherwise Caution. |
| Poor maintenance (cracks in spillway wider than ½ inch, poor grass cover; vegetative growth in spillway higher than 1 ft) | May provide preferential paths for water to erode spillway and lead to uncontrolled release. | Alert if water is discharging in an uncontrolled manner or structural capacity of the element is in question; otherwise Caution. |

Table 5-10 Some Elements to look for in a Visual Inspection of Reservoir

| Performance Indicator | Why Significant | Importance |
|---|---|---|
| Unstable slopes anywhere on perimeter of reservoir | Sudden failure and flow of large mass of earth into reservoir can create a wave that overtops the dam. | Alert if volume of moving earth is significant and rate of movement is increasing; otherwise Caution. |
| Floating debris at booms or around perimeter or materials that could become floating debris with rise in reservoir | Might float down current and block the spillway | Alert if debris could inhibit the correct functioning of the spillway; otherwise Caution to be corrected with maintenance. |
| Large changes in land use upstream of dam | Could increase runoff and exceed discharge capacity of spillway. | Caution to be addressed in next dam safety review. |

**Table 5-11 Some Elements to look for in a Visual Inspection of Drainage Control Features (Drainage Galleries, Blanket drain outlets, toe drains, relief wells)**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Discharge rate has decreased | Is drain becoming clogged which would cause pore pressure build up or a seepage breakout in another location? | Caution. |
| Discharge rate has increased | Is the seepage barrier within the dam becoming less effective?<br>Are fines being removed from the dam in ways that develop preferential flow paths? Is dissolution of soil or rock occurring? Can the flow rate exceed the discharge capacity of the drain? | Alert if increase is sudden and more than expected in the design; otherwise Caution. |
| Discharge carries soil particles | Indicates loss of soil from the dam or its foundation which can lead to faster seepage rates, piping and uncontrolled release of water | Alert if recent and increasing; otherwise Caution. |
| Flow is bypassing the drainage element | Allows uncontrolled discharge of flow from the dam with potential for loss of soil particles. | Alert if recent change and significant flow; otherwise Caution. |
| Flow has developed at a new location | Indicates an increase in the rate of flow through the dam or a change in the path of previous flow. | Alert if flow rate is sudden and significant; otherwise Caution. |
| Poor Maintenance (damaged release components, clogged filters) | Reduce the effectiveness of the drainage control measure | Caution to be corrected by maintenance. |

**Table 5-12 Some Elements to look for in a Visual Inspection of Monitoring System**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Damaged Components | May affect the reading from the instrument or make reading impossible. | Caution as instrument may become of no value. Data are unavailable or questionable. |
| Erratic or non-reproducible reading | Unreliable data | Caution. Do not include results in performance report until fixed. |
| Vandalized | Reduces reliability of the monitoring system. | Caution. Replace the instrument if still needed. Take steps to better protect the monitoring system and/or rid of the vandals. |
| Poor Maintenance (poor connectors, tangled wires, lost labels, readout out of calibration) | Increases the amount of questionable data and reduces reliability of the monitoring system. | Caution. Take corrective action. |
| Key instrument not functional | A key instrument is considered vital to the safety program for the dam. | Alert. Instrument needs to be repaired or replaced immediately. |

**Table 5-13 Some Elements to look for in a Visual Inspection of Operating Equipment Related to Dam Safety**

| Performance Indicators | Why Significant | Importance |
|---|---|---|
| Condition of discharge gates | Failure to operate when needed can lead to buildup of water behind the dam with potential to overtop the dam. | Alert if high runoff season is approaching and gate is significant safety element; otherwise caution. |
| Operating restrictions (are these known and followed?) | Exceeding these restrictions may damage an important component of the dam and produce an uncontrollable release of water | Alert if operating personnel are not knowledgeable to follow these restrictions. |
| Availability of Emergency Back-Up Power Supply | Lack of power can lead to inability to operate spillway gates in an emergency. | Caution if manual operation capability is present and accessible; Alert if manual control is unavailable or access to operating equipment may be blocked by debris, flooding or ice. |
| Vulnerability of dam access roads to flooding or landslides | Loss of dam access could preclude emergency response to release inflow floods, which could lead to loss of the dam. | Caution if access road instability vulnerability is present; Alert if access road is damaged or subject to flooding by rising flood flow. |

(includes only items potentially related to dam safety)

**Table 5-14 Some Elements to look for in a Visual Inspection of Concrete/Masonry Dams**

| Performance indicators | Why significant | Importance |
|---|---|---|
| Deteriorated surface conditions | Spalling, scaling, surface cracking cavitation and surface erosion could expose rebar to corrosion and ultimately reduce the strength of the structure. Excessive surface deterioration can introduce structure vulnerability by reducing the dam's ability to resist design loads. The presence of alkali-aggregate expansion cracking can indicate excessive internal stresses, which can have serious impacts on the performance of embedded steel, gates, conduits, turbines, etc. | Caution if poor surface concrete conditions are shallow; may be associated with temperature cracking and normal weathering. Alert if deterioration begins to undercut rebar, if deep cracking is observed, and deteriorated pieces fall out. |
| Alignment | Miss-alignment of construction, contraction or expansion joints can indicate potential sliding or overturning movement. | Normal if alignment discrepancies are within construction tolerance; Caution if alignment issues may be the affect of thermal expansion/contraction; alert if sudden changes or increasing rate of change are observed. |
| Deformation | Relative displacement of blocks and/or absolute movement of the structure may signal adverse trends. | Caution if deformations observed result in cracking or increased seepage. Alert if change is sudden, continuing as an accelerated rate, or more than expected for type of structure. |
| Abutment-Dam contacts | Contact between dam and abutment could cause excessive seepage around dam and lead to collapse. | Caution if seep or slide potential exists; Alert if cracking, extreme seepage, or landslides observed. |
| Missing or loose stones and joints | Reduce structural stability | Caution if confined to small areas; Alert if significant areas are present or if undermining of adjacent areas is observed. |
| Vegetation | Vegetation roots open joints; can cause increased seepage and structural deterioration. | Caution if vegetation present; Alert if deep penetration occurs or if seepage becomes significant. |

continued

## Table 5-14 Some Elements to look for in a Visual Inspection of Concrete/Masonry Dams (continued)

| Performance indicators | Why significant | Importance |
|---|---|---|
| Drain discharge rate has decreased | Is drain becoming clogged which would cause pore pressure build up or a seepage breakout in another location? | Caution if sudden change observed. |
| Drain discharge rate has increased | Is the drain water carrying suspended or dissolved solids from foundation? Are the seepage flows changing in the rate and character of flow? Is the foundation solution or erosion foundation deterioration? | Alert if increase is sudden and more than expected in the design; otherwise Caution. |
| Leakage/Seepage | Flows from the foundation and from the joints and cracks in a dam can indicate crack enlargement, faulty waterstops, and unbounded lift surfaces. Cracks are likely to be the first indication of concrete distress. May be accelerated by the ingress of water and consequent leaching. Deep cracking may adversely affect the monolithic action of the dam, increasing stress concentrations. May lead to higher internal water pressures and accelerated damage by freezing and thawing. | Caution if sudden increase or decrease is noted and correlated with the reservoir level. |
| Instrumentation | If instrumentation is out of service or if data is not promptly collected and evaluated, significant changes in readings can be missed and automated or remotely operated equipment can cause miss-operation with dam safety consequences. | Caution if instrumentation is out of service; Alert if reservoir operation depends on accurate timely readings to stay within safe operating levels. |
| Weathering effects and/or discontinuities in foundation rock | Main cause for failure of concrete dams. Discontinuities are very important for analyzing weakness in the foundation. Hydraulic pressure in a joint causes large forces on its rock walls with increasing aperture and then permeability. | Caution if foundation seepage begins to increase in time; Alert if flow is excessive or if hydraulic pressure affect stability calculations assumptions. May need underwater inspection to monitor. |
| Spillway or tailrace foundation erosion | Forces of water, whether falling, seeping or eddying can undermine dam; leads to structural instability | Caution if erosion approaches structure base; Alert if undercutting begins. May need underwater inspection to monitor. |

Figure 5-13 Structural Crack Monitoring
(Rizzo Photo, 2007)


Figure 5-14 Structural Crack
(Rizzo Photo, 2007)

Figure 5-16 Structural Crack Monitoring
(Rizzo Photo, 2007)

Figure 5-15 Surface Cracking - Alkali-Aggregate Expansion
(Rizzo Photo, 2007)

Figure 5-17 Spalling
(Rizzo Photo, 2007)

Figure 5-18 Scaling
(Rizzo Photo, 2007)


Figure 5-19 Displacement of Joints
(Rizzo Photo, 2007)

The times to conduct visual inspections depend on the type of dam, the consequences of the dam failing, its condition, and changes in environmental conditions. *Table 5.15* provides some guidelines for the frequency of regular visual inspections once the dam is put into service. Guidelines for visual inspections during construction and first filling should be established by the designer of the dam to take into account its specific circumstances. A visual inspection should be conducted of every dam whenever a report is received of unexpected or unusual behavior of the dam. Visual inspection should also be made during and after a storm event that is greater than the 25-year storm for the area, or after a seismic event, including nearby blasting, that causes a peak particle velocity at the ground surface of greater than 1 in/sec, or at any other time as recommended by the designer.

**Table 5-15 Recommended Minimum Frequencies for Visual Inspections**

| Hazard Potential | Performance State | | |
|---|---|---|---|
| | Normal | Caution | Alert |
| **Low** | Once per year | Once per quarter to once per month. | Once per month to once per week. During 25-year event or larger. |
| **Intermediate** | Once per 6 months | Once per month to once per week | Once per week to once per day. During and after event that exceeds the design event. |
| **High** | Once per quarter | Once per week to once per day. During and after event that exceeds the design event. | Once per day to continuous. During and after event that exceeds the design event. |

Notes:
1. A visual inspection should be taken following major events such as large rainfalls and earthquakes that might affect the dam's condition.
2. Rates are suggested typical values for guidance only. Each dam is unique and visual surveillance frequency should be selected to capture all significant performance elements of that dam.

With the increasing availability of high quality cameras and low cost of communications, it is possible to supplement visual monitoring through site walks with visual monitoring via remote cameras. These tools are useful to monitor an area where there is a known problem to determine if it is worsening; however they do not replace the need for a visual inspection by a qualified person at the scheduled intervals to locate new problems.

Visual inspections by inspectors and monitors must be documented. Standardized forms with areas for comments are strongly recommended. A sample schedule for various levels of visual inspection and sample inspection checklist forms for operations checks, operations inspections, and engineering inspections are provided in *Appendix E*. All inspection forms and checklists should be modified to suit site specific conditions at the dam to be inspected. Completed inspection forms should be provided to the inspector's supervisor or other designated person as soon as practical after the inspection is complete. Photographs should be taken of points of interest, documented with date, time and location of the photo and placed into an organized storage system. Each photograph of a specific point of surveillance interest should include a means of determining scale and ideally a color chart to help document changes in appearance and the size of changes. Photographs should be catalogued and labeled so they can be identified and reviewed at any point in the dam's life.

A continuous log of visual inspections should be maintained that documents each visual inspection with date, time, weather, person, summary of any changes found, and actions required. Visual observations by operators, maintenance personnel or other people should be entered into this log. Changes detected by these inspections that might relate to the safety of the dam should be immediately reported to the Monitoring Supervisor who will order an immediate visual inspection by a trained dam safety inspector.

## 5.3 Overview of Instruments

Visual inspections can only indicate what is occurring to the dam as manifested on its surface. Most significant failure mechanisms develop below the ground surface and may not be visible until the failure mechanism is well under way. The medical analogy is a physician trying to determine what might be wrong with a person solely from a visual examination and no information from the person. Obviously the physician is seriously hampered in arriving at a proper diagnosis for many of the possible ills. Tests and measurements to reveal what is going on below the skin are essential for proper diagnosis and treatment. Such is the case with determining the health of a dam. Instruments must be placed within the dam to indicate its vital performance parameters. Due care should be given to a proper installation procedure. Faulty installation may leave an otherwise suitable instrument placed at the right location, useless.

Numerous instruments exist to monitor physical and environmental factors for a dam and its related structures. Many are adaptations of sensors developed for other industries and adapted to dam monitoring. A few like the inverted pendulum and plumb lines have been developed specifically to monitor some aspect of safety for dams.

***Table 5.16*** summarizes the more common types of instruments used to monitor dam performance. ***Table 5.17*** summarizes some newer instruments with potential for dam safety monitoring. ***Appendix B*** provides an abbreviated review of each type of sensor, how it works and where it is used. More information can be found in Dunnicliff (1988, 1993) and on the Web sites of equipment vendors. ***Appendix B*** provides a list of web sites for the instrumentation manufacturers for dam applications.

## Table 5-16 Common Instruments Used in Dam Monitoring Programs

| Instrument Type | Use |
|---|---|
| Ground reference point, displacement monitoring point, settlement point, heave point, movement monitoring point | Indicate horizontal and vertical change in position of the point. Used to monitor settlement and horizontal movement at the surface of the ground or on a structure. |
| Settlement plate, settlement platform, settlement cell | Change in elevation of a plate buried within a fill. Used to monitor settlement of a compressible foundation during and after construction of an embankment. |
| Vertical inclinometer | Horizontal movement along a vertical pipe installed in a boring. Used to monitor horizontal movement with depth in a slope to detect development of shear slide. |
| Horizontal inclinometer | Vertical movement along a horizontal pipe installed in a trench or bottom drainage gallery. Used to monitor vertical movement (settlement or heave) along a horizontal distance. |
| Tilt meter | Change in angle relative to direction of gravity. Used to measure rotation of a structure from vertical. |
| Crack meter | Change in width of a crack. Used to determine if crack is growing. |
| Extensometer | Movement of a fixed point below the ground surface relative to the ground surface. Multiple extensometers in the same location are used to identify the distribution of movement with depth. |
| Observation well | Depth to water below the ground surface. Used to locate surface of water. |
| Piezometer | Pressure of the pore water in the voids of soil and rock. Used to determine how water pressures change within a dam and its foundation. |
| Strain gage | Elongation or contraction of a small reference length on a portion of a structural element. Used to indicate the change in stress experienced by the structural element. |
| Load Cell | Amount of force. Used to measure force in a structural member such as a tie down anchor or a compression member. |
| Earth Pressure Cell | Normal stress on a plane in soil. Measures total stress normal to the face of the pancake-shaped cell. |
| Contact Pressure Cell | Normal stress applied to the face of a structural element. |
| Seismograph | Velocity of ground motion or structure during shaking. Used to determine if vibrations from impact equipment, blasting, or seismic activity might impact the structure. |
| Accelerometer | Acceleration of ground motion or structure during shaking. Used to determine if dynamic forces from impact equipment, blasting, or seismic activity might damage the structure. |
| Thermister, thermocouple, RTD | Measure temperature. Used to measure temperature changes in curing concrete, temperature differences in groundwater to indicate potential flow sources, and thermal gradients in soil and rock. |
| Turbidity Meter | Measures turbidity in seepage from embankment. Used to investigate potential piping of dam materials. |

**Table 5-17 Newer Instruments for Potential use in Dam Monitoring Programs**

| Instrument Type | Use |
|---|---|
| Time Domain Reflectrometry | Measure where a coaxial cable develops a kink. Measure distance to a shear plane. |
| Acoustic Emission Monitoring | Measure increases in acoustic energy emitted by soil or rock particles sliding relative to each other. Measure potential development of a shear slide. |
| Liquid Level Gages | Precise measurements of change in elevation of point located along a horizontal liquid filled pipe. Used for precise measurements of settlement. |
| Automated total station, robotic total station | Motorized total station with laser distance meter to precisely measure distance, azimuth and zenith to a reflecting target. Used to precisely measure change in position of reflecting targets located on visible targets placed on dam components over time. Can measure x, y, z movements to ±1 mm. |
| Differential Global Positioning System (DGPS) | Radio receiver mounted on a surface location that uses satellites to precisely determine its position. Used to precisely measure change in position of GPS receivers placed on dam components. Can measure x, y, z movements to ±1 mm. |
| LIDAR (Light Detection and Ranging) | Airborne equipment that uses satellite positioning and light reflection to develop precise contour maps of the surface of the earth. May be used to detect movements on the surface of a dam to a resolution of about ½ inch. |
| InSAR (Interferometric synthetic aperture radar) | Satellite based radar equipment that provides centimeter scale maps of surface changes in elevation over time. |
| Fiber optic sensor | A temperature, strain or pressure sensor made integral to a fiber optic cable that provides highly accurate measurements at high speed. In distributed fiber optic systems, hundreds of sensors may be placed on a single fiber cable. |
| Digital Camera with reference targets | Digitized calibrated images are used to precisely measure the horizontal and vertical movements of targets located at distances away from the camera such as once located along the crest of the dam to indicate settlement and horizontal translation of the top of the dam. |

*Table 5.18* summarizes the most common modes of performance that are monitored with instruments and the types of instruments applicable to each mode.

Almost every instrument type can be read by manual means or with electronic sensors; however the specific sensor may be different for manual readings than for electronic sensors.

Table 5-18  Instrument Types for Potential Failure Modes

| Potential Failure Mode | Applicable Types of Instruments |
|---|---|
| Overtopping | Reservoir water level indicator such as a pressure transducer mounted on the upstream face of the dam. Spillway discharge using marked staff rod on side of spillway read visually or by remote camera. Remote cameras trained on crest of dam. Visual observation. |
| Settlement or horizontal movement of ground surface | Reference points placed on dam and read with a level survey performed by surveyor or by automated total stations. Visual observation for movements more than a few inches. Geomatic methods including total stations, GPS, LIDAR and InSAR. |
| Settlement below ground surface | Telltales fixed on points and carried to surface where read with a level survey by surveyor or by automated total station. Borehole extensometers. Electronic settlement gages in some applications. |
| Horizontal movement below ground surface | Inclinometers that give changes in the horizontal position of a vertical pipe installed from ground surface into dam's foundation. Read manually with a probe or fitted with tilt sensors at fixed intervals for continuous readings. |
| Rotation of a structure | Electronic tilt sensors mounted on structure to measure tilt, preferably in both x and y axes, inverted pendulum. |
| Differential movement between or across components and intersections | Crack gages, extensometers, settlement gages, targets measured with surveying equipment |
| Internal pore water pressure and uplift | Hydraulic piezometers read manually or with pore pressure transducers |
| Pore water pressure distribution within dam | Piezometers to help define flow net, collection and measurement with weirs. Dyes and radioactive isotopes to locate paths of excessive seepage. |
| Excessive seepage through dam, foundation or abutments | Visual observation. Flow meters or flow weirs installed on seepage collectors. |
| Clogging or overloading of drains | Visual observations. Flow out of drain. Pore water pressure around the drain. |
| Removal of soil by flowing water (boils, internal erosion, piping) | Visual observations. Turbidity meters, collection basins. |
| Joint or crack movement | Crack meters, reference points across the crack |
| Load change in tie down rods, anchors, structural members | Load cells, strain gages, extensometers |

continued

**5-18 Instrument Types for Potential Failure Modes (continued)**

| Potential Failure Mode | Applicable Types of Instruments |
|---|---|
| Strains in structural members | Strain gages, extensometers |
| Dissolution of soil or rock materials | Mineral content of water seepage |
| Concrete deterioration | Visual observations. Swede hammer, Loss of section survey. Core and test. Non-destructive testing methods. |
| Concrete growth | Visual observation. Precise position surveys of reference points. Tiltmeter |
| Steel deterioration | Visual observation, sonic thickness measurements, corrosion sensors. |
| Response to earthquakes | Strong Motion accelerometers mounted on crest and at base. |
| Large vibrations such as caused by nearby blasting | Seismographs |

## 5.4 Instrumentation Locations

Locations of instruments are specific to each dam and its potential failure modes. Locations should be established by the designer before the start of construction, modified as appropriate by the designer during construction and first filling, and subsequently modified by knowledgeable people based on how the dam performs over time. In all situations, the number and locations of instruments must be established based on a specific purpose and with the benefits stated of how the instrument helps manage risk by answering a question or removing an uncertainty.

Locations of instruments are typically based on the following factors listed in decreasing order of importance:

- Water level in the reservoir.
- At locations with the highest likelihood of creating an uncontrollable release of water from the reservoir.
- At maximum and/or typical section(s) to affirm design assumptions.
- At locations that deviate from the typical conditions in ways that create higher likelihoods of poor performance.
- At locations in the foundation or abutments that could lead to cracking, internal erosion, leakage, high pore water pressures, or instability.
- At locations to provide redundancy to the most important instruments.

## 5.5 Monitoring Frequencies

***Table 5.19*** provides an overview of conceptual monitoring programs for a dam that depends on the hazard potential category of the dam and its condition. It includes the recommended minimum frequencies for visual surveillance given in ***Table 5.15***. The general guiding principles for dam monitoring programs are:

- The extent of the monitoring program and frequency of monitoring should increase with the hazard potential category of the dam.
- The frequency of monitoring should increase with any decrease in the condition of the dam.

As reference for the reader, ***Section 2*** defines hazard potential categories and dam performance states and ***Section 8*** provides more specific recommendations on conceptual monitoring programs for dams in different hazard categories.

**Table 5-19 Monitoring Components for Hazard Potential and Performance State**

| Hazard Potential | Dam Performance State | | |
|---|---|---|---|
| | Normal | Caution | Alert |
| Low | Visual inspections, maximum reservoir water level once per year.<br><br>Rarely monitored by instruments. | Items in Normal plus reservoir level once per quarter to once per month. | Items in Caution plus additional PFM instrumentation and monitoring with manual readouts if beneficial once per month to once per week and during or after a 25-year event or larger |
| Intermediate | Visual inspections, reservoir water level,<br>selected PFM instrumentation monitoring usually with manual readouts once per 6 months.<br>Surveys of alignment and crest settlement annually. | Items in Normal plus additional PFM instrumentation and monitoring with manual readouts if beneficial once per month to once per week. | Items in Caution once per week to once per day and during or after an event that exceeds the design event. |
| High | Visual inspections. Reservoir water level.<br>Surveys of alignment and crest settlement.<br>Selected PFM instrumentation with automated monitoring, including weather forecasts and possibly video cameras. | Items in Normal plus weather forecasts daily and possibly adding additional instruments to monitor critical PFM and video cameras if they can indicate develop of PFM. | Items in Caution plus selected PFM instrumentation continuously monitored with emphasis on providing timely warning of a possible sudden failure. |

Notes:
1. PFM = potential failure mode.
2. Visual inspections to be performed by a qualified dam safety inspector.
3. A visual inspection should be taken following major events such as large rainfalls and earthquakes that might affect the dam's condition.
4. Instruments installed to address specific issues may need to be read more frequently than values given in the table.
5. Rates are suggested typical values for guidance only. Each dam is unique and visual surveillance and monitoring frequency should be selected to capture all significant performance elements of that dam.

## 5.6 Data Collection from Instruments

Data from instruments may be gathered by manual reading, semi-automatic readings or fully automated systems. The appropriate method to use depends on several factors, including number of sensors, required frequency of reading, need for simultaneous reading of multiple sensors, difficulty of access, safety to instrumentation crew, and costs. Manual monitoring is the most cost effective when there are only a few instruments located less than 50 miles from the office and are easy and safe to access on a monitoring interval of longer than once per week and values are not expected to change much over the monitoring interval. Automation becomes cost effective when number of sensors exceeds 50, frequency of reading exceeds two per week, readings on multiple sensors must be taken within one second of each other such as monitoring earthquake effects, the site is remote and requires more than 1 hour travel time each way, access to the instruments is difficult and presents safety concerns for the monitoring crew, or the project needs real-time monitoring for an early warning system. ***Table 5.20*** summarizes some of the advantages and drawbacks of each approach to collection of data that are discussed in more detail in the following sections.

**Table 5-20 Consideration on Manual, Semi-automated, and Automated Data Collection**

| Method of Monitoring | Advantages | Drawbacks |
|---|---|---|
| Manual | • Simple with low level of training<br>• Make visual observations when reading instruments<br>• Repeat reading<br>• Perform maintenance and make minor repairs<br>• Lower capital cost to purchase and install | • Limited data over time<br>• Higher error rate in readings<br>• Unable to detect rapid changes<br>• Don't know if instrument is functioning until next site visit<br>• Delay in providing data to decision makers<br>• Cannot provide automated alarms<br>• Higher cost to collect, process and report data |
| Semi-automated | • Can log data more frequently than with manual methods<br>• Fewer site visits when more frequent reading intervals are required<br>• Requires little power to run for months<br>• Less human error in data logging<br>• Lower capital cost than fully automated systems | • Don't know readings until manually visit the site or log in remotely where possible.<br>• Don't know when a sensor has exceeded Action States or failed until download the data.<br>• Does not provide real-time data<br>• Cannot provide a warning<br>• Higher capital cost than manual systems.<br>• Operational costs may be more than for automated if site visit costs are frequent and high |
| Automated | • Monitor sensors in real time<br>• Higher frequency of reading to permit early detection of potential failure modes.<br>• Provide electronic messages when readings exceed alert values<br>• Fewer errors in the data<br>• Immediate reporting of data by Web and automated production of reports to established criteria<br>• Know when a sensor or component is not working<br>• Lower operating costs. | • Higher skill level required to operate and maintain<br>• More components to fail<br>• Higher capital cost and maintenance cost |

### 5.6.1 Manual Collection of Data

Manual methods to read instruments employ an instrumentation crew traveling to the instrument and using a readout device to obtain a reading that is manually recorded on paper or typed into a handheld electronic device. While at the instrument the crew can repeat the reading if required, observe the condition of the instrument and it surroundings, and make minor repairs. The manual readings may be converted to engineering units with hand calculations and plotted on a manually prepared graph but today they are typically entered into a spreadsheet or data management system to convert the manual readings into engineering units and plot the data versus time.

The cost to read instruments by manual means includes the cost of the readout equipment and its annual calibration, training costs for the crew, the cost for the crew to travel to and from the site, any costs to support the crew onsite such as a safety monitor, the costs for the crew to obtain the reading, the cost to enter the reading into the data management system, and the cost to check that all work was completed correctly and accurately. Manual readings may be taken once per year to several times a day, depending on the condition of the dam and stage of a failure mode.

Some advantages of the manual approach are the opportunity to make a visual inspection at the time the reading is taken; the opportunity to correct a malfunctioning sensor and to perform maintenance on others to maintain their functionality over a long time; and, lower front end capital cost. Some drawbacks of the manual approach are the lack of data between trips to the site during which a sudden change may occur to the dam's condition; the tendency for people to make errors in taking the reading, recording the data, or entering it into the data management system; instruments readings become infrequent to save labor costs; and the inability for the system to provide an alert message should something change quickly.

### 5.6.2 Semi-Automated Collection of Data

Semi-automated monitoring systems use electronic sensors to read instruments at programmed times and store the data in a data acquisition unit. A person visits the site periodically and downloads the data to a portable computer to physically take the data back to the office. A variant of this approach is that data from several sensors may be collected at the site by a local data logging unit and stored in that unit. Periodically a person will manually make a communications link from the office to this remote unit and download the data. The field equipment has no ability to push data to the office unit automatically or send a message that an alert level has been reached on a sensor. Data management is performed on the office computer and is typically done by entering the downloaded data into a spreadsheet. Manual steps may be required to format the data for spreadsheet use, remove incorrect information, convert the readings to engineering units and scale the reports produced by the spreadsheet. Semi-automated systems cannot provide automatic alarms of readings outside allowable values.

Costs for semi-automated systems are: outfitting the instruments with electronic sensors, the data logger, the field communications system, and a power supply; service calls and maintenance of the field equipment; travel time and data collection time for someone to go to site and download the stored data to a portable device; service calls and maintenance of the office computer equipment; and labor to take the field data and reduce and report it, check the operation of the system, examine the data and respond to alert messages from the system.

Advantages of semi-automated systems are that they are relatively inexpensive to purchase; they can log much more data than is possible with manual means; they require very little power and can run for months off of AAA size batteries; when they are operating correctly they provide more reliable data than what can be obtained with manual means; and the capital cost is less than for a fully automated system. Disadvantages of semi-automated systems are that one has to wait for the site visit to retrieve the data so nothing is known about performance between visits; one doesn't know if a sensor or the data logger has malfunctioned during the interval between visits; they cannot be used for real-time monitoring and warning systems; and operating costs may be more than for automated systems due to the cost of sending someone to the site each time to collect data from the logger.

### 5.6.3 Automated Collection of Data

Automated methods to read instruments can remotely read the instruments and place the data into a data management system where tables, graphs and messages are immediately available for examination by anyone with a need to know. Today's automated systems are typically web based and provide alert messages by phone, email and/or text messaging when an instrument indicates a reading outside the acceptable range of readings for that instrument. *Figure 5.20* provides an illustration of the typical components of today's automated reading systems. Readings are obtained at the site with a data logger attached to one or more sensors. The data management system in the office and the data logger in the field automatically connect to each other via an existing communications systems. These may be a dial up connection, an IP connection or a satellite connection. The IP connection is very new but very effective. It provides on demand, instant communications between the office data management system and the field communications link at low cost. The office computer can request a reading (called pulling the data) or the field system can send the reading (called pushing the data). Having the field system push the data to the office data management system provides the capability of quickly detecting a reading at alert level and notifying users rather than wait for the office data management system to request an upload at a regularly scheduled time interval. Data management, conversion of readings to engineering units and producing tables and graphs for reports is reliable, quick and requires little man time.

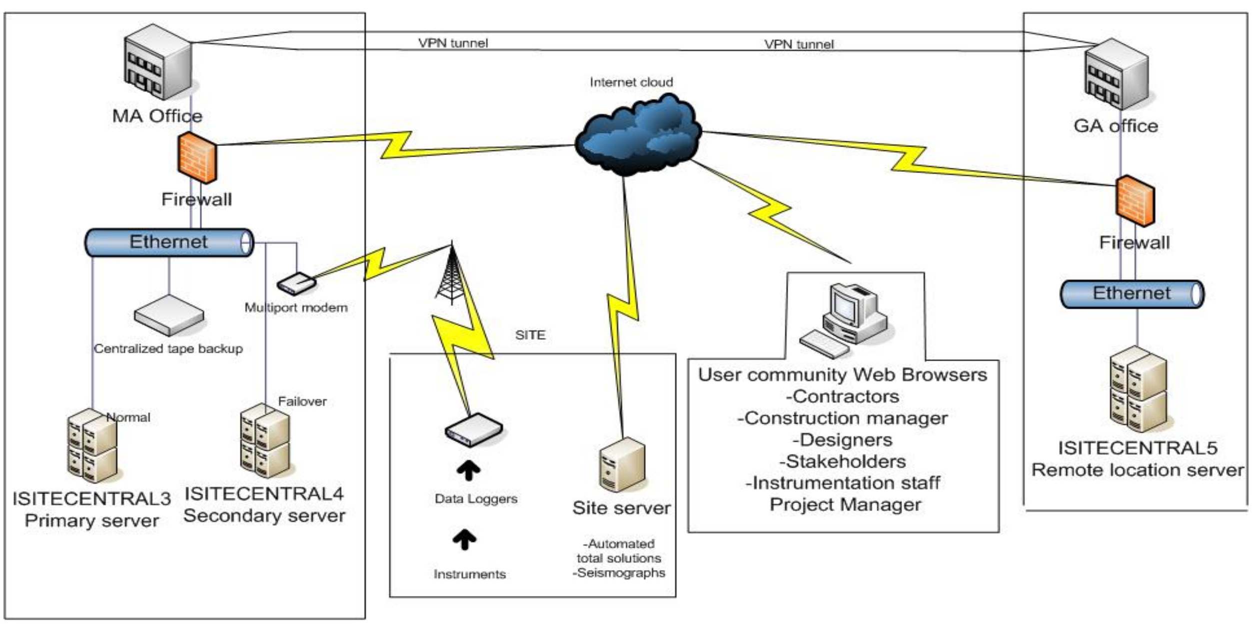


**Figure 5-20 Schematic of Advanced Automated Data Acquisition System**

Additional costs for automated systems are: outfitting the instruments with electronic sensors, the data logger, the field communications system, and a power supply; service calls and maintenance of the field equipment; communications costs between field and office equipment; office computer and software to communication with the field device, store the data and produce reports; service calls and maintenance of the office computer equipment; and a small amount of labor to check the operation of the system, examine the data and respond to alert messages from the system. Automated systems can be designed to provide readings as rapidly as 1,000 times per second for each sensor or more to once a month or less. Automated systems are typically set to read at least once per day.

The authors have found the following approaches for automated reading systems work well:

- Read each sensor at least once per day between midnight and 4 a.m. to minimize the impact of daily variations of temperature on the readings.
- If reading more than once per day which is recommended with automated systems, read at least four times a day (midnight, 6 am, 12 pm and 6 pm) to determine the effects of temperature variation on the readings.
- Read as often as required to track changes in the instrument readings with sufficient detail to understand how and why the readings are changing and to detect undesirable values at the earliest possible time.

Advantages of using an automated monitoring system are:

- Lower operating costs where there are a considerable number of instruments, or the site is distant; or the frequency of reading is more than once per week or access to the instrument is difficult, restricted or unsafe;
- Ability to monitor sensors in near real-time and provide electronic messages whenever an instrument exceeds alert values or some component of the system fails to work;
- The ability to know quickly when an instrument is not functioning; and the ability to provide a near real-time warning system to trigger immediate contingency actions.

Some drawbacks of automated monitoring systems are higher up front capital costs; more components to fail; significant power (50 to 200 watts) from a solar panel or local power source is required to power the communications systems; higher skill level required to maintain the system and fix problems; and the need for a high quality installation to provide long-term reliability. Some of these drawbacks are decreasing as the cost of electronic sensors, computer equipment and communications systems fall, communications systems become more robust and can be troubleshot and fixed remotely; and the general skill set of people at all working levels to use computers and other electronic gear improves.

The life expectancy of an automated monitoring system depends on the robustness of the initial installation, the quality of the maintenance program and the diligence of staff to protect the components of the system from damage. Theoretically electronic components and sensors can last indefinitely provided they do not rust, are not physically damaged, and are not electrically overloaded. However, these failure modes may be very difficult to prevent over a long time. Rust can corrode a wire connection within a few months if dissimilar metals are exposed to moisture and heat. Instruments can be damaged by construction and maintenance equipment if not adequately protected. Lightning strikes can take out an entire system if the system has not been designed and installed to properly manage electrical surges. But these failure modes can be avoided with a system that is well designed, properly installed and maintained. A life expectancy for a system of 30 or more years is quite possible, but periodic maintenance will be required. Actions that can increase longevity of the hardware elements include:

- Design system with robust components that will survive the environment into which they are placed.
- Design system with modular elements that allow easy replacement.
- Follow the systematic approach outlined in this document to get equipment installed properly and functioning at a high level.
- Verify that lightning and electrical overload protection measures are in place and functional at all possible electrical entrance and exit points.
- Develop and execute a maintenance program, that includes annual inspections at a minimum. Document these activities in a collective log.
- Replace suspect and defective components if they are still required. Remove those components no longer required.

It is probably unrealistic to expect that a performance monitoring system will last for the life of a dam, especially when we consider that may dams with good maintenance may last indefinitely. A more reasonable approach should be to design the monitoring system for a 25-30 year life and program for a complete replacement at that time just as one would do for other equipment on the project. Using risk assessment procedures outlined in this approach, it is generally possible to show that a good performance monitoring program delivers value within a few years so that a 25 year replacement cycle can be justified.

Likewise software and data management systems, once functioning properly, can last indefinitely. However two factors cause periodic changes. One is that the user interfaces change as the technology advances. Just consider the changes over the past 30 years as software systems have moved from distributed mainframes to PC-DOS to PC-Windows to iMacs to iPads, Androids and Blackberrys. Systems have to change to keep up with the changing knowledge base. Consider the difficulty one would have trying to run a data management system today on a Digital VAX which was a very popular mainframe computer in the early 80's for such applications. It seems reasonable to expect that software systems for storing, managing and reporting data will change significantly once per 10-20 years simply because the users skill sets will change as the technology advances. This factor's primary effect is on data base maintenance. Data must be stored in ways that it can be easily moved from one system to the next generation without loss.

The second factor is the evolution of technology. Who can imagine what tools may be developed over the next 20-30 years that will greatly improve our abilities to monitor hundreds or thousands of points on a dam for much less cost than we spend today. Imagine for example a remotely controlled drone with a camera that we can fly whenever we want and collect a visual log and geometric position of every exposed point on a dam. The data management system for this device would be quite different than that for today's monitoring systems. Incidentally, this drone exists today (2012) but cannot yet be flown for commercial applications. This suggests that we should be choosing data management systems than can be easily scaled to handle orders of magnitude more information and different types of information, such as lots of video. Data storage systems should follow modern commercial approaches that will be widely used in many business applications so we can be assured that there will be a regular upgrading of the underlying system and a migration path to move data into the next generation. The most common means of doing this today is Excel spreadsheets and Structured Query Language (SQL) data bases.

Custom software developed specifically for one or a few dams should probably be avoided unless there is a very specific need for the customization. Such customization is expensive to develop and expensive to maintain. It also makes the system totally dependent on the original developer which introduces a risk. This approach made sense decades ago when spreadsheets and database systems were not available, but they are no longer practical. The alternative is to select software tools with the following features:

- Use Excel or SQL data storage formats
- Provide one or more user interfaces that support devices in current use and can be upgraded to future user devices.
- Are used by multiple clients across diverse applications so that most of the bugs and deficiencies have been defined and removed.
- Are supported by a viable, sustainable organization so that future upgrades will be available at a reasonable cost because the development cost is spread across many clients.
- Have been successfully deployed to monitor dams and other retention structures.
- Is underlain with a strong software QC/QA program.

The increased consequences of dam failures coupled with the expectations of society that dams should not fail is causing many dam owners to consider more active monitoring and warning systems for their facilities. Earlier warnings of unexpected performance give more time to develop and implement actions that reduce the likelihood of a failure or reduce the resulting consequences. Developments over the past twenty years in low cost communications, more robust instrumentation and relatively unlimited computational capabilities now make it practical to incorporate the instruments used in a dam safety program into a more active warning system. Instrumentation used in an active warning system must be electronic and read through an automated system.

There have been many instances over the past 40 years where automated monitoring systems put onto dams failed to function as desired. There were many varied reasons for these failures but the industry has learned a lot and the equipment has improved to the point that automated systems can work for many years with high reliability. ***Table 5.21*** lists some of the causes and the lessons learned to avoid them in the future.

**REASONS TO AUTOMATE PERFORMANCE MONITORING**

- ✓ To monitor performance on a real time basis
- ✓ To provide alerts
- ✓ To reduce total monitoring costs on projects with more demanding monitoring needs (many sensors, frequent readings, remote, difficult access, safety concerns.)
- ✓ To identify monitoring problems quickly so loss of good data is minimized.
- ✓ To improve management of risk
- ✓ To closely monitor effectiveness of remedial actions
- ✓ To identify cause and effect so the failure mode is better understood.

Table 5-21 Failures of Automated Monitoring Systems

| Failure Mode | Solution |
|---|---|
| Fried by lightening | Add lightening protection and properly ground. |
| Corroded away | Use noncorrosive materials and anti-corrosion practices. |
| Sensors failed during installation | Use systematic approach to installing instruments to reduce errors; use qualified installers. |
| Readings drifted over time | Use sensors proven to be stable for many years in rugged environments. |
| Readings erratic over time | Use high quality sensors and recommended installation practices. Maintain system. |
| Sensors failed over time | Add redundancy for key instruments. Maintain system. |
| Modems failed | Use latest IP and wireless technologies that are more reliable and self fixing. Provide redundant communications paths. |
| Component hung up requiring visit to field | Better design of systems to automatically reboot at set times. |
| Power lost | More efficient systems require less power and allow backup power supplies with self monitoring capabilities. |
| Software bugs | Current system much more reliable. Multiple pathways provided to get to data so user has a solution most of the time. |
| System broke down | Plan and budget systematic maintenance and upgrades. |

Automated systems may require knowledge beyond the domain of the typical civil engineer. To effectively use today's technology in automated field instrumentation systems requires individuals with current knowledge and experience in software, instrumentation, electronics, signal processing as well as geotechnical engineering. A team with a weakness in any of these areas can create the opportunity for failure.

Once an instrumentation system is automated, the cost of collecting data more frequently is relatively low. Frequent data collection, i.e., several times a day, can help us establish a response signature for the facility that includes the normal fluctuations from temporal environmental effects. With this response signature, it becomes much easier to separate the true effects of our activities from the normal response of the facility. This more complete data set helps us avoid the difficult situation of what to do when we have a single reading that has suddenly changed and there is no explanation for the change. Readings taken several times a day can indicate periodic changes caused by environmental conditions that otherwise appear as data scatter in manual data sets. By monitoring these periodic changes, we get confirmation that the automated system is functioning properly and we can remove the effects from the data set to get a true record of the facility performance. These benefits can greatly increase the reliability and believability of the data.

Internet-based systems will radically change the way we use performance monitoring of dams in the future. As these systems become more reliable and their costs decrease, expect to see more measurement points, more monitoring in real-time and faster evaluation of data. These changes will help make performance monitoring a key part of every effective risk management program for dam safety.

## 5.7 Guidelines for Success

Every instrument must have a defined purpose, i.e. it must answer an identified question or reduce an uncertainty. If there is no question or no uncertainty, then there's no reason to instrument. Each instrument must be explicitly selected for a purpose and that purpose should be put in writing so it is not lost over the life of the dam.

Instrumentation program must be planned and executed in a systematic way. *Section 6* provides the detailed steps of a systematic approach to designing, procuring, installing, operating and maintaining an instrumentation program. Following a systematic approach will greatly increase the probability of success for the monitoring program. Success means that: as many of the instruments as possible function for their design life; the data are reliable; and, appropriate contingency measures are invoked when the data indicates the need.

**IMPORTANT KEYS TO SUCCESS FOR MONITORING PROGRAM**

- ✓ **Get the right team working together.**
- ✓ **Train, train, and train.**
- ✓ **Stay systematic and organized.**
- ✓ **Watch the details & check, check, check.**
- ✓ **Document, document, document.**
- ✓ **Aim for 100% success rate because it is possible.**

The benefits of performance monitoring result only when the work is performed in an effective manner. Components of an effective performance monitoring program include:

- ✓ Measure one or more Key Performance Indicators.
- ✓ Action Levels and responses must be established up front.
- ✓ Data must be reliable.
- ✓ Measurements must be taken with sufficient frequency to capture the unexpected performance as earliest possible stage.
- ✓ Measurements must be evaluated in a timely manner.
- ✓ Preplanned action must be taken when Action Levels are reached.

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## 6.0 SYSTEMATIC APPROACH TO MONITORING PROGRAMS

Instrumentation systems must be designed, installed and maintained with considerable care to be effective. Insufficient attention to this point can lead to defective instruments, instruments that fail at some time, loss of the instrument, suspect data that reduces the value of the entire monitoring program, or missing data that misses a developing failure mode. The key to minimizing problems with instrumentation and the data from the instruments is to follow a systematic approach to design, procure, install, operate and maintain the monitoring system and to collect, evaluate, interpret and act on the data from the system.

Design of a performance monitoring system for a new dam or an existing dam involves team work among those familiar with the site and its geology, the dam's designers, the operation and maintenance staff, the instrumentation and monitoring staff, and someone familiar with interactions between construction of the dam and placement and maintenance of the instruments. These specialists should work together to complete the steps in a systematic process. For an existing dam, the original designers may not be available and the performance of the dam may indicate potential failure modes that were not considered in the initial design. Special care should be applied in this case to assemble a team well qualified in dam design, subsurface conditions, previous dam performance and the existing monitoring program to reassess potential failure modes and the need to add new instruments, retire existing instruments and perform maintenance on others.

Dunnicliff (1993) developed 21 steps a systematic approach to plan an instrumentation program and another 10 steps to carry out the program. This Section simplifies Dunnicliff's 31 steps into 10 steps with the intent of making the process easier to remember and apply. For more details refer to Dunnicliff.

*Table 6.1* summarizes the ten elements.

**KEY PRINCIPLES TO SUCCESS**

**Develop and execute a detailed systematic, written plan, or the instrumentation program is guaranteed to fail.**

**Systematic planning and execution requires the special effort of dedicated and responsible people.**

**Avoid shortcuts.**

Table 6-1 Description

| Steps | Description |
|---|---|
| 1 | **Assemble and review information about the dam.**<br>o site investigations and siting studies<br>o design documents, construction documents<br>o history of operation to extent such is available<br>o monitoring program and data |
| 2 | **Identify the Probable Failure Modes.**<br>o How can failure potentially occur?<br>o What uncertainties exist?<br>o What questions need answering? |
| 3 | **Identify what measurements can and should be made.**<br>o Define purpose of instrumentation to answer questions and reduce uncertainties<br>o Select parameters to be monitored and frequency of monitoring<br>o Predict magnitudes of change<br>o Identify possible remedial actions if readings show unsafe conditions<br>o Assign tasks and responsibilities |
| 4 | **Design appropriate monitoring system.**<br>o Select instruments<br>o Select locations for instruments<br>o Select data collection system<br>o Establish threshold and limit values<br>o Establish procedures to check data<br>o List purpose of each instrument<br>o Prepare instrumentation design report<br>o Write specifications to procure and install<br>o Prepare budget and cost justification<br>o Revise program if necessary |
| 5 | **Plan installation, calibration, maintenance, and data management.** |
| 6 | **Procure, test, install, and commission instruments.** |
| 7 | **Calibrate and maintain instruments.** |
| 8 | **Collect, process, and evaluate data.** |
| 9 | **Interpret and report results.** |
| 10 | **Take action when indicated.**<br>o Invoke contingency measures if safety is in question<br>o Modify monitoring frequency up or down<br>o Repair, replace, add or remove instruments |

Adapted from Dunnicliff (1993)

## 6.1 Design, Installation, and Monitoring of a Performance Monitoring System

The elements of the ten step approach are briefly described below.

### 6.1.1 Step 1: Assemble and review information about the dam

Design of an instrumentation monitoring program and interpreting the results of the measurements requires a thorough understanding of the site conditions and the construction of the dam. Instruments are installed to collect data to answer specific questions about how the dam, its foundation and the abutments are performing. Consequently any instrumentation design must consider the information gathered during siting studies and site investigations. This information may show locations with potential for anomalous behavior and areas where information is incomplete or uncertain. Design documents will indicate the assumptions used by the designer and areas of concern about possible performance of the dam. These should be evaluated to determine which should be verified by measuring field performance. The construction records may indicate anomalies discovered during construction, such as unexpected subsurface conditions, displacements larger than expected, springs or seeps. Any of these conditions may indicate locations where additional instruments should be installed to monitor the effect of the anomaly on dam performance. If the dam has been in operation, the records should be examined for unusual events and unexpected performance. Monitoring data should be reviewed to determine if any instruments require maintenance, others should be added or some can be removed.

### 6.1.2 Step 2: Identify the Probable Failure Modes. What uncertainties exist and what questions need answering.

Instrumentation and monitoring are used in dams to reduce uncertainties and answer questions inherent in the design. No amount of site investigation, testing, analysis and design can remove uncertainties and answer all questions about how the dam may perform during construction, first filling, and operation over its life. Due to the highly variable nature of subsurface materials and earthen fills, questions always remain. Experienced designers employ conservative design practices and take precautions to minimize the potential impact of unanswered questions and uncertainties where the cost impacts are not significant. However concerns always remain about how the dam may deform and how water will flow through the dam, its foundation and its abutments. In ***Step 2*** the project conditions and the mechanisms that will affect the performance of the dam and the design assumptions are reviewed with the designers to define each of the concerns or unknowns and determine what questions remain after design that might degrade the performance of the dam during construction, filling and operation. A Potential Failure Mode Analysis (e.g. FERC, 2005), is one very effective way of accomplishing ***Step 2***. See ***Section 2.1*** for more discussion of Potential Failure Mode Analysis and ***Appendix D*** for a potential failure mode analysis tool.

### 6.1.3 Step 3: Identify What Measurements Can and Should Be Made

The uncertainties and questions from ***Step 2*** are examined to determine which can be answered and removed or reduced with an instrumentation and monitoring program. Each question is examined to define what measurements can be made to answer that question or reduce the uncertainty. For example, if there are concerns about how water may flow through the foundation of the dam because of a complex geology, then piezometers can be used to measure water pressures at representative locations in the foundation and along the base of the dam. If there is an important question about how the dam may perform and no instrumentation can be defined that will help answer that question, then the design might be changed to remove that question or minimize its potential impact on future performance of the dam. Every instrument placed in or on a dam should be there to answer a specific question (Dunnicliff, 1993). Some typical instrumentation types for dams are presented in ***Section 5.*** ***Appendix B*** provides more information on specific instrumentation types.

The performance of the dam must be predicted to provide the baseline with which to evaluate data from a monitoring program. Without a prediction of performance, it is rather haphazard to determine where to locate instrumentation to be of maximum effectiveness, size the instrument with the appropriate accuracy and range of measurement, and establish warning levels based on readings from the instruments. Potential contingency plans and remedial actions to invoke when measurements exceed allowable values must be identified and their effectiveness assessed. If an action plan cannot be devised to manage safety for unexpected measurements, then the design should be altered. Responsibilities for the various steps of the monitoring program should be defined at this point because these may affect how the instrumentation is laid out, the data are collected and evaluated, and action plans are conducted.

In this step, it is also useful to establish acceptable levels of readings for each instrument. This is done using the predicted values for each sensor. From the predicted values, one defines *Threshold Values* and *Limit Values*. For additional information on Action Levels, see ***Section 7.5.***

### 6.1.4 Step 4: Design Appropriate Monitoring System

***Step 4*** consists of the efforts to select instruments and their locations, and to design the data collection system, including procedures to check the data. Some instruments may be used to verify design assumptions about site conditions. Others may indicate how natural materials and man-made materials perform during construction of the dam. Additional ones may be added to monitor performance during first filling and life-long operation of the dam. ***Table 6.2*** summarizes various types of instruments typically used to monitor dams. There are other less common ones, such as inverted pendulums, not included on ***Table 6.2*** but ***Appendix B*** provides further descriptions of instruments by type and function.

Factors to be considered in selecting instrument types and locations include:

- Locating instruments where they will answer important questions, have a high likelihood of survival, and provide data on the true performance of the dam;
- Provide redundancy and cross checks for other key instruments;
- Selecting instrument types that have high reliability, durability, ruggedness and simplicity;
- Selecting instruments that provide the required accuracy; and
- Methods of collecting, processing, and evaluating the data.

The data collection system needs to be considered at this point because it is tied to the types of instruments that have to be used. For example, automated data collection systems will require electronic instruments and measuring systems. Data collection systems consist of manual systems where readings are recordings of visual observations, semi-automated systems where readings are automatically read with a device that stores the readings for manual download to an electronic device at some future time, and automated systems where readings are taken, transmitted to a computer that stores and processes the data and provides results and warnings in near real-time.

Capital investments are highest with the automated systems but total life cycle costs are generally the least with the automated systems due to the much lower labor hours required to collect and manage the data. While data collection labor may be reduced with automated data acquisition systems, more resources are required from IT and instrumentation technicians to maintain and trouble shoot these systems.

Data from dam monitoring systems must be reliable or the value of the system quickly degrades. Careful procedures to check the instruments before installation, verify that the system works properly at the completion of installation, obtain initial readings, and provide quality assurance that all data collection and processing steps are accurate must be in place in and diligently followed. Collected data must be examined for correctness before it is used to generate any warning. This step often requires a review by a person knowledgeable with how the monitoring system works and the expected performance of the dam. Key questions to consider include:

- Do the data make sense?
- Is the reading repeatable?
- Are the instrument and monitoring system working correctly?
- Is the measured point an outlier (something for which there is no reasonable explanation and the reading cannot be repeated)?
- Are the data consistent with past readings?
- Is the change in readings indicated in other sensors?
- Is there an identifiable cause for the recent change in the data?
- Are the changes in readings consistent with the performance mechanisms expected for the dam?
- Can immediate action be delayed until the reading can be verified?

Consideration of these questions during the design of the instrumentation system may affect how many sensors are used, where they are located and the procedures for collecting and processing the data.

***Step 4*** should be closed out with the preparation of an instrumentation design report. The report should define the purpose of the monitoring program and show the layout of the instrumentation plan. It should include a table that identifies each instrument, preferably with a unique identification number, and gives the purpose of the instrument. It is also very helpful for this table to include the recommended range and accuracy of the instrument and to provide the *Threshold Value* and *Limit Value*. ***Table 6.2 shows a simple example***.

**Table 6-2 Sample Instrumentation Design Report**

| ID | Type | Purpose | Units of Measurement | Range | Accuracy | Threshold Value | Limit Value |
|---|---|---|---|---|---|---|---|
| P-1001 | Piezometer | Demonstrate that core of dam is functioning as designed | Total head in ft (m) | 250 (75) | 0.1 (0.03) | 35 (11) | 45 (14) |
| DMP-2001 | Displacement monitoring point | Show that foundation is sufficiently stiff | Inches (mm) | 12 (300) | 0.1 (3) | 6 (150) | 9 (230) |
| LC-5004 | Load cell | Show load in tie down anchor is acceptable | Force in pounds (kN) | 200,000 (900) | 100 (0.5) | 120,000 (500) | 160,000 (700) |
| LC-5005 | Load cell | Redundant measurement for SG-5004 | Force in pounds (kN) | 200,000 (900) | 100 (0.5) | 120,000 (500) | 160,000 (700) |

Range is the maximum possible reading from the sensor. It should typically be 1.2 to 2 times the largest posible value of the measured quantity and large enough to prevent damage to the sensor. Accuracy is the desired closeness of the measured value to the true value. Range and accuracy are required to specify the required instrumentation. ***Table 6.3*** provides some typical accuracies recommended for various types of measurement on dams. The indicated accuracies are more demanding than what some might expect. This is due to the importance of measuring rate of change for dam monitoring rather than the true value. As an example, it might be acceptable to know the settlement of the crest to only about 1 inch, but that accuracy is insufficient to monitor increases in rate of settlement of the crest.

Another important element of a sensor is its precision. *Precision* is the closeness of agreement among a series of individual measurements. It is dependent on the quality of the instrument, the readout device, and the measuring technique. Precision can be thought of as the standard deviation of a series of repeated measurements. Readings can be precise but inaccurate. Precision and accuracy are often incorrectly interchanged in usage. In dam safety, we seek both precise and accurate instruments and readout systems.

Two other qualities are important for sensors. These are stability and reliability. *Stability* is the ability of a sensor and readout to give the same value from a sensor located in a non-changing environment over the required life of the sensor. A sensor that drifts over time when all other factors are constant will give misleading and useless readings. Reliability is the ability of the sensor and readout system to perform the required function over the design life of the system. Some sensors may perform well for a few months after installation and then completely fail. Dam safety monitoring requires sensors and monitoring systems with high reliability over many years of operation.

**Table 6-3 Some typical Accuracy Requirements for Instruments**

| Instrument Type | Recommended Accuracy |
|---|---|
| Piezometer | 0.01 ft of water ( 0.005 psi) (0.03 kPa) |
| Flow meter | 5% of the anticipated flow or better |
| Turbidity meter | ±5% of the reading |
| Displacement point | 0.01 ft (3 mm) |
| Horizontal inclinometer | 1/5,000 |
| Tiltmeter | 1/5,000 to 1/40,000 depending on the application |
| Strain gage | 1 to 10 micro strain depending on the application |
| Earth pressure cell | 1% of the expected reading |
| Contact pressure cell | 1% of the expected reading |
| Load cell | 1% of the expected reading |
| Accelerometer | ±0.001 g |
| Seismograph | ±0.02 in/sec (±0.5 mm/sec) |

***Threshold Value*** is the reading that indicates a larger than expected value. A reading above this value indicates a caution condition and triggers further study to understand the cause for the reading and how to prevent it from becoming larger. It is typically set at 1 to 1.2 times the predicted value for the instrument.

***Limit Value*** is the maximum allowable value of the reading. At this value, the dam may be placed in the alert performance state and protective measures must be undertaken, including the possibility of lowering the reservoir, to prevent the value from getting larger and to reduce its value. The *Limit Value* is typically set at 1.3 to 1.5 times the predicted value for the instrument location but it might be considerably higher for some measurements like turbidity. Other values may be selected based on detailed studies.

Threshold and limit values are discussed in some more detail in ***Section 7.5***.

The instrumentation design report should also lay out the specifications for the procurement, installation and commissioning of the monitoring system. The entire program should be reviewed once again to determine that each instrument has a defined and important purpose. If there's no question to be answered by the instrument, it serves no purpose and should be removed from the monitoring plan.

### 6.1.5 Step 5 - Plan Installation, Calibration, Protection, Maintenance, Data Collection & Management

Instrumentation programs require attention to detail to be successful. Planning to capture all of these details and demonstrate that the plan will work is an important step that is often missed. Installation plans must be prepared to ensure that sufficient time is allowed to install the instruments and collect baseline readings. The plans must consider potential interferences with construction and operating activities. Planning should also include consideration of how the instrument will be replaced should it malfunction and how the instrument will be safely abandoned when it is no longer needed. Calibration checks should be done before instruments are installed. Annual calibrations of readout devices should be planned. Plans to protect the equipment from damage during installation, severe weather and vandals should be developed. A maintenance program should be developed to keep sensors and readout equipment in good working order and repair those that malfunction. Methods to collect readings, process the raw data into final data and store that data for the life of the project must be developed with directions on how those plans will be implemented and who will do the work. The following additional steps should be developed, at least in draft form.

- Written procedures for data collection, reduction, processing, presentation, interpretation, reporting and implementation. Dunnicliff, (1997) provides some guidance.
- Written procedures for communicating results and initiating remedial action
- Staff training to carry out instrumentation program, including remedial action. (See ***Section 5.1*** for discussion of training.)
- Schedule with time allowed to correct problems with the monitoring system and train the monitoring staff.

***Steps 1 through 5*** define the components and work elements of the instrumentation program. It also determines how much the program will cost as an upfront capital investment and as a long term operating budget. These costs should be detailed and complete. Many monitoring programs lose their effectiveness because they were not properly budgeted from the beginning. Monitoring is an essential part of a dam's safety program and it must be appropriately budgeted as other essential items of the dam. The budget needs to include the cost of instruments and installation as well as the additional costs of collecting data, maintaining equipment, processing the data and evaluating the results. Budgeting for these costs are equal to if not more important than budgeting for construction and operational costs of the dam. The annual O&M budget should also include contingencies to replace damaged equipment and add additional instruments if the data reveal significant surprises. The maintenance program developed in ***Step 5*** should include the justification for these costs.

#### 6.1.6 Step 6: Procure, Test, Install and Commission Instruments

Careful execution of this step is critical to the long-term success of the instrumentation program. Purchasing lowest bid services and using inexperienced personnel can lead to questionable data that take a lot of effort to resolve, or which could destroy the usefulness of the data. This step should be overseen by a person experienced in the installation and verification of dam instrumentation. Equipment should be purchased from qualified vendors and installed by people experienced in similar work. Detailed and accurate installation records should be prepared for each instrument. These may become important in helping to interpret subsequent data that does not follow expected trends. A step-by-step installation process should be followed and each step verified as complete before proceeding to the next step. For most of the instruments used in a dam safety program, once they are installed, little can be done to correct installation errors or problems. Measures to protect the instruments from damage by other site activities, severe weather and vandals should be put in place as part of the installation effort. Special care should to be taken to obtain accurate initial data readings. All future readings will be interpreted in relation to the initial readings.

The following recommendations are useful to improve the chances of success:

- Follow the specifications.
- Be careful using substitutions without a good technical case.
- Provide submittals of proposed instruments, including manufacturers' cut sheets to increase likelihood of success.
- Obtain a detailed order list from vendor and check that each entry is what you need.
- Receive instruments at a location where they can be unpacked, check for damage, check that model number and wiring are correct, check that cable length is sufficient, check manufacturer's quality assurance inspection checklist, check wiring and connections, verify that they read correctly with the selected readout equipment, check zero stability, perform 2-point approximate calibration with one point reading at 0-10% of the working range and the other point at 90-100% of the working range.
- Label the cable at the sensor end and at two locations separated by at least 5 ft on the connector end. Labels at other locations should be used wherever there is a possibility for the cable to be accidently cut.
- Prepare a pre-installation checklist report.
- Prepare installation record form with known details for the instrument and its location.
- Check that pre-installation checklist report was completed and sensor cables are labeled as required.
- Review the installation process for each instrument with the members of the team to be clear on location, depths, materials, installation methods and responsibilities of each team member.
- Check orientation and functionality of instrument at each step of the installation process. If instrument shows suspect behavior, stop the installation and sort out the problem. Do not continue installing an instrument that has shown any erratic or unexplainable behavior. Replace it.
- Document the details of the installation steps on the installation report.
- After installation is complete, check the readings of the instrument for reasonableness and stability.
- Once readings have stabilized, take a minimum of three readings with stable conditions to obtain a baseline reading. Readings should be stable and agree within the manufacturer's specification for repeatability.
- Place measures to protect the instrument from damage by construction or maintenance equipment or vandals. Be proactive, aggressive, and conservative with the protection measures. They are key to long life of the instrument.
- Check that installation report is complete and correct.
- Commission the instrument.

#### 6.1.7 Step 7: Maintain and Calibrate Instruments and Readouts

Construction of a dam may take years and it may operate well past its design life. Instruments and readout equipment must be kept maintained and operational so they can give reliable readings over time and immediately after an unexpected event. Many sensors cannot be calibrated once they are put into place so it is important that they be installed with valid and verified calibration data. Readouts can and should be calibrated according to the manufacturer's recommendations. Calibration intervals are typically once per year or after the readout goes through a traumatic event.

Exposed instrument wires and readout terminals should be kept labeled, clean, unfrayed and dry. It is good practice to use a "tag out" system where suspect equipment is tagged with a "Do Not Use" card until it can be checked, repaired and verified by a qualified person.

It is also good practice to place a "dummy" instrument of each type at a fixed, protected location so that it gives a constant reading. This may be done in an office or storage area that is protected from the elements. These are used to check each piece of readout equipment before the beginning a day's work and to provide verification checks before time is wasted or inaccurate data is entered into the reading database. Examples include:

- A short piece of inclinometer casing permanently mounted to a fixed wall at an angle of a few degrees. The inclinometer probe can be positioned at the same place in this casing and read. The reading for the same probe should be the same every time.
- An inclinometer casing is placed in the ground at a location that should not move over time. The inclinometer system is periodically used to read this casing and demonstrate that the readings show no movement. This system can also be used to train new users.
- An observation well is installed at a location where the depth to water can be measured by more than one independent means. The well should be sufficiently deep to allow measurement of a water head at least one half of the maximum value being read at the dam. A piezometer identical to that used in the dam can be lowered in the observation wall and readings taken at various depths. This provides a check of the piezometer readout device and can be used to check dip meters used to read observation wells. Note that the inclinometer casing described above can also be used for this purpose if it can be placed well below the ground water level.
- Strain gages can be mounted on unstressed pieces of metal and placed in a secure location to evaluate the durability of the gage and its mounting system and to check the readout device.
- Similar approaches can be devised for most other readout devices. The use of a fixed setup to check the accuracy and reliability of read out devices is strongly encouraged.

The following recommendations are useful to improve the chances of success:

- Calibrate readout units at least once per year with a National Institute of Standards and Technology (NIST) traceable standard.
- Perform calibration check tests once per 3 months or whenever the readout unit has been dropped more than 3 feet, submerged in water, damaged, repaired or shows questionable behavior.
- Store readout units in a dry, warm environment to minimize potential for water migration into cable or readout unit over time.
- Keep all covers and screws in place and connectors in good working order.
- Replace any readout equipment once it shows significant wear or has unreliable performance.
- Establish reference tests as described above to check readout devices and use them frequently.

#### 6.1.8 Step 8: Collect, Process, and Evaluate Data

Data from instrumentation are collected with sufficient frequency to catch the significant changes that may occur in the performance of the dam. One rule of thumb is that the frequency of data collection must be sufficient to capture at least 10 readings over the period of change to capture a reasonable representation of the magnitude and rate of the change. Historically data were collected weekly to monthly during construction and quarterly to annually during operation. Given the increased risks associated with dam safety, more frequent rates are justifiable. Increasingly, automated instruments are read several times daily. This nearly continuous record helps identify periodic events from seasonal and daily environmental factors and remove their effects from the data. Data showing these periodic changes help to provide heartbeat signals of the instruments and data acquisition system to show that it is functioning correctly.

Data processing consists of the steps to convert the raw reading from the sensor to engineering units. For example, the instrument readout might be in volts but the engineering quantity we desire is in length units of inches or millimeters. Raw data are filtered to remove extraneous and wrong data, and then converted with the sensor calibration factor to engineering units. The filters may be designed to remove environmental effects, faulty data records, outliers and other factors for which reliable, consistent rules can be fashioned. Filters help reduce the incidence of wrong information and false alarms.

The following recommendations are useful to improve the chances of success for collecting reliable data:

- Check readout unit against a reference instrument prior to start of the day's activities. The reference instrument should be a permanently mounted installation at the office or at the site that will give the same reading over time.
- Take readings at the required frequency.
- Check any questionable readings as quickly as possible to identify and discard wrong data.
- Treat instrument and readout unit with care to avoid damage.
- Keep instrument cable end clean and dry and protected from unauthorized access.
- Keep readout unit and connection cable clean and dry throughout the day.

Only people trained and tested to do the work accurately and correctly should perform data collection, processing and evaluation. People collecting the data must understand how the instrument and its readout work. They must know what to look for to identify anomalous or questionable readings. They must understand the factors that may influence the readings. They must know the warning signs of a defective instrument or readout. They must be committed to obtaining accurate and reliable data. They should know the previous reading or range of expected readings, especially the limit values. This information should be incorporated on the data sheets/forms used during recording sensor data.

People processing the data must understand the relationship between raw data and reported results. They must understand calibration factors and the factors that may influence the readings. They should be able to recognize unrealistic values. They should understand the meaning of *Threshold* and *Limit Values* and how these are obtained. See ***Section 6.1.4*** for more discussion on these values.

Evaluation of data focuses on ensuring that the data are accurate and reliable. People evaluating data must understand what the data mean and how the readings should change and trend. They must understand how all components of the monitoring system work, how they can fail and what data looks like when they fail. They should constantly ask: are the components of the monitoring system working properly, do these data look reasonable, and how can I explain what is being measured? They should know when to request additional readings to verify questionable values. They should identify and check all suspect readings. Their goal should be to provide accurate, verified data at all times.

#### 6.1.9 Step 9: Interpret and Report Results

The interpretation step seeks to explain what the evaluated data indicate about the performance of the dam. The evaluated data from ***Step 8*** are compared to the threshold and limit values established for each sensor and to the values predicted for the sensor. Data, which exceed limit values or exceed predicted values or show increase rate of change, should trigger immediate examination by someone familiar with the design of the dam and the monitoring system. Trends of the data and relationships between events to the dam and response of the sensors are examined. Observations from the visual surveillance program are reviewed for possible correlation with measured changes. If the interpretation results in concerns or questions about the performance of the dam, or if the trends are consistent but not explainable, then the designer or engineer in charge should be brought into the interpretation. This interpretation should occur soon after the data are collected. Delays can lead to serious consequences.

Trends of data are sometimes more important than the actual readings. A reading may be within its normal condition but if the rate of change is increasing and a threshold or limit value will soon be reached, remedial action may be required. However, before jumping to action, one must consider what is causing the trend and is it likely to continue. Instrument readings may change due to environmental effects, disturbance, error, or a malfunction of the equipment. These causes must be considered and removed as factors before one reacts to a trend. Furthermore, more than two data points are required to establish a trend. A minimum of three readings that are confirmed to be valid and changing due to the dam's performance should be required to establish a trend. If one has obtained a reading that is considerably larger than past readings and which might indicate a new trend, that reading should always be validated by taking another reading before remedial action is called for.

People who interpret the data must understand how the elements of the dam function, the potential failure modes for the dam and the basis for the threshold and limit values established for each instrument. They must be able to consider and answer the question – What will be the consequence of the reading continuing to change until it goes past the Limit Value and what needs to be done then?

***Figure 6.1*** shows an illustrative example for piezometer data evaluation for an earthfill dam. The piezometer in the upstream shell tracks the reservoir level consistently over the entire monitoring period. Data from this sensor is likely to be reliable. Data from the piezometer in the core lags the change in reservoir level, which can happen in cores with low permeability. This sensor even gives values above the reservoir level during September 2009. This is possible in cores with low permeability where the pore pressure response to changes in reservoir level is delayed.

A cause for concern involves two "outlier" readings in January 2010 involving readings for the core and the downstream shell piezometers. The cause of these outliers may not be immediately clear. They may indicate a problem with the sensors or readout device. Without further explanation, these outliers make the performance of this system suspect and lower the reliability of the sensor.

A one time occurrence of an outlier in the core sensor can be dismissed since historically there is an expectation that there should be a lag time response for the core. This reading may indicate a large rate of increase that sets off an alarm based on rate of change but that would be a false alarm.

Data from the piezometer in the downstream shell tracks the reservoir level in the first year and has a value somewhat higher than the designer anticipated. Note that the amount of increase in the second year relative to reservoir level is significantly less than the first year. This difference indicates a change in the flow pattern through the dam and the possibility of an increase in permeability for a portion of the downstream shell, which suggests a potential loss of fines and early stages of piping. This behavior warrants further attention.

This example and discussion is meant to give an idea of the thought process one must go through when evaluating data from performance monitoring systems. The intricacies of dam performance as revealed by instrumentation require an experienced dam safety engineer to sort out.

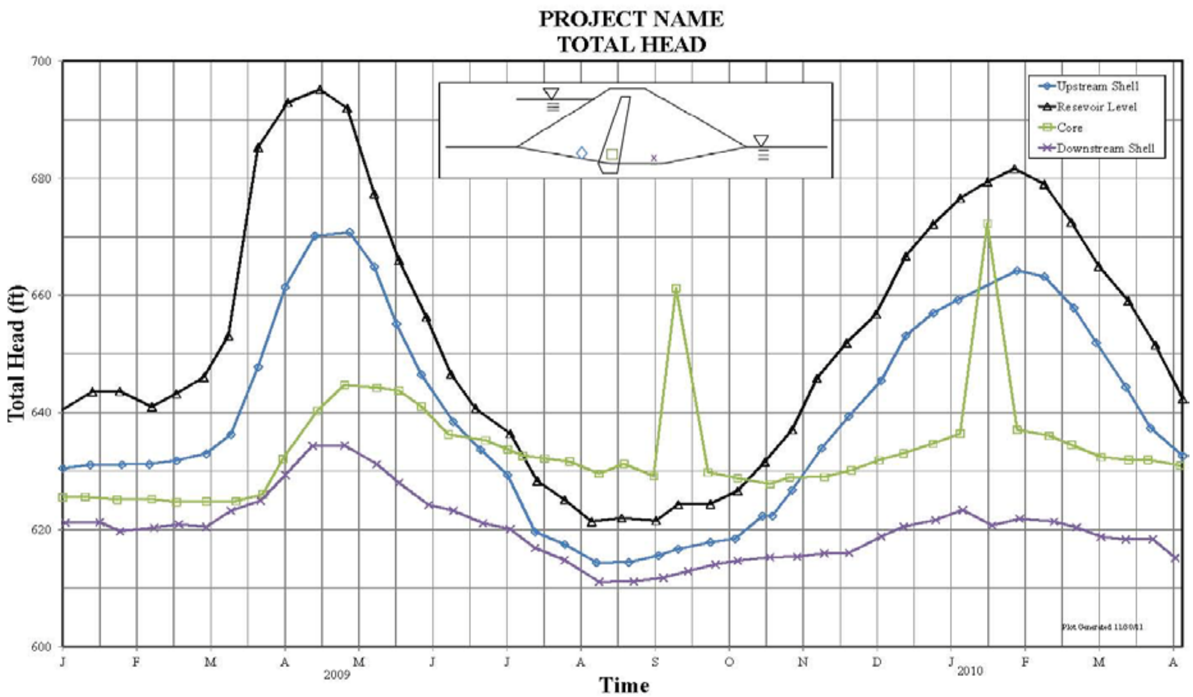


**Figure 6-1 Piezometer Data from an Earthfill Dam**

### 6.1.10 Step 10: Take Action

Every instrumentation program for dam safety must have an Action Plan that indicates what to do when data exceed the *Threshold and Limit Values*. The Action Plan must be in writing and unambiguous with clear lines of authority for executing the plan. The Action Plan should be integrated with the Emergency Action Plan for the dam. The Action Plan should give a timeline for required responses so those performing the plan have a sense of what level of urgency is required (after ASCE Task Committee on Instrumentation and Monitoring Dam Performance, 2000). It is beneficial to keep the action plan as simple, direct, and understandable as possible so that it can be executed effectively. An Action Plan is also known as a Contingency Plan.

The Action Plan must be executed quickly and responsively when *Limit Values* are exceeded. See ***Step 3*** for definitions of Action Levels. In some cases, unsafe conditions can develop rapidly once an instrument's reading exceeds the Limit Values. In some cases, it may be advisable to stockpile materials and/or equipment to perform the corrective action as soon as possible. Action plans should be reviewed once per year to ensure that they are up to date and can be implemented should they be required. *Threshold and Limit Values* should be reviewed periodically to determine if they can or should be revised up or down.

As time passes and more is learned about how the dam reacts to various conditions, an experienced engineer's understanding of the dam's performance improves. This additional information provides observations and measurements that can support adjustment of the Threshold and Limit Values.

### 6.2 Systematic Approach for Older Dams

The layout and discussion of ***Section 6.1*** focuses on a new project where the instrumentation is planned and designed before the dam is constructed. However the same approach is easily adapted and strongly recommended for older dams. Generally older dams will not have the documentation to show exactly the purpose of each instrument or its design parameters. It is helpful to take the existing monitoring system and review it using the same ten steps of the systematic approach given in ***Section 6.1*** This review process will reveal any existing weakness in the existing program and help identify the need for any new instrumentation, any required maintenance and the possibility of retiring some of the instruments that no longer serve any purpose.

### 6.3 Repairing Instruments

Components of the instrumentation system may degrade or break and require repairs. Repair plans should be developed as part of the instrumentation design, documented and followed when the repairs are being made. All repairs should be documented and kept as part of the instrument records. Those doing repairs must understand what to do and what not to do. For some instruments, it can be possible to trigger an unexpected chain of events that produces a disaster so, a repair plan must be followed closely. Any instrument requiring repair should be "tagged out" of the normal monitoring routine until it has been repaired and shown to be fully functional.

### 6.4 Replacing Instruments

Malfunctioning instruments that cannot be repaired and that are still important to the monitoring program, must be replaced. A replacement program should be planned and budgeted. This becomes a more important issue as the dam ages. Considerable caution must be used when replacing an instrument that is located below the ground surface. The replacing activities may open a pathway for uncontrolled seepage to begin and either increase piezometric levels downstream of the sensor or initiate internal movement of soil particles and possibly piping. Drilling through the core of a dam of a zone with elevated piezometric levels is particularly problematic and is typically avoided.

When replacing instruments one must consider what to do with the old instrument. Ideally, it should be removed and the empty space filled with a cement or cement-bentonite grout that is compatible with the surrounding soil. Mickelson and Green (2003) and Contreras, et al (2007) provide recommendations for grout mixes. If it cannot be removed, consideration must be given to what the consequences are of it being abandoned and left in the dam. If there are no conceivable consequences, than the upper three or more feet of the instrument should be removed and the hole filled with two or more feet of grout covered with topsoil. If it cannot be removed, then engineers familiar with the design and functioning of the dam must devise a customized way to retire the instrument.

## 6.5 Removing Instruments

Abandoned instruments should be removed and the impacted areas restored to conditions compatible with the surrounding materials. Many of the instruments used to monitor performance of the dam during its construction and initial filling may no longer be needed and can be removed. The most common method to remove a buried instrument is to dig it out if shallow or use a drill rig to overcore with an inner bit to chew up the instrument. The remaining hole is then tremie grauted to within 3 ft (1 m) of the surface.

Care must be taken removing instruments to avoid safety issues such as electrical shocks from adjacent power cables, escaping flammable gas, artesian heads and falling hazards. Artesian heads, where the piezometric head is higher than the ground surface can be particularly troublesome because they can create uncontrolled escape of water that carries soil out of the dam. Holes in concrete should be cleaned and filled with a suitable tremied or pressure grout. Bare areas on steel should be cleaned and painted to match the surrounding metal. Holes in soil or rock should be filled with a tremied or pressure grout that is compatible with the surrounding materials. Vertical holes may be grouted to within 3 ft of the ground surface and the remainder of the hole filled with materials compatible with the near surface conditions.

## 6.6 Adding Instruments

Conditions may develop in a dam where additional instruments are required. This is particularly the case when some aspects of the dam are not performing as expected and there are insufficient instruments to monitor the unexpected performance. This might be the case where evidence shows unexpected seepage through the foundation or the dam itself. Instances of unexpected deformations that could lead to sliding may also justify the addition of instruments in and near the area that is moving. Instruments may also be added to monitor the repair, upgrading or expansion of some aspect of the dam. The same precautions discussed in ***Section 6.4 Removing Instruments*** apply to adding instruments. The systematic approach outlined at the beginning of this section should be followed when adding instruments to an existing dam.

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# 7.0 GUIDELINES FOR SUMMARIZING AND EVALUATING PERFORMANCE MONITORING DATA

> "Monitoring programs have failed because the data generated were never used. If there is a clear sense of purpose for a monitoring program, the method of data interpretation will be guided by that sense of purpose. Without a purpose there can be no interpretation."
>
> Dunnicliff, 1988

Data collected from an instrumentation system must be processed, presented, evaluated and interpreted for it to be of any value. Raw data taken from an instrument is of little value until it is evaluated and interpreted by a knowledgeable person who knows what the data mean in the context of the dam's safety. These steps are essential components of a dam monitoring safety program; yet they often are understaffed and/or under budgeted. These steps need to be accomplished in a timely manner after data collection. Initial steps need to include procedures for performing an initial review of data in the field and immediately following collection so that detection of potential problems can be achieved and timely action taken at the dam. A major part of the procedures for evaluating and summarizing data is to have the work done by engineers knowledgeable and experienced in dam investigations and design and who have a good understanding of the site specific geologic and geotechnical characteristics of the dam and its foundation and abutments including knowledge and understanding of the site specific potential failure modes. They also need to know what data collected may be in error or give a clue that a problem may be developing. This section provides some guidance to perform these steps. We strongly recommend that procedures and processes be developed and documented for each dam using the guidance provided in this section.

## 7.1 Data Reduction

Most instruments provide raw data that must be converted to useable engineering units. For example, piezometer data should be converted to the equivalent elevation of water head (call total head or piezometric level) so that differences in water head among piezometers and relative to reservoir level can readily discerned. The arithmetic calculations required to convert data are described as data reduction. The data reduction may be done in the field or office. Quality control procedures should be adopted to ensure that calculation errors are avoided. Raw and reduced data should be summarized in tabular form showing the date, time, measurements, reduced data, and comments.

This step was traditionally done with hand calculations on the data sheet. However, it is now mostly done in data management software or spread sheets on portable computers. A spreadsheet provides a quick and versatile method to reduce the data for multiple instruments. Each set of readings is entered on a row that contains date and time of reading, raw readings, calibration factors and reduced values. The data may then be set up for printing or graphing to the specific requirements of the user. Spreadsheets require relatively little training for their use. Many people already have some familiarity with the method.

The main drawback of the spreadsheet approach is that it becomes very labor intensive and provides delayed results for projects with many sensors and lots of data. In addition, it is relatively easy for the data reduction formula in a spreadsheet to become altered and the results go unnoticed. There are ways within the spreadsheet to prevent this error but many users do not use the protections. Reports from spreadsheets also tend to vary in scaling over time which complicates the efficient evaluation of the data as discussed in a later section. Spreadsheets cannot work effectively for real-time monitoring of dams.

A more comprehensive data reduction approach is to use a dedicated data management system running on desktop, laptop or server. These systems take the raw data as input, store it in a database, perform the required calculations to reduce the data and then output the results as fixed formatted tables and graphs. These systems can be set so that a user does not accidently alter the calculation methods or the raw data changed. They are more secure and robust than the spreadsheet approach. They also provide results in a systematic and consistent report across instruments and over time. Increasingly these more comprehensive data management systems operate over the Internet. Input options take in data from manual readings and automatically read systems. Options may be available for rather sophisticated reduction and correlation of data. Output options provide a wide variety of electronic reports over the Internet to most net-enabled devices. Examples of commercially available systems include:

- ARGUS by ITM-Soil, Floreat, WA, Australia, http://www.itm-soil.com.au/content/argus-monitoring-software-0, web-based data management, calculation, and presentation tool
- ATLAS by Slope Indicator Co, Mukilteo, WA, USA, http://www.slopeindicator.com/atlas/index.html, web-based data management system for automatic data processing
- AvaNet® by Bergsker, Göteborg, Sweden, http://www.bergsaker.se/, web-based data management system for processing and displaying measured data in real-time
- Canary Systems, Inc., New London, NH, USA, www.canarysystems.com, data acquisition systems and software solutions for local or remote database management;
- DamSmart by URS Corp., www.damsmart.com, a sophisticated system developed specifically for dams;
- Datgel by Data Solutions, Ultimo. Australia, http://datgel.com/, gINT add-on software that allows monitoring data to be linked with other subsurface data in one comprehensive database
- GEOSCOPE by SolData, Nonterre, France, http://www.soldatagroup.com, web-based data and information management system capable of consolidating and processing data from multiple sources.
- GeoViewer by RST Instruments, Coquitlam, BC, Canada http://www.rstinstruments.com/GeoViewer%20Real-Time%20Monitoring.html, data viewer that provides console viewing of large data sets from automatic data acquisition systems.
- HoleBASE by Keynetix Ltd. , Redditch, UK, http://www.keynetix.com/holebase, comprehensive data management and borehole logging software package
- HYDSTRA by Kisters AG, www.kisters.net, a data management software package for water resources.
- INSITE by Maxwell Geosystems , Sheung Wan, Hong Kong, http://www.maxwellgeosystems.com/insite.php, GIS systems for supervision and monitoring of data in real-time
- iSiteCentral by Geocomp Corporation, Acton, MA, USA, http://www.geocomp.com/field_systems.asp, web-based data management software with data collection, reporting, and alerting capabilities.

- Multilogger Suite by Canary Systems, New London, NH, USA, http://www.canarysystems.com/multilogger-data-logger-client.html, application designed to manage automatic data acquisition systems
- SHMlive by Roctest Ltd., http://www.shmlive.com/, Saint-Lambert, Quebec, Canada, a web-based, real-time structural monitoring solution for viewing and interpreting data
- Willowstick Technologies, Draper, UT, USA, www.willowstick.com, mapping and monitoring for subsurface water.
- Vista Data Vision by Vista Engineering, http://www.vistadatavision.com/, Reykjavik, Iceland, application for data management, visualization, and analyses of field measurements

***Table 7.1*** provides a summary of the capabilities of these various systems to the extent that information could be determined. All of the above companies were contacted to be included in ***Table 7.1***, but many did not respond to repeated requests.

Software evolves, so dam owners should consider performing a critical assessment of available systems prior to acquisition of such systems. A lot of effort can be required to set up a database with various instruments and data reduction formulae. Dam owners should also be aware of the need for software upgrades over the long term and the need for data storage security. Operational maintenance of hardware and communications systems should be included in the planning budget for acquisition.

## Table 7-1 Comparison of Data Management Systems

| | ARGUS | DamNET | Datgel | GEOSCOPE | iSiteCentral | Multilogger | Vista Data Vision |
|---|---|---|---|---|---|---|---|
| Time Series of multiple sensors | Y | Y | Y | Y | Y | Y | Y |
| Dual scales for y-axis | Y | Y | Y | Y | Y | Y | Y |
| User control on scales | Y | Y | Y | Y | Y | Y | Y |
| Plot one sensor versus another for correlation analysis | N | Y | N | Y | Y | Y | Y |
| Combine a string of sensors and plot as reading versus distance | Y | Y | Note 1 | Y | Y | Y | Y |
| Show readings from multiple sensors on a section through the dam | Y | Y | Note 1 | Y | Y | Y | Y |
| Show readings on a plan with contours of equal values | Y | N | N | Y | Y | Y | N |
| Plot can include Threshold and Limit Levels | Y | Y | Y | Y | Y | Y | Y |
| Real-time automatic updating of graph | Y | Y | N | Y | Y | Y | Y |
| Web-enabled user access | Y | Y limited | N | Y | Y | Y | Y |
| Automated Alarm/Alert capable | Y | Y | N | Y | Y | Y | Y |
| GIS based | Y | N | N | Y | Y | N | N |
| Numerical Operation on date from multiple Sensors | Y | Y | N | Y | Y | Y | Y |
| Database Engine | MY SQL | MS SQL Server | Access or SQL Server | Firebird or Oracle SQL | MS SQL | Firebird SQL | MY SQL |

Note 1: could be developed on a gINT fence report

Some owners of larger dams or networks of dams have developed customized data management and reporting systems. Some of these are stand-alone software programs that store, manage, archive and report the reduced data. Others are built on to a SCADA-based system used to operate mechanical and electrical equipment. SCADA is the acronym for Supervisory Control and Data Acquisition system. These customized systems can be developed to provided very high reliability and integrate instrument measurements with system control. However, they also tend to require a lot of specialized maintenance and support specialists who may not understand much about geotechnical and structural instrumentation. It can be very difficult to obtain reduced data from these systems in formats that allow evaluation more than originally envisioned in the system design.

Instrument data should be reduced and reviewed for results that are significantly different from previous measurements and for data exceeding *Limit Levels*. Usually this step should be completed soon after the data are obtained. Any questionable measurement should be retaken and appropriate corrections made. A reading that is considered anomalous or inaccurate but cannot be physically corroborated should be noted in the presentation of the data. Elimination of anomalous data from the data set should only be made if the inaccuracy is confirmed by equipment malfunction or data collection error. Please note that "anomalous" readings may indicate behavior of the dam that is unexpected and can reveal an unknown potential failure mode so it is advisable to not discard such readings. One approach is to flag data that are considered anomalous and provide a way to report the data with and without the anomalies. Over time, it may become apparent that what was considered anomalous has a pattern and an explanation.

## 7.2 Data Presentation

The primary aim of data processing and presentation is to provide a means for rapid assessment of data to detect changes that may require immediate action. The second aim is to summarize and present the data in a timely manner in order to show trends and to compare observed with predicted behavior for determination of the appropriate action to be taken.

Data from performance monitoring is most useful when plotted versus time using an appropriate time scale. Another type of useful plot is one set of data plotted versus another set. An example would be to plot readings from a piezometer versus reservoir level to determine their relationship and identify departures from normal behavior. Others include plotting readings on a cross section of the dam to illustrate the change in total head from upstream to downstream and plotting readings on a plan with contours of the values or change in values to identify areas of dissimilar performance. Other plots showing potential cause-effect relationships can be helpful in detailed evaluations of dam performance. Where possible it is useful to include predicted values and/or Action Levels in the plot to provide a reference with which to assess the performance of the dam.

Each graph should have a purpose to convey a specific message. Think carefully through what should be graphed and why. Design all elements of the graph to help convey its message. Strive to keep the graph as simple as possible but with sufficient elements to make it complete and understandable. All information on a graph should be readable, even if printed in black and white.

Graphical presentations, or plots, of collected data facilitate screening of data, allow quick comparison with expected and historic data, and facilitate evaluation and identification of long-term trends. Plots of predicted behavior and causal data are often included on the same axis. This includes water level readings, seepage, movement, stress-strain, and other measurements as appropriate. Spreadsheet type software used to compile the data generally includes graphing capabilities and can facilitate this step. The actual and reduced instrumentation data should be compiled in easy to read and interpret spreadsheet formats. From this data, a set of time-history plots should be developed.

Graphical presentations should use formats that deliver the important information in an easily understandable layout. The following list gives some guidelines to help achieve this requirement.

- Use standardized scales for x and y-axes for a group of graphs of the system type of instrument. For example, graphs of piezometer data should use the same axis scales values of total head for the y-axis and the same time scale for the x-axis for all plots of piezometer data.
- Include a chart title with font larger than used for axis titles.
- Include project name on plot.
- Include date and time the graph was generated and a reference to the source of the graph. This information should be in small but readable font along the edge of the graph.
- Use appropriate scale type, i.e. linear or log depending on the mechanism behind the data being shown.
- Time scales should use standard calendar date and time. Avoid using days since some reference date that has nothing to do with the project.
- Add the time zone to the time axis label if there is possibility of confusion. Take into account "Daylight Savings Time" when applicable. The easiest way to do this is to use a reading time interval greater than 2 hours on the day that the time change occurs. Most data loggers require a manual change of time to match local time changes.
- Scales for axes must be readable.
- Use reasonable divisions on scales to promote easy interpolation of data
  - 0, 1, 2, 3, 4, 5…
  - 0, 5, 10, 15…
  - 0, 2, 4, 6, 8…
  - Factors of ten times the above
- All numbers on an axis scale should have the same number of significant digits and that number should be appropriate for the precision of the data. The exception is 0 at the origin, which should be simply 0.
- Avoid using scales that match the maximum and minimum of the data. Stick to previous guideline.
- Titles for each scale must be included and show the units for the axis. For example "Pressure Head, ft" Font size should be larger than scale labels and smaller than graph title.
- Legend must be included and be understandable.
- Legend entries must distinguish each data set without ambiguity.
- Symbols for data points should be of size and type to discriminate the data.
- Use symbol shape, symbol color, line type, line thickness and line color to differentiate each set of data. The combinations must be such that each data set is distinguishable in the plot and in the legend, including when the graph is printed in black and white.
- Show each data point with a symbol, unless there is so much data that the information becomes too cluttered and local trends are obscured with the symbols.

- Do not show a continuous line between data points where there is missing data that should have been readings. Break the line and show dotted or no line across the missing data.
- Limit the number of data sets included in one graph to not more than 6 if possible. More will create confusion and difficulty to interpret the data.
- Use a grid consisting of main gridlines and sub grid lines. Make these lines with light colors, thin lines and broken line types so they appear in the background as subtle guidelines. Grays are good colors to use. Show sub grid lines lighter than grid lines. Box all four sides of the graph area with a solid line with larger line width.
- Provide guidance on graph to help interpret the data. This may include lines to show predicted values for the instrument that can be compared to the measurements. More commonly, this should show the *Threshold* and *Limit Levels.*
- Include data on the graph that relate to the cause of the trends in the measurements. For example for piezometer data that change with reservoir level, include the reservoir level with the piezometric data on the graph. For settlement data taken during the construction of an earth dam, include the height of the embankment versus time together with the measurements. Flow data might include reservoir level, or rainfall data. Temperature data might include ambient air temperature.
- Include a simplified plan and/or section showing the location of the instruments on the plot if possible.
- Add comments on causes for sudden changes or unusual elements in the data.
- Choose colors, line thicknesses and labels that will show all elements of the graph if it is printed in black and white and in gray scale. It is best to check representative graphs as they are being set up by printing them without color to confirm that all elements of the graph can be discriminated.
- Notes that quantify, limit, bound or otherwise describe the data should be within the graph area and not in the figure title.

Some examples of data presentation for various types of instrumentation associated with a concrete gravity dam are presented in ***Figures 7.1*** through ***7.4*** below. ***Figure 7.1*** is an illustration of data presentation for one piezometer showing threshold and action levels. An example of measured drain flows and headwater/tailwater elevations is presented in ***Figure 7.2.*** This graph suggests significant drain flows in the right non-overflow section of the dam. Also note the seasonal variation in drain flow which is probably associated with expansion and contraction of concrete joints due to seasonal water temperature variations ***Figure 7.3*** presents crack movement data in a concrete gravity dam with action thresholds. Precise survey vertical movements along the crest of dam are shown in ***Figure 7.4.***

An example of data presentation of seepage monitoring in an embankment dam is presented in ***Figures 7.5***.

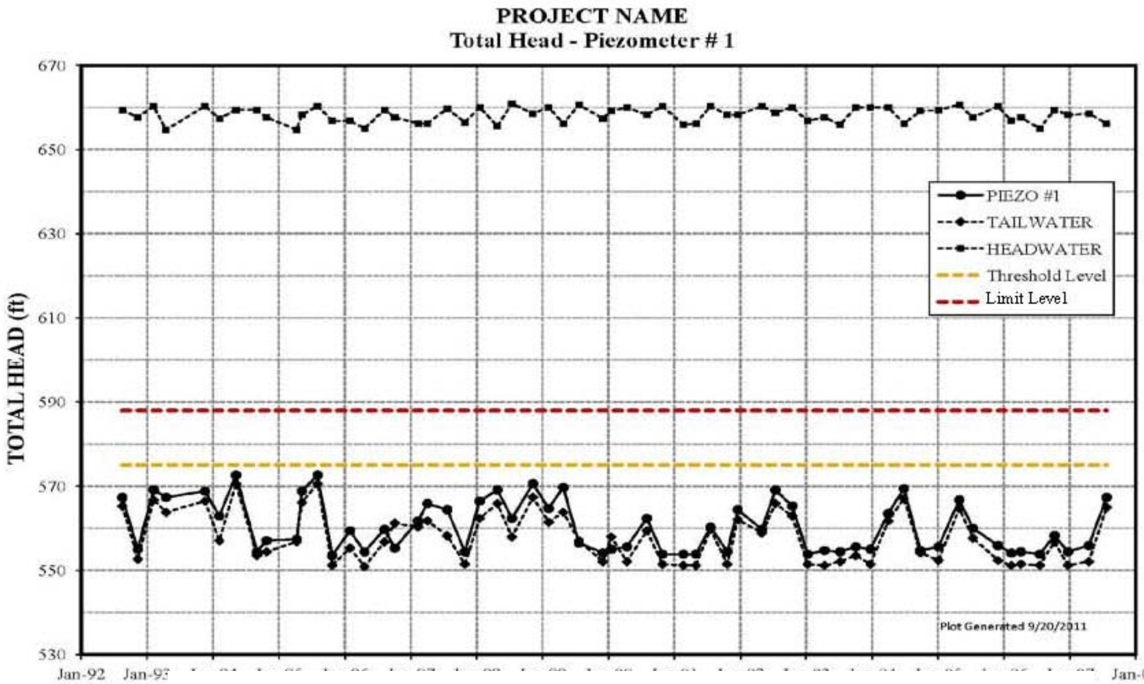


Figure 7-1 Piezometric Data Plot

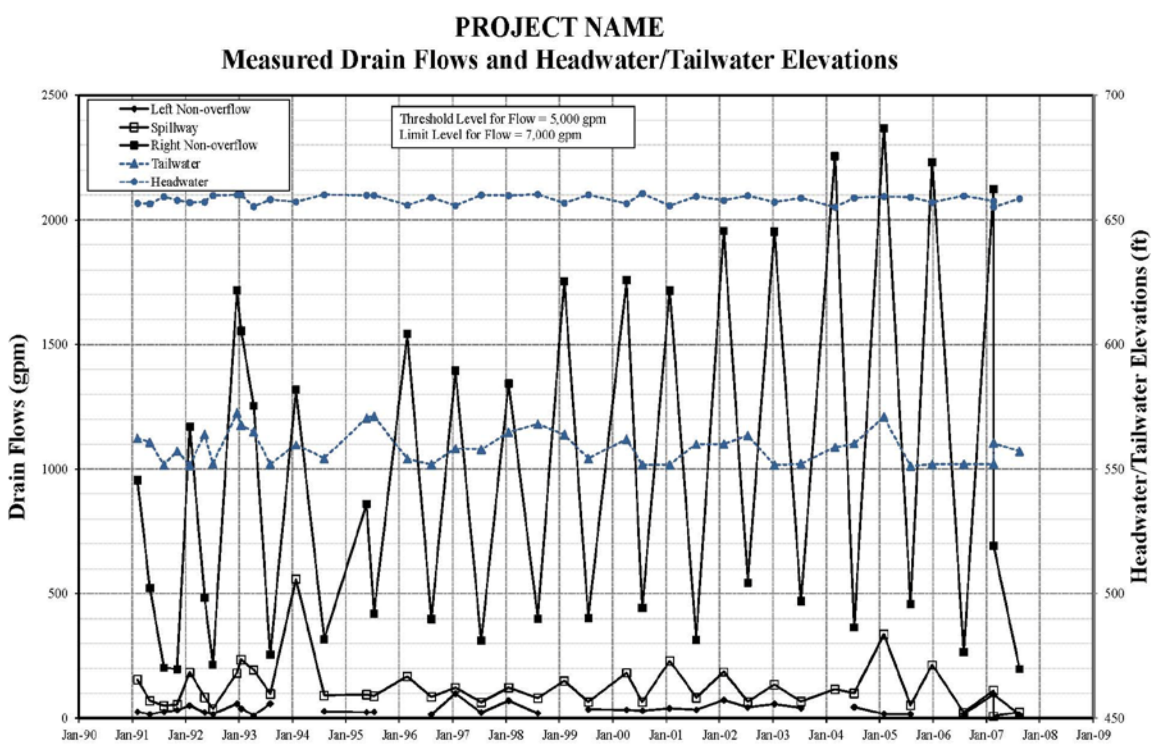


Figure 7-2 Measured Drain Flows and Headwater/Train Elevations
Concrete Gravity Dam

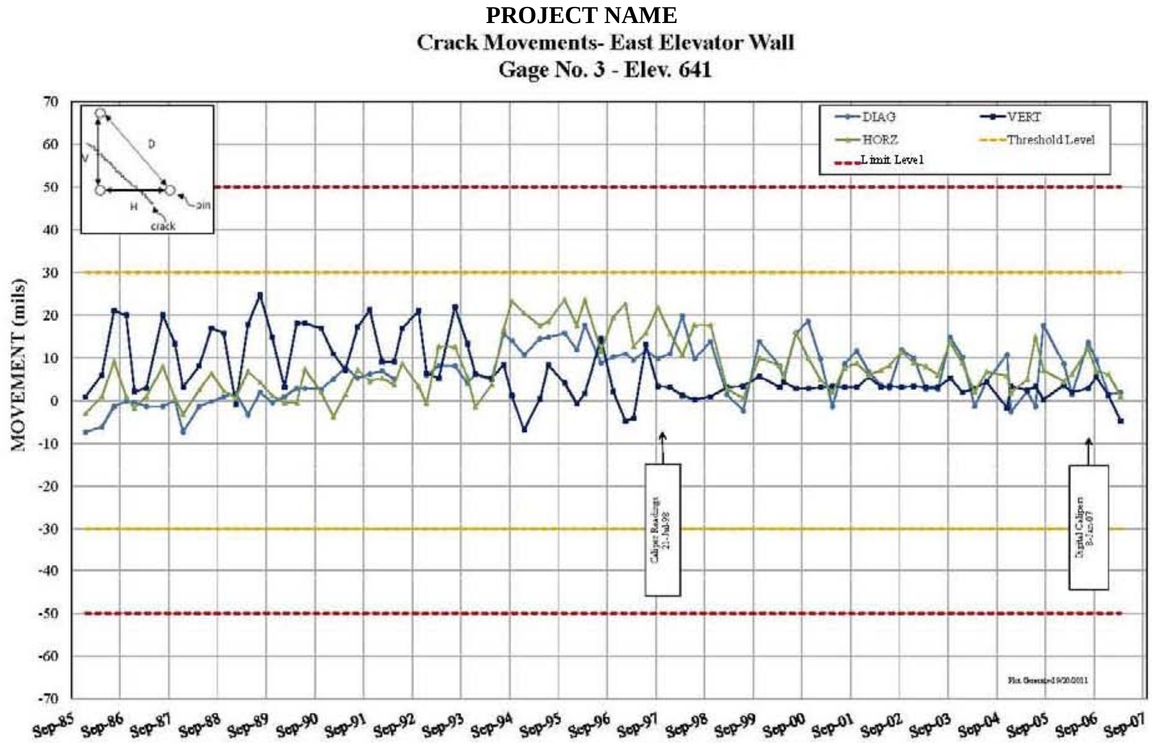


Figure 7-3 Concrete Gravity Dam Crack Movements

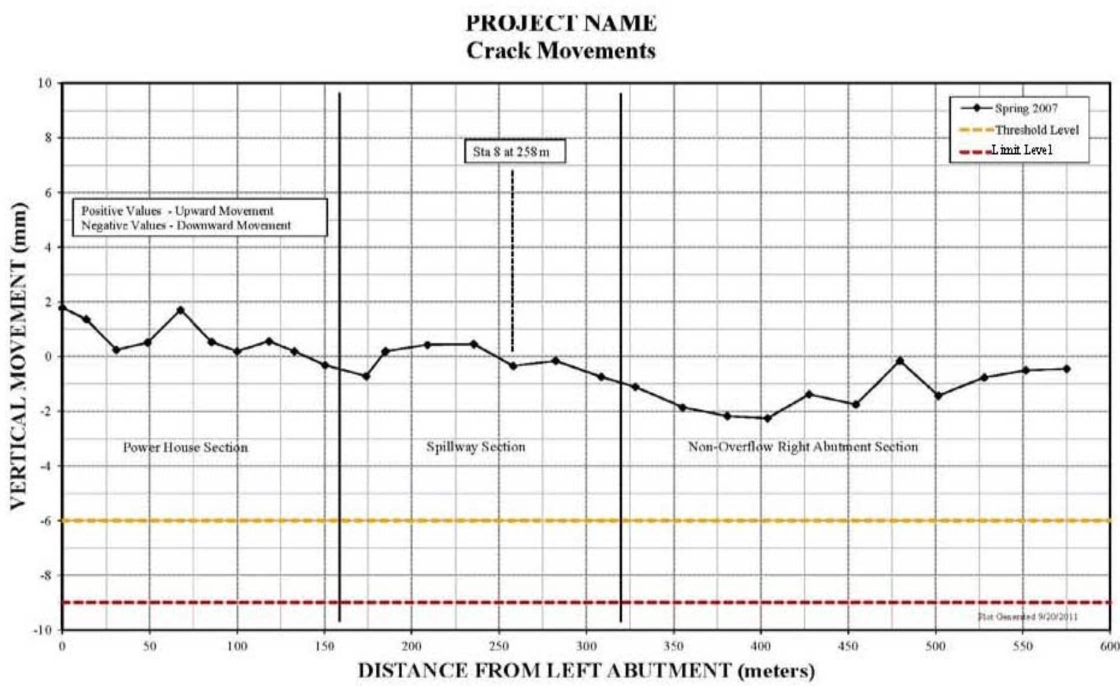


Figure 7-4 Precise Survey Vertical movements Deformed Shaped Relative to Spring 1992 Survey lines A B (Crest)

**PROJECT NAME**
**Embankment Piezometric Data - Wells W1 and W2**

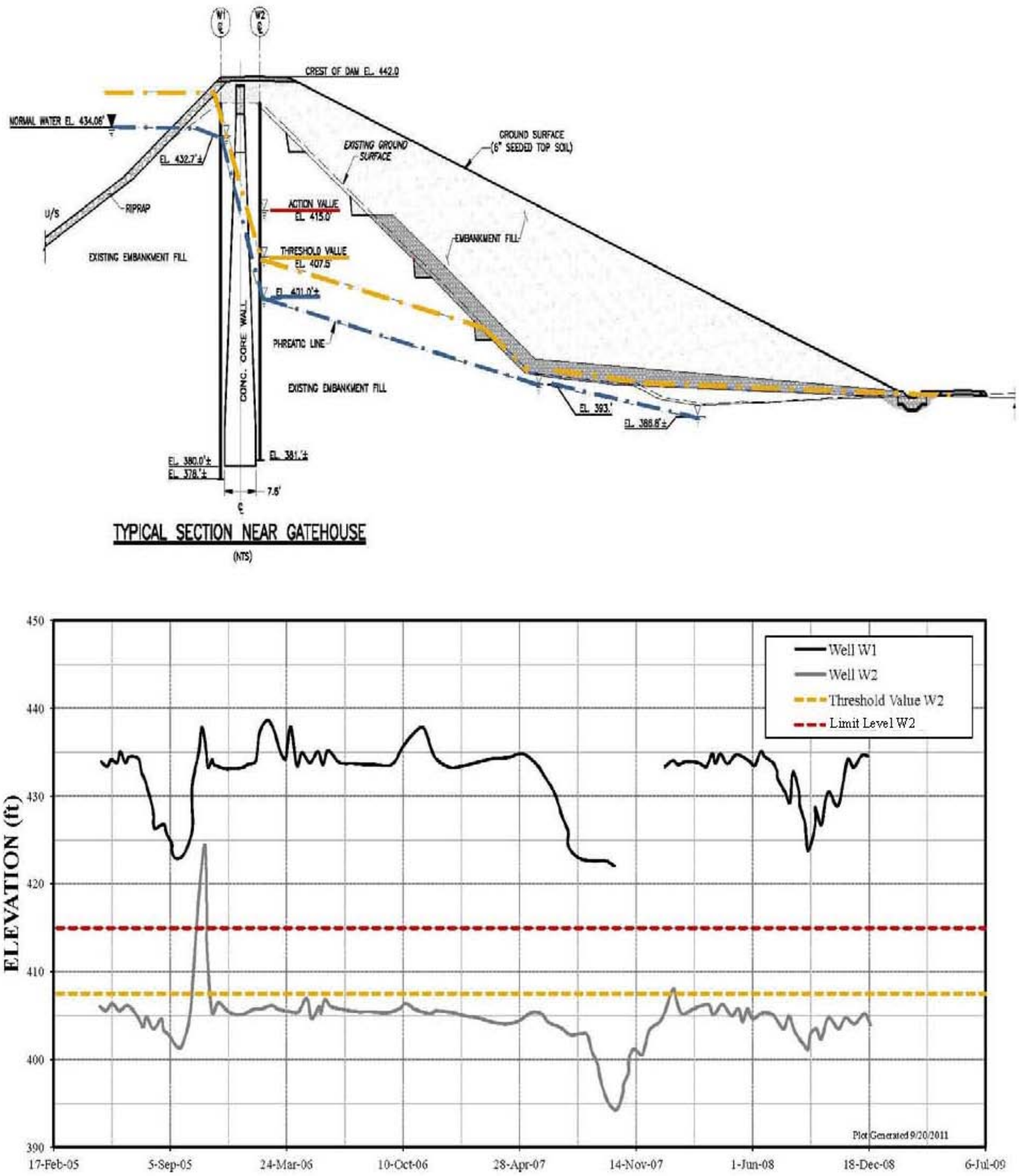


**Figure 7-5 Embankment Piezometric Data**

## 7.3 Data Evaluation

Evaluation consists of steps to establish that the data are reliable. Data that is taken but not evaluated is worthless. The data should be evaluated on a real time basis, by the data collector, in order to provide the greatest opportunity to discover the development of a failure mode with sufficient time to take a remedial action to either arrest development of the failure mode or initiate an Emergency Action Plan. Data evaluation should be done by a trained evaluator as soon as possible after collection of the data.

Data evaluation must be performed by someone who is familiar with the instrumentation system and data collection equipment and processes (modified from ASCE Task Committee on Instrumentation and Monitoring Dam Performance, 2000; Carpenter et al., 1988). This step requires attention to detail and skilled judgment to separate bad data from good. Data evaluation generally consists of asking questions about the data:

- Do the recent data make sense compared to previous data and expected values?
- Is the most recent data similar to the previous values?
- Does the trend in the data make sense compared to what is occurring with the dam?
- Does the change in data correlate to construction activities, environmental events, or operational changes?
- Does the change in data correlate with observations from visual surveillance?
- Is the change in reading of any particular instrument indicated by other instrument or observation?
- Has the instrument showed a similar reading in the past?
- Does the reading make sense?
- Are the readings within the operating range of the instrument and readout equipment?
- Is the expected accuracy of the instrument greater than the change of reading and thus the reading is possibly noise?
- Have the data been correctly recorded and entered into the data management system without human error?

A “no” answer to any of these questions raises suspicion about the reliability of the data. Any “no” answer should make one consider taking another reading as soon as possible to determine if the value can be reproduced. If it cannot be reproduced then the data point is suspect and should be marked as unreliable. If it can be reproduced and the reading processes and equipment are validated to be correct, then the data must be considered as valid data. Unreliable data should be kept in the data file but not be considered in the subsequent interpretation phase.

It is important to distinguish between accuracy and precision when dealing with measurements. Accuracy is the nearness to the true value and reflects any bias in the reading. Precision is the degree of refinement of the measurement and represents the randomness in the measurement. A measurement may be precise without being accurate and vice-versa. For example, a pressure transducer may be capable of measuring water depth to 1 millimeter, but the location of the transducer may be known to only several tenths of a meter. Since attaining precision complicates data evaluation, the need for precision and the level of precision should be carefully evaluated so unnecessary data are not collected and/or costs are not increased.

## 7.4 Data Interpretation

The purpose of data interpretation is to determine what the data indicate about the safety of the dam.

A first step in interpretation is to correlate the instrument readings with other factors (cause and effect relationships) and to study the deviation of the readings from the predicted behavior. When faced with data that appears to be unreasonable, there is a temptation to reject the data as false. However, such data may be real and may in fact carry an important message. A significant question to ask is: "Can I think of a hypothesis that is consistent with the data?" The resultant discussion, together with ensuring reading correctness described in the prior section, will often lead to an assessment of data validity.

All data will follow trends, such as decreasing or increasing with time or depth, seasonal fluctuation, direct variation with reservoir or tailwater level, direct variation with temperature, or a combination of such trends. The trends are usually evident in the plotted data. Statistical analysis of data may be useful in evaluating trends that are obscured by scatter. However, such analyses are no substitute for judgment based on experience and common sense. Data inconsistent with established trends should be investigated. Readings deviating from established trends should be verified by readings that are more frequent. Erroneous readings should be so noted on the original data sheets and should be removed from summary tables and plots.

All data should be compared with design assumptions. For example, measured phreatic levels and uplift pressures should be compared against those used in stability analyses. If the data are available for unusual load cases, such as rapid drawdown and floods, they should be compared with assumed pressures.

More than one phreatic line may exist where there are impervious strata in the foundation or embankment. A phreatic line is the elevation that water will rise to in piezometers positioned across a stratum. Technically it is the total head in the stratum which will vary horizontally and vertically if flow is occurring. If flow is occurring through a dam or its foundation there will be different phreatic lines for each soil strata and perhaps multiple phreatic lines for different elevations within a stratum. Phreatic lines are determined from a flownet. Piezometric data should be evaluated with geologic and construction data to identify multiple phreatic lines. If the phreatic line for any strata is above the ground surface, the stability of the dam should be evaluated using the elevated phreatic line.

If no unusual behavior or evidence of problems is detected, the data should be kept for future reference. If validated data deviates from expected behavior or design assumptions, action should be taken. The action to be taken depends on the nature of the problem, and should be determined on a case-by-case basis. Possible actions include:

- Perform a detailed visual inspection;
- Obtain additional measurements to confirm behavior;
- Verify that instruments and reading devices are working properly;
- Reevaluate safety using new data;
- Change frequency of measurements;
- Install additional instrumentation;

- Undertake special investigations;
- Design and construct remedial measures;
- Operate the reservoir at a lower level; and,
- Emergency lowering of the reservoir.

Data should be reviewed for reasonableness, evidence of incorrectly functioning instruments, and transposed data. The magnitude of data should be near the range of previous data. Data that are significantly different may be incorrect. For example, water levels in piezometers should not be above the reservoir level, except possibly during rapid drawdown or construction or where the local groundwater is higher such as at an abutment.

Data should be within the limits of the instrument. For example, data from open standpipe piezometers must be below the top and above the bottom of the pipe. If open standpipe readings are observed at the top of the pipe, these readings are ambiguous because the phreatic line could be exactly at the top of the pipe, or it could be well above the pipe. The standpipe must then be raised or have a pressure gage added to it to clarify the reading. Whenever the phreatic line is above the top of a standpipe it may indicate a developing problem and should be investigated. Reading levels near the bottom of a piezometer may indicate only the trapping of water in the cap at the base of the piezometer, when actually the piezometer level is lower.

Instrument data may be difficult evaluate. For example, weirs can be highly influenced by precipitation, but interpretation may be possible in non-rain periods or by observing if the readings consistently return to a low reading.

Data will generally follow trends, such as decreasing with time or depth, increasing with time or depth, seasonal fluctuation, direct variation with reservoir or tailwater level, direct variation with temperature, or a combination of such trends. The trends are usually evident in the plotted data.

All data will have scatter from instrument error, human error, and from changes in natural phenomena such as temperature, wind, and humidity. The true accuracy of data will not be apparent until a significant number of readings have been taken under a variety of conditions.

Statistical analysis of data may be useful in evaluating trends that are obscured by scatter, but may not always yield useful information if that data is taken annually or infrequently because there are not enough readings to reveal underlying factors. Statistical analyses are no substitute for judgment based on experience and common sense.

Data inconsistent with established trends should be investigated. Readings deviating from established trends should be verified by readings that are more frequent. Erroneous readings should be so noted on the original data sheets and can be removed from plots, if confirmed. Anomalous data should be plotted, even if errors are suspected, for two reasons. First, the anomalous data may reveal changes in a previously stable failure mode. Secondly, if monitoring for good health, anomalous data may reveal unknown potential failure modes (PFM). Unexpected readings are the ones most likely to reveal an unknown PFM.

Constant measurements or widely varying measurements may indicate improperly performing equipment. For example, a piezometer that reads a constant value and does not change with headwater level, tailwater level, or season may not be functioning properly. Similarly, if an entire series of dam deformation monuments are all-trending in the same direction, the base monuments may be moving rather than the dam.

Instruments that do not appear to be functioning properly should be further investigated. For example, data should be checked against data from similarly located instruments to determine whether or not trends and magnitudes are the same. Accessible sensors or gages should be replaced to see if the error remains. Calibration of the instruments should be checked. Often, tests can be devised to evaluate proper functioning. For example, piezometers and observation wells could be filled with water (or bailed out) and the rate at which the water returns to its original level measured and compared to the results of similar tests done at the time of installation, or with expected behavior.

Special investigations may be required where the instrumentation indicates concerning data but the reliability of the instrument cannot be determined or the data cannot be explained. Such investigations are aimed at determining more about what may be causing the unexplainable instrument readings. They might include such steps as performing more borings in the area, installing additional instruments, or causing a change in loading that should produce a predictable change in the instrument reading and monitoring the actual response of the instrument.

Improperly functioning instruments should be abandoned or replaced. Instruments that are vital to the safety evaluation of a dam should be replaced. Instruments that provide no meaningful information should be abandoned.

## 7.5 Performance Monitoring Action States

*Threshold Level* and *Limit Level* for instrument readings help interpret data and indicate what actions should be taken. Below the *Threshold Level*, the readings are as expected and all indications are that the dam is functioning safely. The dam is in a Normal performance state. Verified readings above the *Threshold Level* indicated that more attention is required. The dam is in either a Caution or Alert Performance state. It is common to use the concept of GREEN, AMBER, and RED states as defined in ***Table 7.2***.

The *Threshold Level* for an instrument represents the value beyond which the reading indicates an unexpected value or unexpected change. The performance state of the dam has transitioned from Normal to Caution. Data exceeding the *Threshold Level* should trigger an effort to understand the meaning of the unexpected value. The *Limit Level* for an instrument represents the reading that indicates an unacceptable or unsafe value for the instrument. The performance state of the dam has transitioned from Caution to Alert. Data exceeding the *Limit Level* should trigger immediate work to lower the value of the reading or alter the dam to restore it to a safe condition.

The *Threshold Level* is a reading that indicates a significant departure from the normal range of readings and prompts action to determine the cause and implication of the unexpected reading. Exceeding the *Threshold Level* usually does not itself directly imply a perceived instability of the structure. For example, a high reading of one piezometer in an earth dam may exceed the phreatic line used in the stability analysis at that location, but other piezometers along the same cross section could indicate the overall phreatic line is lower than assumed in the design stability calculations. The same logic holds for piezometers used to evaluate uplift pressure beneath a concrete gravity dam.

For these cases, a single instrument indicating values above design level does not automatically indicate a process headed towards instability.

Table 7-2 Performance monitoring Action States

| ACTION STATE | DESCRIPTION | RESPONSE |
|---|---|---|
| NORMAL – PERFORMANCE AS EXPECTED | | |
| NORMAL – GREEN | Observations and measurement indicate expected and acceptable values | Continue inspection, monitoring, and maintenance program. |
| THRESHOLD LEVEL | | |
| CAUTION - YELLOW | One or more indicators of performance are above expected values | Review the data for reliability.<br>Meet with Evaluation Team to decide what to do.<br>Inform all involved parties of the current condition and the recommended plan of action.<br>Take steps to reduce chance that reading will exceed the Limit Level. |
| LIMIT LEVEL | | |
| ALERT – RED | One or more indicators are above the Limit Levels established for each instrument. | Inform all parties to stop any work in affected area.<br>Implement contingency plan.<br>Develop safe steps to proceed. |

In some cases, a *Threshold Level* may be a lower limit; i.e. a decreasing trend of piezometric level may indicate the opening of a flow path to the downstream side of the dam. Alternatively, it may be desirable to maintain a certain piezometric level in order to retain submergence and prevent deterioration of wooden piles. For this reason, the setting of *Threshold Levels* should include a careful consideration of Potential Failure Modes and more than one *Threshold Levels* may be appropriate if development of different PFMs would result in different responses.

Once an instrument reading exceeds the *Threshold Levels,* an action is necessary. The range of responses will vary greatly according to the severity of the situation. It may be necessary to designate multiple *Action Levels* that are progressively serious. These should account for:

- A departure from the predicted values for the instrument.
- A minor departure from the historical record (possibly in order to produce an alert verifying that measurements are being made);
- A major departure from the historical record (possibly indicating a developing failure mode);
- A departure from historical reaction to other instruments; or,
- Levels indicating the approach of instability or other forms of failure such as piping.
- Review of actions to keep readings from reaching *Limit Levels* and those to implement immediately if reading exceeds Limit Levels.

- Review of *Threshold* and *Limit Levels* to determine if they can be modified using the latest information without compromising the safety of the dam.

Depending on the performance and response of the instruments to changing conditions, *Action Levels* related to magnitude and rate of change limits as well as to address daily, seasonal, or other cyclic relationships may need to be established.

Actions to be taken may include double checking the readings(s); checking the instrument; increasing visual surveillance and the monitoring frequency; review of design analysis assumptions and/or additional analyses; supplemental field investigations; or, actions to prevent the reading from increasing to exceed the Limit Levels.

A *Limit Level* is the instrumentation reading that triggers actions to reduce the excessive reading or otherwise modify the dam to restore a safe performance state. Such actions should be preplanned with labor and materials prepared to initiate the action quickly should that become necessary.

*Threshold* and *Limit Levels* should be established for each instrument taking into the account the expected performance of the dam, the location of the instrument, and the measurement characteristics of the sensor. In some cases, the numeric values can be based on theoretical or analytical studies (e.g. uplift pressure readings above which stability guidelines are no longer met). In other cases, they may need to be developed based on observed behavior (e.g. seepage from an embankment dam). One always assigns values of readings that the responsible engineer thinks should trigger further evaluation and acction. Limits for both magnitude and rate of change limits may need to be established. If trends or inter-relationships between data are not clear, it may be appropriate to take more frequent measurements or collect additional complementary data, or to add additional instruments.

*Threshold* and *Limit Levels* should be periodically evaluated to determine if settings may need to be changed to address daily, seasonal, or other cyclic relationships, new information, or changes to the dam. For example threshold and action levels may be set by the designer based on his/her understanding of how the dam will perform. During actual operation, the dam may perform differently with some of the instruments showing readings exceeding the threshold or action levels. A further evaluation of the construction experience and overall performance of the dam may indicate that these readings do not indicate unacceptable performance. These values would then be revised based on the more complete picture of how the dam is performing. The reverse is true also where undesirable performance occurs at levels below the limit levels and they should be adjusted downward. These levels should be evaluated every few years during operation to determine that they remain consistent with dam performance. Considerable care and thought must be given before revising action levels. Engineers knowledgeable in dam performance should be involved to determine that the proposed revisions are compatible with safe performance.

## 7.6 Monitoring Summaries, Conclusions, and Recommendations

After each set of data has been interpreted, conclusions should be reported. Initial communication of these conclusions may be verbal but should be confirmed in writing. The report should include updated summary plots, a brief commentary that draws attention to all significant changes that have occurred in the measured parameters since the previous report, probable causes of these changes, and recommended actions. These periodic reports form a valuable bank of experience and should be distributed to the owner.

All data should be compared with expected behavior based on the engineering concepts of dam safety. Variations from expected behavior may suggest development of conditions that should be evaluated further. For example, at a concrete gravity dam, increasing uplift pressure, or decreasing drain flow may indicate that the foundation drains need to be cleaned.

All data should be compared with design assumptions. For example, measured pore pressures and uplift pressures should be compared against those used in stability analyses. If data are available for unusual load cases, such as rapid drawdown and floods, it should be compared with assumed pressures.

Multiple phreatic lines may exist in the dam and its foundation. Piezometric data should be evaluated with geologic data to identify multiple phreatic lines. If the phreatic line for any strata is above the ground surface, the stability of the dam should be evaluated using the elevated phreatic line, otherwise misleading factors of safety will be obtained.

If no unusual behavior or evidence of problems is detected, the data should be filed for future reference. If data deviate from expected behavior or design assumptions, action should be taken. The action to be taken depends on the nature of the problem, and should be determined on a case-by-case basis. Possible actions include:

- Performing detailed visual inspection;
- Repeating measurements to confirm behavior;
- Reevaluating stability using new data;
- Increasing frequency of measurements;
- Installing additional instrumentation;
- Designing and constructing remedial measures;
- Operating the reservoir at a lower level; and,
- Lowering the reservoir level.

## 7.7 Adequacy of Instrumentation and Monitoring

The last step should be to assess whether the instrumentation and monitoring program is sufficient to evaluate if a dam is performing as expected and warn of developments that could endanger the safety of the dam. The evaluation should include answers to the following three questions.

- Are the type, number, and location of instruments proper for the behavior being monitored?
- Is the frequency of readings appropriate?
- Are the data being collected, processed, and evaluated in a timely and correct manner?

If there is a discrepancy between the measured and expected behavior of the dam, it may indicate that data do not adequately represent the behavior of the dam, or that conditions exist that were not accounted for in the expected behavior. In either case after detailed evaluation and interpretation, it is often useful to perform field investigations and install additional instrumentation to evaluate the unexpected behavior.

If trends or inter-relationships between data are not clear, it may be appropriate to take more frequent measurements or collect additional complementary data.

If data are not being processed and evaluated in a timely and correct manner, personnel involved in the instrumentation and monitoring program should be reminded, and further trained if necessary, in the importance of each phase of the program and its importance to the dam safety program. A dam safety program is inadequate if the performance of a dam is not understood. Performance monitoring with visual surveillance and instrumentation provides a powerful aid to that understanding.

> ***"We need to carry out a vast amount of observational work, but what we do should be done for a purpose and done well."***
>
> Peck, 1972

## 7.8 A GIS Based Approach to Dam Safety

Good record keeping is critical to making well-informed decisions regarding the performance state of dams. Information required to make an informed decision may be missing, scattered throughout numerous reports, or filed at different locations. When abundant but scattered dam information is available, the engineer must spend time to find relevant data to access the condition of the dam, which poses an inconvenience as well as a possible safety concern. Ideally, dam information would be readily available and organized for a straightforward and efficient assessment of the performance state of the dam. One such commercially available GIS database program is ESRI ArcGIS software. This Package is a GIStool set that requires programming to achieve a specific need.

In its simplest terms, a Geographic Information System (GIS) creates maps tied to data tables. Within the context of dam safety, information collected from instruments on the dam site, physical observations, and field exploration data are combined into a single software platform to provide organized information to an engineer, operator, dam safety official, or dam owner that aids informed decisions relating to the condition or operation of a dam.

The advantage of GIS is that it contains spatial information that displays a table of attributes linked to features on a map. The features are shown as vector (points, lines, polygons) or raster (imagery, scanned maps) data or both. The various layers of data can be grouped into themes and organized into hierarchal tiers. For instance, instrumentation data gathered from a dam can be grouped together and divided into layers depending on the instrumentation type (i.e. weir, piezometer), and sub-tiered by individual instrument name (weir #1, weir #2, etc.) A GIS could then display the associated readings for one weir, or create a graph of all of the instrument recordings, depending on the analysis needs.

The data can be selected based upon:

- Its usefulness for dam safety analysis (for instance, evaluating developing hazards, verify engineering design assumptions, and identifying potential failure modes);
- Availability; and,
- Quality (for instance, completeness and metadata description).

The data available as related to dam safety usually falls into several categories: instrumentation data, geologic information, photographs, design documents, installation logs for instruments and operating history.

Instrumentation data and photographic information gathered on a recurring basis can be viewed spatially, and the plots can be automatically updated as the database is being populated. Abnormal readings or observations can be cross-referenced with geologic information to help in interpreting the abnormal readings. Displaying dam safety information geographically simplifies the analysis of technical information that could reveal distributions, relationships, or trends not detectable when reviewed separately.

These customized systems can be developed to provide very high reliability and to integrate instrument measurements with other data useful for evaluation and analysis of performance state. However, they also tend to require a lot of specialized maintenance and support specialists who may not understand much about geotechnical and structural instrumentation. It is therefore essential that an experienced dam safety engineer assist with the development and management of these GIS database tools. They provide most value to owners with a portfolio of dams.

Intentionally Bank

# 8.0 TYPICAL DAM SAFETY PERFORMANCE MONITORING PROGRAMS

## 8.1 Components of an Effective Monitoring Program

Procedures and criteria to develop a Dam Safety Performance Monitoring Program should be based upon "failure mode thinking," the dam's hazard potential, and the Performance State of the dam (NORMAL, CAUTION and ALERT defined in ***Section 2.1***). An effective dam safety-monitoring program involves three key elements. These are the availability of all pertinent supporting technical information about the dam; an understanding of potential failure modes for the dam and its appurtenances; and, the execution of an effective surveillance and monitoring plan. (FERC, 2005) The results of surveillance and monitoring should be documented in a report, which presents the evaluation of monitoring data and an assessment of the dam's performance with respect to its design basis. Each of these components is briefly described below.

The typical performance monitoring programs presented in ***Sections 8.2***, ***8.3***, and ***8.4*** are provided for general guidance. Individual programs need to be tailored to meet dam specific needs for prudent risk management and the dam owner's resources. The visual inspection components for dams of various hazard potential classification and performance state that are discussed in these sections should be performed by fully trained professionals (i.e. dam safety engineers). ***Section 5.2*** provides a discussion of visual inspection requirements. In all cases there is a presumption that operations and maintenance staff will visit the dam on a proscribed routine basis and will be sufficiently trained in dam safety issues to identify changed or developing conditions at the particular dam they are working at.

### 8.1.1 Supporting Technical Information

The purpose of the Supporting Technical Information is to summarize project elements and related details. This information should be summarized in an organized and understandable document that is normally assembled by the Owner with assistance from the Designer or a Consultant if necessary. This document should contain the information necessary to have a complete and thorough understanding of the dam and the available analyses and assessments that support the fundamental safety of all structures associated with the safety of the project.

The Supporting Technical Information document should include sufficient information to understand the design and current engineering analyses for the project such as:

- A description of the project and project works.
- A summary collection of design and as-built drawings in plan and section that show the geometry, materials and subsurface conditions for all representative sections of the dam as originally constructed and for any successive repairs, modifications and upgrades.
- A description of all site-specific potential failure modes.
- A summary of the construction history of the dam including any problems that developed, how they were remedied, and any changes in design during construction.
- A summary of the operating history including any unexpected occurrences during construction and operation of the dam that potentially relate to its safety.
- A summary of standard operating procedures.
- A description of geologic conditions affecting the project works.
- A summary of hydrologic and hydraulic information.

- Summaries of flow, stability and stress analyses for the project works.
- Description of procedures used to select input parameters for all analyses including published literature, direct measurements, and laboratory testing used for determining strength parameters for the various loading conditions analyzed.
- Description of procedures to predict pore pressures for each type of loading analyzed.
- Summaries of instrumentation and surveillance for the project to include tables, plans and sections showing locations of each instrument, purpose of the instrument and last known status of each instrument.
- All reports containing results from the surveillance and monitoring program; and
- Pertinent correspondence with regulatory agencies related to safety and performance monitoring of the dam.

The Supporting Technical Information document should use summary tables, figures, and drawings to aid analysis of data and to expedite review by others. Only key paragraphs of the original reports should be included in this document for clarity and ease of access. The source of each element of the summarized information should be cited with the information. A list of all reports, published materials, and safety related communications should be compiled and maintained. Reports on any analysis should include a summary of the field and laboratory investigations along with a clear understanding of the procedures used to develop the all input parameters to each different type of analyses completed.

The Supporting Technical Information document should be a working document. As new data or analyses become available, they are appended to the initial document and outdated material removed. The complete Supporting Technical Information document should be reviewed periodically and kept in good order.

Owners of small risk dams may think that this document will be too expensive to prepare and applies only to large dams therefore they do nothing. Even a simple diary with representation photos of key events in the life of the dam can be of great value in addressing a potential problem.

#### 8.1.2 Potential Failure Modes Analysis (PFMA)

A Potential Failure Mode (PFM) is the chain of events that causes a component of a dam or a containment structure to fail to perform its intended function. As related to dam safety, a PFM is a chain of events with the potential to cause an uncontrolled loss of contents.

A Potential Failure Modes Analysis (PFMA) is intended to broaden the scope of a safety evaluation to include scenarios that may have been overlooked in past "standards based" investigations, which typically cover hydraulic capacity of spillways and stability of structures under a set of pre-defined load conditions. A PFMA seeks to identify all potential failure modes for all potential loads and conditions that have the potential to produce significant undesirable consequences.

A PFMA is an evaluation of "potential" failure modes for a dam or other project works by a team of persons who are qualified by experience, education and training to evaluate a particular structure. It is based on a review of existing data and information, first hand input from field and operational personnel, a site inspection, completed engineering analyses, and identification of potential failure modes. It considers failure causes, failure development, and the consequences of failure. It is intended to provide enhanced understanding and insight on the risk exposure associated with the dam. The potential failure mode process has the ability to (FERC, 2005):

- Enhance the dam safety inspection process by helping to focus on the most critical areas of concern unique to the dam;
- Identify operational related potential failure modes;
- Identify hydraulic structural and geotechnical related potential failure modes, including those not covered by formal analysis;
- Enhance and focus the visual surveillance and /or instrumented monitoring program;
- Identify shortcomings or oversights in data, information or analyses necessary to evaluate dam safety and each potential failure mode;
- Help identify the most effective dam safety risk reduction measures; and,
- Document the results of the study for use on future dam safety inspections.

PFMAs should be conducted by the Owner's Engineers and Operators with assistance from Independent Consultants as necessary. Potential Failure Modes should be identified and described during the design phase of the project and then updated in the construction phase. Additional potential failure modes or more specific definition of existing ones may be identified during the operational phase if any element of the dam performs different than expected. An example of a potential failure mode only being defined well into the operational life of a dam is the problem with alkali-aggregate reaction (AAR) in some concrete dams. This failure mechanism was not known when many of the early-concrete dams were constructed.

Consideration of failure modes is an ongoing process. As new information becomes available, or as the condition of the dam changes, periodic revaluation of the Potential Failure Modes (PFMs) is required. For additional information about PFMs, see *Section 4.1* and *Appendix D.*

### 8.1.3 Surveillance and Monitoring Plan

Based on the above two steps, a Surveillance and Monitoring Plan should be developed to define the appropriate monitoring for the water retaining project works. *Section 5* and *6* provide detail guidance to develop this plan. An integral part of the Surveillance and Monitoring Plan is the integration of the Owner's operations, maintenance and inspection programs with the overall dam safety-monitoring program. The Plan should be a written monitoring plan that is prepared following completion of the PFMA. It should address site-specific potential failure modes. It may be expanded after first filling and modified as appropriate during operations to keep it up-to-date and complete.

The integration of the Surveillance and Monitoring Plan with the Potential Failure Modes Analysis and the Summary of Technical Information Document provides a more efficient and effective dam safety program. The added value to dam safety includes:

- Uncovering data and information that corrects, clarifies, or supplements the understanding of potential failure modes and scenarios;
- Archiving the key technical information supporting the evaluation of the dam;
- Identifying potential risk reduction measures;
- Focusing surveillance, instrumentation, monitoring and inspection programs to provide information on the potential failure modes that present the greatest risk to the safety of a dam;

- Developing operating procedures to assure that there are no weak links that could lead to mis-operation failures;
- Formulating response plans to quickly address new safety issues identified by the surveillance and monitoring program and thereby effectively manage risk; and
- Responding quickly and effectively during any dam emergencies.

All water retaining elements of the project should be considered within this program including canals, flumes, tunnels, and penstocks.

The Ameren Missouri Dam Safety Program for the Taum Sulk Pumped Storage Power Project has been posted on the Federal Energy Regulatory Commission (FERC) website as an example dam safety inspection and monitoring program for federal regulated dams. Ameren Missouri is in the process of updating its dam safety program based on experience and knowledge since the original plan was developed. Ameren Missouri is currently championing an effort to develop a model dam safety program with a group of dam owners and the FERC through the CEATI-Dam Safety Interest Group. Appendix A of the Consent Order provides an early version of this document. It is available at:

http://www.ferc.gov/industries/hydropower/safety/initiatives/odsp.asp

#### 8.1.4 Surveillance and Monitoring Report

The Dam Safety Surveillance and Monitoring Report provides the owner's evaluation of current performance state of the dam. Generally, this report would be prepared annually for a high hazard potential structure, every three years for intermediate hazard potential structure, and every five years for low hazard potential structures depending on regulatory guidelines and the Owner's approach to risk management. Whatever periodic interval for reporting, the results of the dam safety surveillance and monitoring should be evaluated on a real-time basis and not simply accumulated throughout the year only to be evaluated prior to issuing a formal report. The instrumentation evaluation presented in the report should include how the information was used and how the data were evaluated, potential failure modes, conclusions as to either adequate performance or inadequate performance and recommendations for actions needed to maintain or restore dam safety and reduce risk concerning inadequate performance. Recommendations developed from the evaluation should be clear and concise. They should include enough information to explain the specifics of each recommendation and the plan and action to be taken. A suggested outline for this periodic report includes the following elements:

1. Findings – this section should contain a summary of significant findings, conclusions, actions, and changes or recommendations for the review period. Priorities should be established for dam safety and maintenance issues such as "serious", "moderate", or "minor" with specific time frames for resolution.
2. Potential Failure Modes – this section should list all potential failure modes and discuss how the surveillance and monitoring program relates to the potential initiation or progression of each PFM and helps prevent its complete development.
3. Field Observations – this section should include a summary of items detected during inspections performed by plant personnel, staff inspectors or engineers, regulatory officials, or special inspections such as diving inspections, penstock/tunnel inspections, etc. Include a summary of significant or notable observations or items requiring maintenance or repair. Structural irregularities such as cracks, depressions, and seepage should be shown on plan

and section views if possible. Special attention should be given to changes since the last inspection.

4. Instrumentation Evaluation – this section should include an evaluation of active instrumentation. Timely compilation and evaluation of the data should be performed to determine if the data supports the satisfactory performance of a structure or that the instrumentation is giving reliable data. Timely evaluation ensures that any adverse trends are recognized and that an appropriate response can be initiated. Evaluations should be detailed enough to support the conclusions and recommendations developed. A conclusion that the structures are safe and adequate should be supported by a detailed analysis and discussion to support the conclusion. Merely stating, for example, that piezometric levels are satisfactory is not sufficient. A qualified engineer should help develop this section.
5. Changes – this section should document any changes such as updates to the instrumentation, program, and personnel.
6. Certification – this section should include a signature page indicating who prepared the report and who reviewed the report.

Attachments should include:

A. Significant inspection forms or reports;
B. Supporting drawings including plan views, cross-sections, details, etc.; and,
C. Instrumentation plots of measurements with time.

***Section 7*** provides guidance to summarize monitoring data and evaluate what it means that is helpful in preparing this report.

#### 8.1.5 Owner's Self-Assessment Program

Although a good safety program may not prevent every conceivable failure mode, a poor program can likely lead to problems. The scope of an owner's dam safety program should be commensurate with the potential risk hazard of its dam. There is no "one size fits all" dam safety program. CEATI (2010) discusses this point based on responses from an industry survey. Every dam safety program must be developed to consider the unique aspects of the dam, its foundation, its location, the consequences of failure and its risk. Periodic self-assessments, ideally aided with external peer review, should be made to ensure that the dam safety program is workable and effective, and that it is consistently performed in the intended manner.

As a general rule, owners should consider both the technical requirements and the organizational practices associated with dam safety. Technical requirements include: technical competence of responsible personnel; effectiveness of visual surveillance, performance monitoring, data evaluation, safety assessment, and periodic safety inspections; emergency preparedness; and, timely corrective maintenance and/or modifications for dam deficiencies or vulnerabilities. Organizational practices that affect all levels of the owner's organization includes: recognition of responsibility for dam safety; effective communication up and down the chain of command; allocation of appropriate resources (personnel and budget) for dam safety; emphasis on training and learning; and, clear designation of responsibilities for dam safety. ***Section 4*** discusses these elements further.

### 8.2 Monitoring of Dams with Low Hazard Potential

Dams with low risk in NORMAL condition are almost never instrumented. The cost to procure, install, monitor, maintain and evaluate the readings is prohibitive compared to the value delivered.

The typical monitoring program is annual visual inspections with recorded observations and photographs. The crest elevation at representative points relative to a fixed monument located above high water should be determined at 10 year intervals. Additional visual inspections are recommended during the peak of a storm greater than the 25-year event, or other events that might cause distress to the dam. Reservoir levels are generally not recorded, however the peak water level should be measured relative to a permanently fixed reference point during a 25-year or larger event.

*Figure 8.1* presents a typical small earth embankment dam having a low hazard potential. The potential failure modes are considered to be overtopping, internal erosion (piping), and global stability. The normal monitoring program would entail periodic visual inspections to look for cracks, slippage, wet spots on the downstream face and toe area, soil erosion and piping of soil near the toe, irregular settlement of the crest, and evidence of overtopping.

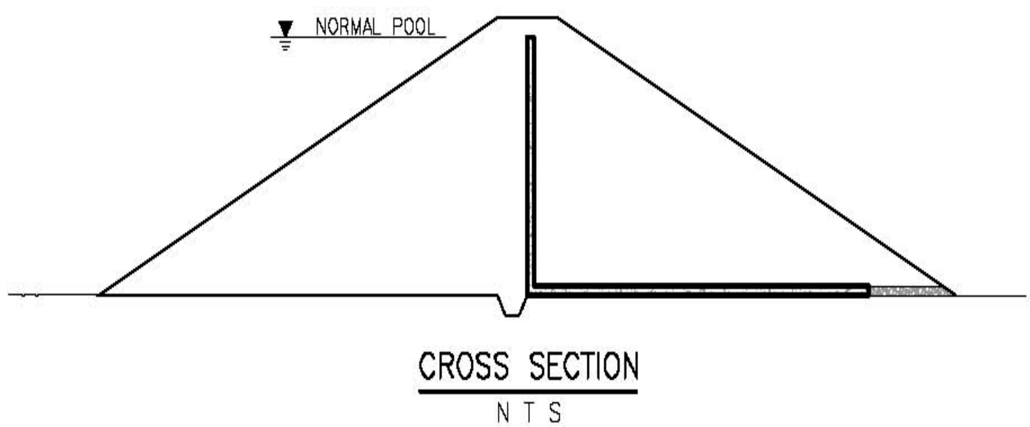


**Figure 8-1 Small Earth Dam with Low Hazard Potential**

Dams with low risk in a CAUTION condition are typically monitored more closely by monthly to quarterly visual inspections. Recording of the reservoir level relative to a fixed reference may be initiated. Visual indications of distress such as increased flow, dirty seeps, widening cracks and differential movement are watched. In some cases, temporary reference points are established on the dam with their positions measured occasionally by surveying from a safe location to determine whether the dam is experiencing movement at an increasing rate, or remains stable.

Dams with low risk in an ALERT condition are typically monitored weekly to monthly by visual inspection. The main objective of the monitoring program is to ensure that nothing has changed to increase the consequences of the dam failing and to warn people downstream of the dam if failure becomes imminent. In the case of low hazard potential dams in alert condition, consideration should be given to creating a plan for a controlled breach of the dam if the visual monitoring indicates a sudden failure is likely. Where low level outlet controls are available, reservoir dewatering should be considered.

## 8.3 Monitoring of Dams with Intermediate Hazard Potential

Dams with intermediate hazard potential should typically have some instrumentation at the main section of the dam and any troublesome location to provide indicators that the dam is performing as expected. The instrumentation should be designed to give indicators that any of the significant potential failure modes might be developing. Additional monitoring may be added at points where anomalies are found during construction that could cause a different performance than anticipated by the design.

*Figure 8.2* shows an example instrumentation plan at the maximum section of an earthen tailings dam with an intermediate hazard potential. In this example, the significant potential failure modes illustrated are global instability; overtopping, and erosion (internal and external). The primary monitoring program in this example would consist of the following:

- visual inspection to look for cracks, slippage, wet spots on the downstream face and toe, soil erosion and piping of soil near the toe, and soft or spongy spots downstream of the toe;
- crest elevation at representative points;
- piezometers within the dam and its foundation, measured monthly, to indicate how well the seepage control measures are working to minimize pore water pressure in the downstream half of the dam and its foundation;
- inclinometers to detect early stages of instability; and,
- water level indicators to warn of water level exceeding crest height.

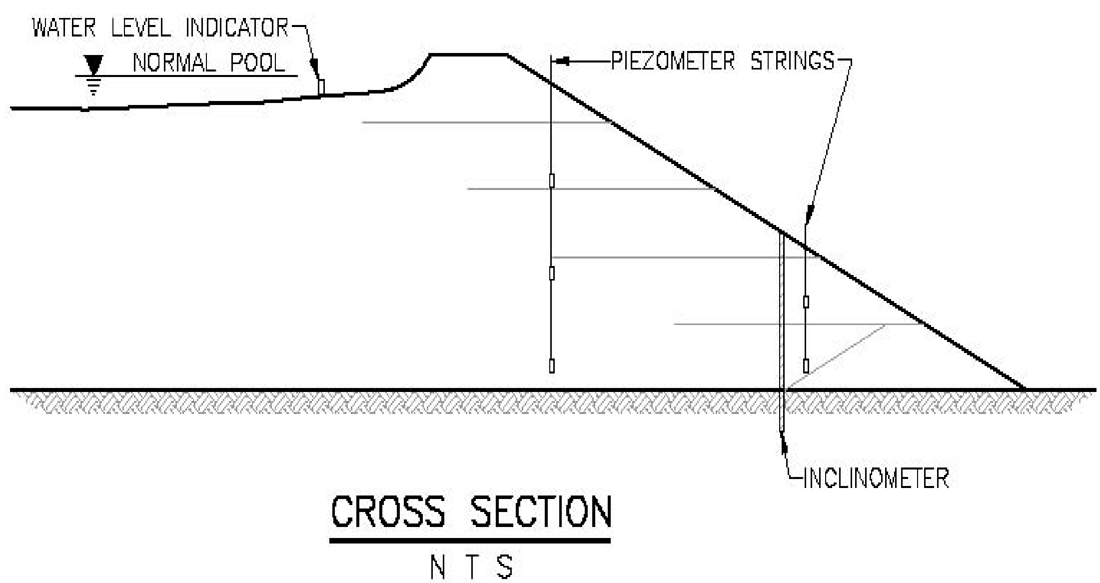


**Figure 8-2 Tailing Dam with Intermediate Hazard Potential**

Some dams with intermediate hazard potential may have developed behavior different than anticipated in the design. Such differences create uncertainty, produce questions and reveal higher risk levels. Instrumentation may be added to answer these questions, reduce uncertainty and decrease the risk level. The number and locations of these additional instruments are directly related to the nature of the unanticipated performance and should be developed by a qualified engineer familiar with the design and performance of the dam.

A dam with intermediate hazard potential in a NORMAL condition is typically visually inspected at 6 month intervals. Instrumentation data may be collected one to four times or more per year. Visual inspections and data collection should also occur during or after a 25-year storm event, or larger, or other geohazards such as earthquakes that might impact the condition of the dam.

A dam with intermediate hazard potential in a CAUTION condition that is not expected to reach an ALERT condition within the coming year should be visually inspected at least once per month. Instrumentation data may be collected once to four times or more per year. Additional instrumentation may be warranted to better understand how the dam is performing and the cause of anomalous behavior so that mitigation measures can be developed to keep the dam from reaching the ALERT condition. Inspections and data collection should occur with sufficient frequency to allow documentation of the rate of change in the condition of the dam. If the rate of change of the condition of the dam is such that it might enter the ALERT condition before the next scheduled inspection, the inspection and data collection frequency should be increased to document the rates of change with enough detail to predict when the ALERT condition will be reached. The monitoring frequency should be sufficient to be able to issue a warning notice as soon as the dam's condition enters the ALERT state.

A dam with intermediate hazard potential in an ALERT condition should be visually inspected and data collected from instruments at least once per week to once per day, depending on the severity of the condition, the potential consequences of a failure and the rate of change of the dam's condition. The observations should be of sufficient frequency that an alarm can be issued whenever failure of the dam becomes imminent. A contingency plan to minimize consequences and reduce the likelihood of failure should be in place and invoked as soon as the dam reaches an ALERT condition if not before.

## 8.4 Monitoring of Dams with High Hazard Potential

Dams with high hazard potential should have instrumentation in place to monitor every potential failure mode that might occur to the dam. The instrumentation should be designed to give indicators (at the earliest possible stage) that any of the significant potential failure modes might be developing. Typically, multiple sections of the dam will be instrumented and redundant instruments will be added at key locations. Additional monitoring may be added at points where anomalies are found during construction that could cause a different performance than anticipated by the design.

***Figure 8.3*** shows an example instrumentation plan at the maximum section of a concrete arch dam with a high hazard potential. The significant potential failure modes are global instability, cracking from excessive displacement, and overtopping. A basic monitoring program would consist of:

- visual inspection to look for new cracks, seeps, displacement and excessive seepage;
- transducers to measure reservoir and tailwater levels in relation to top of dam to indicated potential for overtopping and to help interpret piezometer data;

- piezometers to measure total head along base of dam to check design assumptions for stability;
- inclinometers to determine if and where lateral displacement is occurring;
- movement monuments to measure change is x, y, and z coordinates along crest of dam for indication of unexpected movement;
- crack gages on any active crack; and,
- data logger to read electronic sensors.

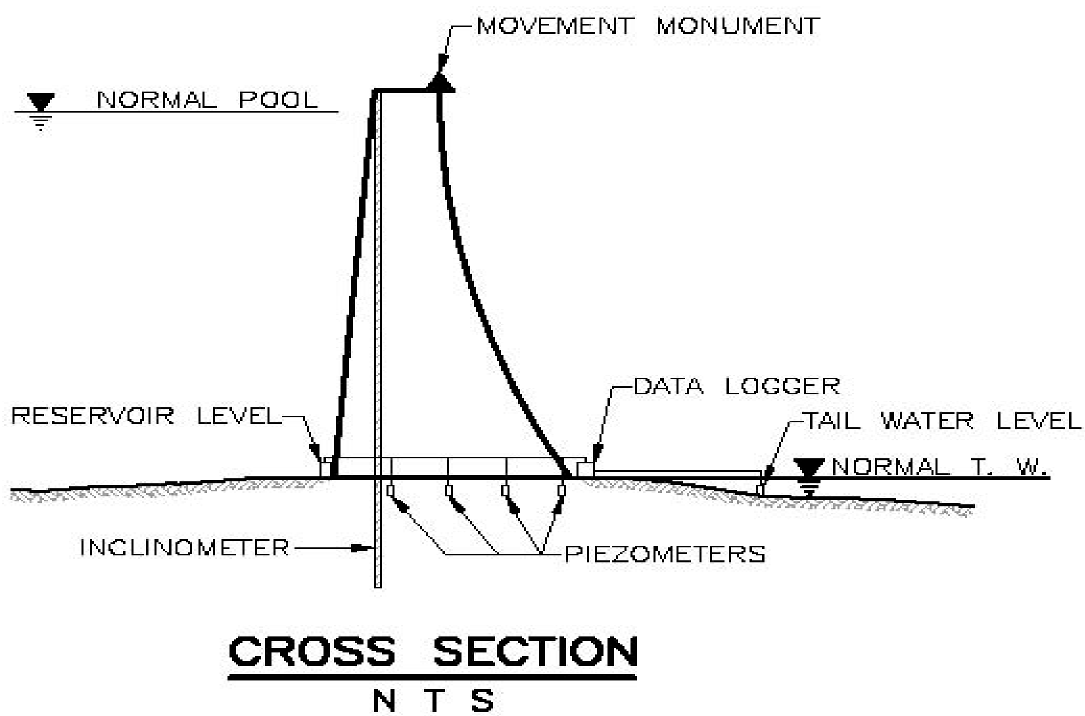


**Figure 8-3 Concrete Arch Dam with High Hazard Potential**

Some dams with high hazard potential may have developed behavior different than anticipated in the design. Such differences create uncertainty, produce questions and reveal higher risk levels. Instrumentation may be added to answer these questions, reduce uncertainty and decrease the risk level. The number and locations of these additional instruments is directly related to the nature of the unanticipated performance and should be developed by a qualified engineer familiar with the design and performance of the dam.

A dam with high hazard potential in a NORMAL condition is typically visually inspected at least four times per year. Instrumentation data should be collected four times or more per year. Visual inspections and data collection should also occur during or after a 25-year storm event or larger or other geohazards such as earthquakes that might impact the condition of the dam.

A dam with high hazard potential in a CAUTION condition that is not expected to reach an ALERT condition within the coming year should be visually inspected at least once per week to once per day. Instrumentation data may be collected once per month to once per week. Additional instrumentation may be warranted to better understand how the dam is performing and the cause of anomalous behavior so that mitigation measures can be developed to keep the dam from reaching the ALERT condition. Inspections and data collection should occur with sufficient frequency to allow documentation of the rate of change in the condition of the dam. If the rate of change of the condition of the dam is such that it might enter the ALERT condition, the inspection and data collection frequency should be increased to document the rates of change with enough detail to predict when the ALERT condition will be reached. The monitoring frequency should be sufficient to be able to issue a warning notice as soon as the dam's condition enters the ALERT state.

A dam with high hazard potential in an ALERT condition should be visually inspected at least once per day. Data should be collected from instruments at least once per day or more often depending on the severity of the condition, the potential consequences of a failure and the rate of change of the dam's condition. The observations should be of sufficient frequency that an alarm can be issued whenever failure of the dam becomes imminent. A contingency plan to minimize consequences and reduce the likelihood of failure should be in place and invoked as soon as the dam reaches an ALERT condition if not before.

A high hazard dam in an ALERT state presents a substantial risk to the public and the dam's owner. Well qualified instrumentation specialists and dam engineers must be involved in the evaluation of the collected data and observations. The evaluation must occur often and the entire project team positioned to take risk mitigation measures as soon as they become warranted. Top management should always monitor the progress of a high hazard dam in an ALERT state.

# 9.0 CONCLUSIONS AND FINAL REMARKS

This project, *Dam Safety Performance Monitoring and Data Analysis Management – Best Practices,* was originated by CEATI Dam Safety Interest Group (DSIG) in 2009 with the objective of documenting best practices for dam surveillance, inspection, instrumentation needs and maintenance, data collection, data analysis, and data management for performance and interpretation. This includes identifying the responsibilities of dam owners to keep the risk of dam failure as low as reasonably practical. Key components for managing the overall performance-monitoring program have been identified with emphasis on proper coordination and communication between and among program components, the use of systematic processes for performance monitoring, and the role of performance monitoring as a risk management tool for dam safety. The emphasis is on detecting and preventing potential failure modes that lead to uncontrolled loss of contents from the contained volume, whether it be a dam or other containment structure. Loss of contents defines dam failures and presents the highest risk to a dam owner.

Because of variables associated with different governance models, ownership configurations and capabilities, and the unique characteristics of each owner's dam inventory, there is no one model for an effective performance-monitoring program. However, current practice in dam safety has developed to suggest key elements that should be considered when creating a new or evaluating an existing program. This report summarizes information obtained from a survey of the state-of-the-practice in the literature and from the active engagement of project sponsors who participated in several workshops and who provided considerable input to this document based on their current dam safety performance monitoring programs and experiences.

## 9.1 Responsibilities for Dam Safety Performance Monitoring

Every dam owner should carry out, or participate in, a dam safety program for each dam under its charge. A dam safety program should be developed based on the type of dam, its condition, and its hazard potential. Each dam safety program should have a performance monitoring program that includes, at a minimum, visual inspections of the dam and its surroundings. These visual Observation are then supplemented with physical measurements using instruments where the risk of a failure is significant. Performance monitoring programs for dam safety must be carried out at regular intervals by qualified professionals who know what to look for and how to interpret what they are seeing.

An effective dam safety performance monitoring program aims to keep the risk of dam failure as low as reasonably practicable. One person should be responsible for developing and maintaining the dam safety performance monitoring program. The dam owner is responsible for providing the resources to keep the dam safety performance monitoring program workable and effective.

## 9.2 Role of Monitoring in Dam Safety Programs

Performance monitoring must occur throughout the life of the dam because: (1) failure can occur anytime during the life of a dam, and (2) the probability of failure is higher during the early phase, drops to a steady value over the service life, and climbs again as the dam approaches the end of its working life. Thus performance monitoring is required over the life of a dam to determine whether any condition is developing that might lead to a breach or overtopping of the dam. The results of a performance monitoring program are also very beneficial to selecting cost-effective maintenance and remedial work programs that are effective at managing risk.

The concepts of risk assessment and risk management are introduced as a way to estimate the benefits of a dam safety monitoring program. This approach can provide dam owners with approximate numerical estimates of the reduction of risk that performance monitoring can provide. An example is given showing how a risk assessment might be done for events that lead to loss of containment and complete breach of the dam.

Performance monitoring consists of two components: visual surveillance and monitoring of instruments placed on and within the structure. Visual surveillance provides a low cost source of very valuable information but it can only consider what can be seen from the exposed surface and can be more qualitative than quantitative. Visual surveillance must be done by someone trained in what to look for and how to interpret what they are seeing. Some elements of visual surveillance must be performed by professionals who understand potential failure modes and the mechanics of how dams and other containment structures perform. Monitoring with instruments provides quantitative data over time from points on and within the dam and its foundation. These data can show precise trends and when interpreted can indicate emerging risks and help gage the effectiveness of risk reduction measures.

Instrumentation systems must be designed, installed and maintained with considerable care to be effective. Design of a performance monitoring system for dam safety involves team work among those familiar with the site and its geology, the dam's designers, someone knowledgeable in instrumentation and monitoring, and someone familiar with interactions between construction of the dam and placement and maintenance of the instruments.

Data collected from instrumentation systems must be processed, presented, evaluated and interpreted for it to be of any value. Raw data taken from an instrument is of little value until it is examined and interpreted by a knowledgeable person who knows what the data mean in the context of the dam's safety.

Data and conclusions from performance monitoring systems are of little to no value without a plan to take action when the results show action is needed to restore safety. Every monitoring program needs a contingency plan that can be executed as soon as the monitoring program indicates it is needed. Management must support the development and use of contingency planning and provide the resources for it to be implemented when needed.

The dam owner is responsible for providing the resources necessary to develop and maintain an effective performance monitoring program and ensuring that all inspectors, operators and engineers understand and carry out their roles and responsibilities in a timely manner. The dam owner is responsible for ensuring that preventive and corrective actions are carried out in a timely manner. Simply fulfilling these responsibilities provides a very effective component of risk management.

## 9.3 Coordination of Operations and Dam Safety

Recent dam failures and safety related incidents have shown that most were not caused by a single, easily analyzed, component failure but rather by interactions between various components and subsystems. Both the structural and operational safety of a dam should to be considered together.

As the systems that control our dams get more complex and more automated, and more dams are remotely operated, the opportunities increase for undetected incidents that can lead to dam failure. Understanding factors relating to dam safety, such as owner risk awareness, management responsibility, personnel training, and system and sub-system interactions, become increasingly important. In order to drive the risk associated with our dams to a level that is as low as reasonably practicable, dam owners need to recognize these systemic failure modes prior to an incident or failure. Owners should develop and implement methods to identify early stages of the failure development.

Dam tenders and operators should actively participate with dam safety engineers in dam safety training, inspections, and performance monitoring. Performance monitoring programs for dam safety should take into account not only how dam safety engineers think the dam was designed to perform but also how the dam is actually operated. Coordination between operations and engineering is essential for the success of the performance monitoring program.

## 9.4 Adequacy of the Dam Safety Performance Monitoring Program

The instrumentation and monitoring program should be periodically reviewed to ensure it is sufficient to determine whether the dam is performing as expected and it can warn of developments that could endanger the safety of the dam. The evaluation should include answers to the following three questions.

1) Are the type, number, and location of instruments proper for the behavior being monitored?
2) Is the frequency of readings appropriate?
3) Are the data being collected, processed, and evaluated in a timely and correct manner?
4) Do the results make sense and are they useful to the dam safety program?

Periodic review of the adequacy of the performance monitoring program must also take into account potential failure modes and the periodic updating of identified potential failure modes as failure modes might be eliminated, new ones identified, or those previously identified modified because of new information.

## 9.5 The Future of Performance Monitoring for Dam Safety

This report provides best practices to develop and implement a performance monitoring program as part of an overall dam safety program to help dam owners manage risk. Various regulatory standards have been developed over many years in an attempt to create favorable performance and exclude unfavorable performance of dams. Dam owners must comply with all regulatory requirements that apply to their dam. Generally these are minimum standards-based-criteria for the stability of individual dam components. However adherence to these requirements does not necessarily control risk associated with a dam failure.

Dam owners have an inherent interest in reducing the risk associated with dams to a level that is as low as reasonably practicable. This requires evaluating the dam as a complex system with interactions of sub-systems that may be difficult to recognize. In recent years, awareness has developed that monitoring individual components against standards-based-criteria is insufficient to assure the safety of dams. In order to continue to accrue the benefits provided by dams, dam owners should continually seek opportunities to identify places where risk can be reduced in a cost effective and timely manner. Effective performance monitoring can be an important element in this process.

Performance monitoring procedures need to change with technological advancement and with the life cycle of the dam. Dam owners have an obligation to ensure that observed deficient practices are corrected and that successful practices are used. It is important for dam owners to continuously re-evaluate their current dam safety policies and procedures based on the history of dam failures and incidents. When we monitor the performance of dams for potential safety related defects, we should consider how the dam might fail. This includes consideration of potential chain of events and interactions that could lead to a failure including the influence of electrical, mechanical, control systems, debris build up, etc.

## 9.6 What Every Dam Owner Should Know

The primary objective of a dam safety program is to ensure the integrity and viability of a dam such that it does not present unacceptable risk to the public, property, the environment and the owner. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe functioning is not explicitly determined by its original design and construction.

Failure of a dam can have major consequences to the public and the owner of dam. ***Section 2*** provided some representative examples, including ones where failure of relatively small dams took the lives of many people. In order to reduce risk of dam failure as low as reasonably practical, every dam owner should develop and maintain an effective dam safety performance monitoring program. The program should include regular visual surveillance combined with monitoring instrumentation as complementary components. It is important to the success of the monitoring program to use a systematic process to design, install and operate a performance monitoring program with every instrument designed to help answer a specific question that relates to the risk posed by the dam.

The current goal of government agencies involved in dam safety is to reduced the potential from loss of life from a dam failure to zero. Risk assessment coupled with a well executed performance monitoring program provide a systematic and cost effective way to help dam owners achieve this goal.

Dams constructed many years ago, as well as some constructed in recent years, may have been designed and constructed without the benefit of current understanding of state-of-practice for dam safety. Due to the many uncertainties that affect dam performance even modern designs may be constructed with deficiencies or give surprising performance. In all cases, Owners should assess current thinking in defensive design measures to determine if potential risks may need to be reduced or eliminated. Additional instrumentation and investigations may be needed to answer these unknowns.

An effective dam performance monitoring and data management program will result in a better understanding of potential failure modes. Regular observations, evaluations, and studies that indicate dam safety and maintenance issues can be organized in a database and risk ranked across the portfolio of dams to prioritize maintenance and remedial work. As such, performance monitoring as input to risk assessment program can provide a very effective tool to determine where best to spend money to manage risk.

The dam Owner's should develop a culture of dam safety awareness throughout the organization. Everyone involved in the operation, maintenance, and performance monitoring of the dam should understand the dam safety program, the performance monitoring program, and the triggers that require action responses. The need for and value of ongoing maintenance and upgrade programs for performance monitoring systems cannot be underestimated. Maintenance includes periodic calibration of instruments, cleaning, repair, or replacement when necessary. Advances in instrumentation and monitoring equipment and technology should be periodically considered to enhance existing monitoring programs. Periodic training of people responsible for every aspect of dam safety performance monitoring should be a priority.

Regardless of the regulatory framework under which a dam is being operated, the dam Owner is ultimately responsible for its safe operation. The Owner should act on all dam safety related findings in a prompt manner in order to reduce risk as low as reasonably possible.

Dam owners have legal, moral and ethical responsibilities to operate and maintain their dams in a safe condition. An effective performance monitoring program that puts the contents of this document into practice will help owners meet these responsibilities.

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## GLOSSARY OF TERMS

The purpose of this glossary is to define the common terms used for dams and water resources development and management. It consists of two parts. The first part defines common abbreviations. The second part defines terms. The terms are generic and applicable to all dams, regardless of size, owner, or location. The terms are listed in alphabetical order. Some of the definitions are similar to or modified versions of definitions found in documents by the USACE, FERC and ICOLD.

### 1. Abbreviations

AAR Alkali-Aggregate Reaction, same as ASR or Alkali-Silica Reaction

ADAS Automated Data Acquisition System

ALARP As Low as Reasonably Practicable

ASCE American Society of Civil Engineers

ASDSO Association of State Dam Safety Officials

CDA Canadian Dam Association

CEATI Centre for Energy Advancement through Technological Innovation

COE Corps of Engineers

DHS Department of Homeland Security

DSIG Dam Safety Interest Group

DSO Dam Safety Officer

EAP Emergency Action Plan

FEMA Federal Emergency Management Agency

FERC Federal Energy Regulatory Commission

GIS Geographical Information Systems

ICODS Interagency Committee on Dam Safety

ICOLD International Commission on Large Dams

MCE Maximum Credible Earthquake

MDE Maximum Design Earthquake

NDSRB National Dam Safety Review Board

NEPA National Environmental Policy Act

O&M Operation and Maintenance

P&S Plans and Specifications

PFM Potential Failure Modes

PFMA Potential Failure Modes Analysis

PMF Probable Maximum Flood

PMP Probable Maximum Precipitation

QA Quality Assurance

QC Quality Control

SDF Spillway Design Flood

SEE Safety Evaluation Earthquake

SEF Safety Evaluation Flood

USACE United States Army Corps of Engineers

USCOLD U.S. Committee on Large Dams (Renamed United States Society on Dams, USSD)

USBR U.S. Department of the Interior Bureau of Reclamation

USDOT United States Department of Transportation

USSD United States Society on Dams

## 2. Definition of Terms

**Abutment** is that part of the valley side against which the dam is constructed. An artificial abutment is sometimes constructed, as a concrete gravity section, to take the thrust of an arch dam where there is no suitable natural abutment. The left and right abutments of dams are defined with the observer viewing the dam looking in the downstream direction, unless otherwise indicated.

**Accelerographs** are accelerometers having provisions for recording the acceleration of a point on the earth during an earthquake.

**Accuracy** in dam safety monitoring is the quality or state of being accurate. It involves performing with care and precision to provide a correct reading or measurement.

**Acre-foot** is a unit of volumetric measure that would cover one acre to a depth of one foot. It is equal to 43,560 cubic feet ($ft^3$) or 1,233.6 cubic meters ($m^3$).

**Adverse consequence** is the outcome of the failure of a dam or its appurtenances, including immediate, short and long-term, direct and indirect losses and effects. Loss may include human casualties, project benefits, monetary and economic damages, and environmental impact. (Adapted from USACE)

**Afterbay** is a reservoir at the end of the channel, pipe line, penstock or tunnel that is used to store water.

**Alert Performance State** is a condition where the dam's performance is in a range where safety of the dam is in question, or performance is deteriorating and not controllable. (Also see **Normal Performance State** and **Caution Performance State** for the other two conditions.)

**Alignment surveys** involve the placing of survey points along a straight line or other specific line on the structure.

**Alkali-Aggregate Reaction (AAR)** is a chemical reaction of an aggregate with the alkali in cement resulting in weakening of the concrete.

**Annual Probability of Failure** is the estimated probability of failure of a dam per year from all causes that result in an uncontrolled release of water.

**Appurtenant structures** are the other features of a dam project such as the control rooms, outlet conduit, outlet tunnel, spillways, penstocks, tunnels, power plants, etc.

**Aqueduct** is a bridge built to carry water across a valley.

**Arch dam** is a concrete, masonry, or timber dam with the alignment curved upstream so as to transmit the major part of the water load to the abutments.

**Ash Pond** (see coal refuse disposal facilities)

**Auxiliary spillway** is a term used to identify a second spillway if it exists on a dam as opposed to the primary spillway.

**Axis of dam** is a plane or curved surface, arbitrarily chosen by a designer, appearing as a line in the plan or cross section to which the horizontal dimensions of the dam can be referred.

**Base width** (base thickness) is the maximum width or thickness of a dam measured horizontally between the upstream and downstream faces and normal to the axis of the dam but excluding projections for outlets and generally associated with contact area between the dam and foundation materials.

**Bedrock** is any continuous solid rock of sedimentary, igneous, or metamorphic material represented as a unit in geology; being a sound and solid mass, layer, or ledge of mineral matter.

**Berms** are a horizontal step or bench in the sloping profile of an embankment dam and are used to add stability to the dam.

**Borrow area** is the area from which natural materials, such as rock, gravel or soil, are excavated to construct the dam and related facilities.

**Breach** is an opening through a dam that allows uncontrolled release of water of other retained materials.

**Buttress dam** is a dam consisting of a watertight part supported at intervals on the downstream side by a series of buttresses. Buttress dam can take many forms, such as a flat slab or massive head buttress.

**Channel** is a general term for any natural or artificial facility for conveying water.

**Calibration** means to determine, by measurement or comparison with a standard, the current value of each scale reading on a meter, sensor, or other device.

**Caution Performance State** is the condition where the dam's performance is outside the range expected in the design, or anomalous behavior not anticipated in the design is occurring, or an indicator of undesirable performance is occurring at an increasing rate. (Also see **Alert Performance State and Caution Performance State** for the other two conditions.)

**Chimney Drain** is a vertical or inclined layer of pervious material in an embankment dam to collect and removed water that flows through the earthen materials upstream of the drain.

**Cohesionless** is a term referring to soil that consists primarily of silt or larger grain sizes that form individual particles when dried.

**Cohesive soils** are very fine-grained unconsolidated earth materials that clump together into clods when dried.

**Cofferdam** is a temporary structure enclosing all or part of the construction area such that construction within the cofferdam can proceed in the dry. A diversion cofferdam diverts a stream into a pipe, channel, tunnel, or other watercourse so that the original streambed can be dried for construction of the dam.

**Compaction** is the mechanical action that increases the density of earth and rock fill by reducing the voids in a material.

**Conduit** is a closed channel to convey water through, around, or under a dam.

**Construction joint** is the interface between two successive pours of concrete where a bond, and not permanent separation, is intended.

**Core** is a zone of low permeability material in an embankment dam to form a seepage barrier. The core is sometimes referred to as central core, inclined core, puddle clay core, rolled clay core, or impervious zone.

**Core wall** is a wall built of impervious material, usually concrete, asphaltic concrete or bentonite, in the body of the embankment dam to form a seepage barrier.

**Cutoff** is an impervious construction of material, which reduces seepage or prevents it from passing through foundation material or dam.

**Cutoff trench** is an excavation that is filled with impervious material to form a seepage barrier.

**Crack meter** is a device that measures the change in width of a crack.

**Creep** is a time-dependent permanent strain of solids caused by stress.

**Crest length** is the measured length of the dam along the crest or top of dam from the left abutment to the right abutment.

**Crest of dam** is the flat top of the dam. It normally contains a foot path or roadway.

**Crest wall** is a wall built of impervious material, usually concrete, on the crest of the embankment dam to increase the effective height of the dam.

**Crib dam** is a gravity dam built of boxes, cribs, crossed timbers, or gabions and filled with earth or rock.

**Cross section** is the elevation view or section of a dam formed by passing a plane through the dam perpendicular to the axis.

**Dam** is defined in this document as a structure that impounds fluids, usually water, and fluid bearing materials behind a barrier . Types of dams include boat locks, weirs, mine tailings dams, and levees. Types of dams include Afterbay, Ambursen, Arch, Buttress, Cofferdam, Crib, Diversion, Double Curvature Arch, Earth, Embankment, Gravity, Hollow Gravity, Hydraulic Fill, Impoundments, Industrial Waste, Masonry, Mine Tailings, Multiple Arch, Overflow, Regulating, Rockfill, Roller-compacted Concrete, Rubble, Saddle and Tailings. Fluid bearing materials include tailings, slurries, and industrial wastes.

**Dam failure** is any event that results in the uncontrolled release of stored materials, usually water, from the dam to the downstream area.

**Dam incident** is any unexpected event resulting from natural causes or human actions that could impact the performance or safety of the dam.

**Dam safety** is the art and science of ensuring the integrity and viability of a dam such that it does not present unacceptable risk to the public, property and the environment. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe functioning is not explicitly determined by its original design and construction. (USACE)

**Dam safety issue** is any issue that could result in the uncontrolled release of stored materials from the dam to the downstream area.

**Dam safety monitoring** is the art of monitoring the performance of structures and other engineering works by combining visual observations and physical measurements of displacements, cracks, stress, pressure, force, fluid flows and vibrations to access the performance of the dam relative to design expectations.

**Dam safety program** aims to protect life, property, and the environment by ensuring that a dam is designed, constructed, operated, and maintained as safely and effectively as is reasonably possible. It consists of activities to continually inspect, monitor, evaluate and document the design, construction, operations, maintenance, rehabilitation and emergency preparedness of each dam and the associated public. (USACE)

**Dam safety surveillance** is the close visual monitoring of a dam, its foundation, abutments and related facilities for indications of unexpected or undesirable performance, including documenting the observations, evaluating their significance and invoking protective measures if warranted.

**Data logging** is the automatic conversion of a sensor's output to digital data that can be stored in various types of memory for later retrieval.

**Deformations** are any alteration of shape, dimensions, or position of a body.

**Dental work** is the removal of loose rock and soil from a dam's abutments or foundation contact area to expose clean, sound rock and to fill irregular surfaces with cement grout or concrete to create a sound surface on which to construct the dam.

**Dewatered** is an area, which previously contained water that has been.

**Diaphragm wall** is a sheet, thin zone, or facing made of an impervious material such as concrete, steel, wood, or plastic used to form a seepage barrier and control pore pressures downstream of the wall.

**Differential movement** is the difference in movement between two objects or points.

**Dike** is a long embankment with no appurtenances.

**Divert** means to make go another way and usually applies to making water take a course around its normal channel.

**Diversion dam** is a dam built to divert water from a waterway or stream into a different watercourse so the main dam can be constructed in the former water channel.

**Diversion channel**, canal, or tunnel is a waterway used to divert water from its natural course to an alternate path.

**Drainage area or catchment area** is the area that drains to a particular point on a river or stream (expressed in square miles or square kilometers).

**Drainage layer or blanket** is a horizontal layer of permeable material placed at the base of the dam downstream of the core to facilitate drainage of fill and dam foundation and prevent buildup of pore water pressure downstream of the core.

**Drainage well (relief well)** a bore hole filled with a pipe surrounded with sand or gravel, usually downstream of impervious cores, grout curtains or cutoffs, that is designed to collect and direct seepage through or under a dam and reduce pore water pressure within the dam, its foundation or its abutments.

**Drawdown** is the lowering of the reservoir level.

**Double curvature arch dam** is a concrete dam that is curved in its vertical and horizontal planes.

**Earthfill dam** is an embankment dam that derives its stability from the weight of compacted earth.

**Earthquake** is a sudden vertical and horizontal motion or trembling in the earth caused by the abrupt release of accumulated stress along a fault. **Maximum Credible Earthquake** is the most severe earthquake that can be expected to occur at the site on the basis of geologic and seismological evidence. **Maximum Design Earthquake** is a postulated seismic event used to evaluate the seismic resistance of the site, the dam and related features. **Operating Basis Earthquake** is the earthquake for which the facility is designed to resist and remain operational.

**Embankment** is a body of earth, or rock fill, with side slopes and a length several times greater than its height.

**Embankment dam** is any dam that derives its stability from the weight of the earth and rock materials used to construct the dam.

**Emergency** is a condition, which develops unexpectedly, endangers the structural integrity of the dam and/or downstream property, life or environment and requires immediate action.

**Emergency Action Plan** is a set of detailed instructions for agencies and individuals to respond to emergencies such as a potential dam failure.

**Equipotential lines** represent surfaces on which the water potential (pressure + elevation head) is the same at every point. Points along an equipotential line have the same potential energy.

**Erosion** is the wearing away of a surface such as the bank, streambed, embankment, or other surface by the flow of water or air.

**Extensometer** measures the change in distance between two anchored points.

**Evaporate** is the process of changing liquid into a gas or vapor which is incorporated into the air.

**Failure**, in the context of dam safety, is defined as any event that results or could result in the uncontrolled release of water and other contained materials.

**Failure mode** is any way that failure can occur.

**Failure surface** is the surface within the dam or through the foundation or abutments on which the overlying materials slip to create significant down slope movement.

**Fetch** is the straight-line distance over a body of water traversed by wind without obstruction.

**Field Instrumentation** is the collection of devices that are used to measure displacements, cracks, stress, pressure, force, fluid flows and vibrations to access the performance of the dam relative to design expectations.

**Flood** is a temporary rise in water surface elevation of a stream or river as a result of significant rainfall in the drainage area. It results in inundation of areas not normally covered by water.

**Flood, Inflow Design (IDF)** is the flood used to design the dam and its related structures, particularly for sizing the spillway and outlet works, determining the volume of temporary storage and establishing the height of the dam.

**Flood, Probable Maximum (PMF)** is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.

**Flood plain** is the area adjoining a body of water or natural stream that may be covered by floodwater. It is also used to describe the downstream area that would be inundated or otherwise affected by the failure of a dam or by large flood flows.

**Flood storage** is the retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

**Flume** is an open channel constructed of concrete, steel or wood used to convey water.

**Fly ash** is a fine particulate, essentially noncombustible refuse carried in a gas steam from a furnace.

**Foundation** is that portion of the valley floor that underlies and supports the dam structure.

**Forebay** is a small reservoir at the head of the pipe line, penstock or tunnel.

**Freeboard** is the vertical distance between a design water level and the top of the dam.

**Gabions** are baskets of wickerwork, strap iron or wire filled with rock used to construct revetments or walls.

**Gage,** or **gauge,** are interchangeable terms for an apparatus that measures something with a graduated scale.

**Gate** is a movable water barrier for the control of release of water. There are multiple types of gates including Bascule, Bulkhead, Crest, Drum, Emergency, Fixed wheel, Fixed roller, Fixed axle, Flap, Flood, Outlet, Radial, Regulating, Skimmer, Slide and Tainter.

**Generator** is the machine that produces electricity from the pressure of water or steam.

**Geosynthetic** is a woven or unwoven fabric or membrane, usually plastic, used to strengthen embankments (geogrid), reduce erosion (geotextile), prevent loss of fines from soil (geotextile), separate one earth material from another (geotextile), promote drainage (geotextile or geocomposite) or create an impermeable barrier (geomembrane or geosynthetic clay liner).

**Graded filters** are a collection of layers of soil and rock with each layer having a larger grain size to allow the controlled release of water without the loss of soil particles.

**Gravity dam** is a dam constructed of concrete and/or masonry, earth and/or rock which relies on its weight and internal strength for stability.

**Groin** is the area along the contact of the face of the dam and its abutments.

**Grout blanket** is a shallow band of drill holes grouted with concrete to consolidate a foundation.

**Grout** is a fluidized mixture of materials (cement and water with other additives, chemical, clay or bitumen) that is injected into soil, rock, concrete and other construction materials to seal openings, reduce flow or increase structural strength.

**Grout curtain** is one or more rows of closely spaced drilled holes used to inject grout under pressure to fill cracks and voids and form a seepage barrier under or within a dam.

**Hazard** is anything that has the potential to harm a valued asset including life, environment, man-made improvements and social setting.

**Hazard potential** is the potential consequence of the failure of a dam or its appurtenances, including immediate, short and long-term, direct and indirect losses and effects. Losses may include human casualties, project benefits, monetary and economic damages, and environmental impact. (Adapted from USACE)

**Head** is the vertical distance from a point to the height that water rises above that point, expressed in feet or meters. See pressure head and total head.

**Headwater** is the elevation of the free water surface on the upstream side of the dam. It is the elevation of the water body retained by the dam.

**Height** of a dam is vertical distance between the lowest point on the crest of the dam and the lowest point in the original streambed. Structural height is the vertical distance between the lowest point of the excavated foundation to the top of the dam.

**High Hazard Potential** indicates a condition where a dam is located in an area where failure may cause loss of human life, substantial damage to homes, industrial or commercial buildings, important public utilities, main highways or railroads, and/or will cause extensive economic loss or environmental damage.

**Homogeneous earthfill dam** is an embankment dam constructed of similar earth material throughout, except internal drains or drainage blankets are sometimes used.

**Hydraulic fill dam** is an embankment dam constructed of earthen materials that are conveyed and place by flowing water.

**Hydraulic fracture** is when the pore water pressure at a point in soil or rock exceeds the minor principle stress in the soil and causing the formation of a crack.

**Hydrology** is the study of water and its properties with respect to its distribution and movement in and through the land areas of the earth.

**Hydrometeorology** is the study of the atmospheric and land-surface phases of the hydrologic cycle with emphasis on the interrelationships involved.

**Hydrograph is** a graphical representation of stage, flow, velocity, or other characteristics of water at a given point as a function of time.

**Hydrostatic pressure**, also known as the gravitational pressure, is the pressure at a point in a fluid due to the weight of the fluid above it. It is also called pressure head when expressed as feet or meters of water.

**Impermeable liner** is a liner, usually man made, that prevents flow of water through the material.

**Impervious soil** does not permit water to pass through. (All materials allow some amount of water flow but a material with permeability less than $10^{-7}$ cm/sec is generally considered as impermeable.)

**Incident** is an event that could potentially result in a dam safety issue. Examples include spillway flood, earthquake, component failure and operational error. Each incident should be investigated, evaluated and documented.

**Inclinometer** is an instrument for measuring the angle of deflection between the vertical direction of gravity and the sensor orientation. An inclinometer probe is passed through a vertical casing installed in a boring to measure horizontal movement with depth below the ground surface. An inclinometer probe may be pulled through a horizontal casing installed in a trench to measure settlement cause by filling over the casing.

**Inclinometer casing** is a specially constructed casing that has slots or channels that keep a probe type inclinometer oriented in a fixed direction when passed from one end of the casing to the other.

**Inflatable dam** consists of a sealed, inflatable, rubber-coated fabric tube anchored to a concrete foundation constructed across a watercourse, usually the spillway for a dam application. It is raised by inflating with air, water, or a combination of the two. When it is inflated, it impounds water and acts like any other dam. However, it is capable of being completely deflated to allow maximum runoff during a storm, thereby reducing upstream flooding, and to allow passage of sediment, debris, and ice.

**Initial filling** usually refers to first filling of a reservoir or other water conveyance feature.

**Interagency Committee on Dam Safety**, ICODS, which was established in 1980, encourages the establishment and maintenance of effective federal programs, policies, and guidelines to enhance dam safety and security. ICODS serves as the permanent forum for the coordination of federal activities in dam safety and security. FEMA also chairs ICODS. ICODS agencies:

- Department of Agriculture
  - Agricultural Research Service
  - Natural Resources Conservation Service
  - Forest Service

- Department of Defense, Army Corps of Engineers
- Department of Energy
- Department of the Interior
    - Bureau of Indian Affairs
    - Bureau of Land Management
    - Bureau of Reclamation
    - Fish and Wildlife Service
    - National Park Service
- Department of Labor, Mine Safety and Health Administration
- Federal Energy Regulatory Commission
- Department of State, International Boundary and Water Commission
- Nuclear Regulatory Commission
- Tennessee Valley Authority

**Instrumentation** refers to an arrangement of measurement devices into a dam, its foundation and its abutments to provide measurements of performance over time to evaluate the structural behavior and performance parameters of the structure. Typical devices used in dams include settlement points, movement points, crack gages, inclinometers, piezometers, strain gages, thermisters or thermocouples, tilt meters, and others.

**Intake** is the structure placed at the beginning of an outlet-works waterway (power conduit, water supply conduit or diversion tunnel).

**Intermediate Hazard Potential** describes a condition where a dam is located in an area where failure may damage isolated homes, main highways, minor railroads, interrupt the use of relatively important public utilities and/or will cause substantial economic loss or substantial environmental damage.

**Inverted pendulum** is a pendulum that is anchored at its lower extremity with a thin wire connected to the upper floated end which is able to move freely in a horizontal plane to reach a state of plumbness or vertical. It is used to measure the horizontal movement of the dam at the level of the float relative to the horizontal movement at the anchored end.

**Irrigation dam** is a dam whose primary function is to supply agriculture water.

**Joint meter** is a device used to measure the relative movement of one side of a joint in concrete or any other material relative to the other side of the joint.

**Lateral translation** is the horizontal movement of all or a portion of the dam cross section.

**Leakage** is water moving through a dam, its foundation or its abutments.

**Levee** is an embankment whose primary purpose is to furnish flood protection from seasonal high water.

**Lift** is the vertical distance measured in feet or meters between successive placements of concrete, soil or rock layers.

**Limit Level** is the instrumentation reading that triggers actions to reduce the excessive readings or otherwise modify the dam to restore a safe performance state.

**Liquefaction** is condition caused by a sudden change in shear stress (from earthquake shaking, blasting or a sudden increase in slope geometry) that causes a soil to try to densify. A saturated soil cannot densify immediately so pore water pressures increase immediately and reduce effective stresses to near zero. This causes the soil's shear strength to decrease to such low values that it starts to behave like a fluid with no shear strength and results in stability failures and large deformations.

**Longitudinal cracking** is cracking of a dam parallel to the axis (or long side) of a dam.

**Length of dam** is the distance from natural material on one side of the dam to natural material on the other side of the dam measured at the crest of the dam.

**Likelihood** is used as a qualitative description of probability or frequency of occurrence of a particular event.

**Low Hazard Potential** describes a condition where a dam is located in an area where failure will damage nothing more than isolated buildings, undeveloped lands, or town or county roads and/or will cause no substantial economic loss or substantial environmental damage.

**Low level outlet** is a conduit at a low level from a reservoir generally used to empty a reservoir, release sediment, or augment downstream flows from the dam. It is sometimes used for irrigation releases and power generation.

**Masonry dam** is any dam constructed mainly of stone, brick, or concrete blocks pointed with mortar. A dam having only a masonry facing should not be referred to as a masonry dam.

**Maximum pool** is the highest reservoir elevation resulting from the inflow design flood.

**Maximum section** is the highest cross section of the dam having the greatest difference between the downstream bottom of the dam and its crest.

**Membrane dams** are dams that are usually constructed of a thin membrane such as rubber or neoprene that is filled with air, water or both.

**Measurement range** is the difference between the highest and lowest values that an instrument is designed to measure.

**Minimum operating level** is the lowest level to which the reservoir is drawn down under normal operating conditions.

**Mitigation** is the implementation of measures to reduce the likelihood of a risk event occurring or lower the consequences if the event should occur, or both.

**Multiple arch dam** is a buttress dam comprised of a series of arches along the length of the dam.

**Meteorology** is the science that deals with the atmosphere and atmospheric phenomena, the study of weather, particularly storms and the rainfall they produce.

**Metrology** is the art of taking physical measurements.

**Minimum operating level** is the lowest level to which a reservoir is drawn down during normal operating conditions. It is the lower limit of active storage.

**Multipurpose project** is a project designed for irrigation, power, flood control, transportation, municipal and industrial supply, recreation, and environmental benefits, in any combination of two or more.

**Nappe** is the intersection of a sheet of water flowing over a barrier and the crest of the barrier.

**Normal Operations** is the loading on the dam resulting from day-to-day pool operations to achieve authorized purposes. For purposes of screening analysis for dry dams, or where pool elevations fluctuate widely and no historical normal pool elevation has been established, the normal loading is usually correlated to a 1 to 10 year return period.

**Normal Performance State** is the condition where the dam's performance is within the design parameters with no anomalous behavior and no indicators of undesirable performance. (Also see **Alert Performance State** and **Caution Performance State** for the other two conditions.)

**Observation well** is a small diameter vertical well drilled in a selected location for the purpose of observing change of groundwater level or groundwater quality over time.

**Open standpipe piezometers** are open pipe or tubes that extend from the bottom screen placed in a soil stratum to the ground surface with a bentonite clay or grout seal placed just above the top of the screen to isolate the reading of water pressure head to just the zone of the screen.

**Operation Restrictions** are changes to operating pool levels and durations, or reduced lockages, power generation, water supply, or conservation operations to maintain safety of the dam.

**Outlet** is an opening through which water can be discharged from a reservoir.

**Outlet works** are facilities of a dam that provide for the controlled release of water from a reservoir.

**Overtopping** usually refers to flood waters passing over the top of the dam.

**Parapet wall** is a solid wall built along the top of a dam used for safety of vehicles and pedestrians, prevention of overtopping by wave run up or for ornamentation.

**Parshall flumes** are a calibrated device for measuring the flow of water in open conduits by measuring the upper and lower heads at a specific distance from an obstructing sill.

**Peak flow** is the maximum instantaneous discharge that occurs during a flood. It is coincident with the peak of a flood hydrograph and is expressed in cubic feet per second (cfs) or cubic meters per second (cms).

**Pendulum** is a rigid body mounted on a fixed horizontal axis, about which it is free to rotate under the influence of gravity in dams, the same as a plumbline.

**Penstock** is a pressurized pipeline or shaft between the reservoir and hydraulic machinery. It is a closed water conduit controlled by valves and located between the intake and the turbine of a hydroelectric unit.

**Performance** is the functioning of a structure in physical terms, such as how much the crest of the dam displaces when the reservoir is filled.

**Performance Evaluation** is a description of how the dam and appurtenant structures have functioned over time. It is based on visual observations and measurements from instrumentation that are compared with the design expectations with reasons for differences explained and their importance to the future safety of the dam discussed.

**Performance Monitoring** encompasses metrology, field instrumentation, monitoring, and surveillance to collect visual observations and data to document the functioning of a dam and related structures over time.

**Performance Monitoring Program** is a systematic process of performance monitoring that includes close visual inspections and instrumentation to document, analyze, evaluate and report the functioning of a dam and its related components over time and make recommendations to improve that performance.

**Performance States** are used to define the status of a dam safety monitoring program element. These states can be *NORMAL, CAUTION, or ALERT.*

**Phreatic line** is a water surface at which the pore water pressure equals zero. Below the phreatic surface, soils are assumed to be saturated. Above the phreatic surface, soils contain both gas and water within the pore spaces.

**Phreatic surface** is the planar surface between the zone of saturation and the zone of aeration, also known as free-water surface, free-water elevation, groundwater surface, groundwater table.

**Phreatic line** is the elevation to what water would rise across a soil or rock layer. It is determined from a flow net. Every situation with flow has multiple phreatic lines.

**Piezometer** is an instrument for measuring fluid pressure (air and water) within the voids of soil, rock or concrete.

**Piezometric Head** is the elevation to what water rises from a given point.

**Piezometric Surface** is the elevation of water head (Total head) along a horizontal line.

**Piping** is the progressive development of internal erosion by seepage, appearing downstream as a hole or seam discharging water that contains soil particles.

**Plumbline** is a weighted line (usually a wire) that is suspended vertically from a fixed point in a structure so that relative horizontal deflections between the fixed points of suspension to the point of the plumb bob.

**Pneumatic piezometers** consist of a porous filter connected to two tubes, which have a flexible diaphragm between. The gas pressure required to open the flexible diaphragm and let gas flow out the second tube equals the piezometric head at the sensor tip.

**Pore pressure** is the interstitial pressure of fluid (air or water) within a mass of soil, rock, or concrete.

**Potential Failure Mode** is any means by which any component of a dam may fail to perform its intended function.

**Precision** is the closeness of agreement among a series of individual measurements. Precision is often, but not necessarily, expressed by the standard deviation of the measurements.

**Pressure Head** is the pore pressure at a given point expressed in feet or meters of water.

**Probability** is the numerical measure of likelihood, chance, or degree of belief that a particular event will occur. Probability is expressed as a value between 0 and 1.

**Probability of failure** is the probability that a potential failure mode will occur.

**Probable Maximum Flood (PMF)** is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.

**Probable Maximum Precipitation (PMP)** is theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location during a certain time of the year.

**Rain gage** is an instrument designed to collect and measure the amount of rain that has fallen, also known as ombrometer, pluviometer, or udometer.

**Redundancy** is the duplication of critical components of a system with the intention of increasing the reliability of the system.

**Refuse Disposal Facilities** (ash ponds) are used to dispose of unusable materials from mining. The unusable materials are used to construct an outer face and top berm to retain the unusable solids, liquids and water. The result is a dam that increases in height as more unusable materials are added. At some sites refuse impoundments also serve secondary purposes such as providing water storage capacity for material processing and flood attenuation.

**Relative density** is the density of soil material with reference to its maximum possible density for a given compaction effort. Relative density can be expressed as a percentage of the maximum possible density, or using descriptive terms such as “loose”, “medium”, or “dense”.

**Reliability** is defined as the likelihood of successful performance of a given project element. It may be measured on an annualized basis of for some specified time period of interest or, for example, in the case of spillway gates, on a per demand basis. Mathematically, reliability = 1 – Probability of unsatisfactory operation.

**Remediation** is the implementation of structural and non-structural measures that resolve Dam Safety issues.

**Repeatability** is the ability of a device to produce the same value when specified parameters are independently adjusted under stated conditions of use.

**Reservoir** is the body of water impounded by a dam and in which water can be stored.

**Reservoir drawdown** is the process of draining a reservoir of water.

**Reservoir regulation** is the process of the compilation of operating criteria, guidelines, and specifications that govern the storage and release function of a reservoir. It may also be referred to as the flood control diagram, or water control schedule. These are usually expressed in the form of graphs and tabulations, supplemented by concise specifications and are often incorporated in computer programs. In general, they indicate limiting rates of reservoir releases required or allowed during various seasons of the year to meet all functional objectives of the project.

**Reservoir rim** is the water surface boundary of the reservoir including all areas along the valley.

**Reservoir surface area** is the area covered by a reservoir when filled to a specified level, usually expressed in square miles ($mi^2$) or square kilometers ($km^2$) at the normal operating pool level.

**Reservoir Storage** is the retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel, usually expressed in acre-feet (ac-ft) or cubic meters ($m^3$). Definitions of specific types of storage in reservoirs are:

> **Active storage** is the volume of the reservoir that is available for some use such as power generation, irrigation, flood control, water supply, etc. The bottom elevation is the minimum operating level.
>
> **Dead storage** is the storage that lies below the invert of the lowest outlet and
>
> that, therefore, cannot readily be withdrawn from the reservoir.
>
> **Flood surcharge** is the storage volume between the top of the active storage
>
> and the design water level.
>
> **Inactive storage** is the storage volume of a reservoir between the crest of the invert of the lowest outlet and the minimum operating level.
>
> **Live storage** is the sum of the active-and the inactive storage.

**Reservoir capacity** is the sum of the dead and live storage of the reservoir.

**Resilience** is the ability of a structure to recover from the effects of adversity, for example the ability of a dam to return to generating power after a design flood event.

**Residual risk** is the remaining level of risk at any time before, during and after a program of risk mitigation measures has been taken.

**Repeatability** is the smallest reading that can be reproduced in multiple readings and usually reflects the stability of the device.

**Reliability** is the stability of the readings from an instrument over time

**Resolution** is the smallest increment in measurement that can be distinguished.

**Risk** is the product of probability of failure and severity of adverse consequences.

**Risk analysis**, or risk assessment, is a systematic decision-making methodology that identifies potential risk sources or events and assesses the likelihood and consequence of each.

**Risk communication** is an open exchange of information about risks to better understand risk and its implications so that informed risk management decisions can be made and implemented.

**Risk exposure** is the population, infrastructure, environment and other valued resources that would be adversely impacted by risk events.

**Risk management** is a process of identifying, analyzing, managing, monitoring and communicating risk to achieve the lowest practical residual risk for a project.

**River basin or watershed** is the area drained by a river or river system or portion thereof. The watershed for a dam is the drainage area upstream of the dam, expressed in square miles ($mi^2$) or square kilometers ($km^2$)

**Risk Reduction Measures** are measures taken to reduce the probability of failure or the consequences of failure.

**Rockfill dam** is an embankment dam in which more than 50% of the total volume is comprised of compacted or dumped cobbles, boulders, rock fragments, or quarried rock generally larger than 3-inch size.

**Rolled-earth embankment** is an embankment dam of earth or rock in which the material is placed in layers and compacted by using rollers or rolling equipment.

**Roller compacted concrete dam** is a concrete gravity dam constructed by the use of a dry mix concrete transported by conventional construction equipment and compacted by rolling, usually with vibratory rollers.

**Safe** means that the dam has little or no chance of dam failure and it meets all required regulatory guidelines and criteria. (**Unsafe** means that there is an unacceptable chance of dam failure.)

**Safety program** is a systematic process to gather, evaluate and report data on the functioning of a dam and its related facilities over time; to determine when the functioning of the dam is unacceptable; and to take action to restore the dam to an acceptable performance state.

**Scour** is an erosion process resulting from the action of the flow of air, ice, or water.

**Seepage** is the slow movement of water or other liquid through a porous medium such as through a dam, its foundation or abutments.

**Seepage path** is the general path that the seepage follows.

**Seepage quality** is a measurement of the turbidity and/or level of dissolved solids in the seepage water.

**Seepage quantity** is a measurement of the seepage, usually in gallons per minute or cubic feet per second.

**Seismic response** is the vibration response of a dam to earthquake shaking. Generally, seismic response is measured by the distribution of peak acceleration of cyclic shear stress throughout the cross section of the dam, or the maximum acceleration measured at the crest of the dam.

**Seismic risk** is an assortment of earthquake effects that range from ground shaking, surface faulting, and land sliding to economic loss and casualties.

**Sensor** is a device that responds to a physical stimulus and transmits a resulting signal. Often used interchangeably with 'transducer.'

**Settlement** is a decrease in the elevation of the dam surface. Settlement can be general, across the entire dam and generally maximum at the maximum section.

**Settlement gauge** is an instrument that measures elevation changes between two or more points.

**Shear strength** is the ability of a material to resist forces tending to cause movement along an interior planer surface.

**Shear zone** is the thickness within a material when the shear strength has been exceeded and permanent deformation (sliding) has occurred.

**Single purpose project** is a project that provides a single purpose, such as navigation only.

**Signal conditioning** is when electronic circuitry is used for converting transducer outputs into signals suitable for transmission over cable or radio and for recording by data loggers and other devices.

**Slide gate** is a gate that can be opened or closed by sliding in supporting guides.

**Slope failure** is the downward and outward movement of mass of soil beneath a natural slope or other inclined surface.

**Slope stability** is the degree of stability of the slopes of a dam, often defined as a factor of safety. Factor of safety is defined as the ratio of the forces tending to cause the slope to slough or otherwise fail to the forces resisting slope movement.

**Slope** is the inclination from the horizontal, sometimes referred to as batter when measured from vertical.

**Spillway** is a structure over or through which flow is discharged from a reservoir. If the rate of flow is controlled by mechanical means, such as gates, it is considered a controlled spillway. If the geometry of the spillway is the only control, it is considered an uncontrolled spillway. An auxiliary spillway is a secondary spillway designed to be operated infrequently as an adjunct or backup to the primary spillway.

**Spillway capacity** is the maximum spillway outflow that a dam can safely pass when the reservoir is at its maximum level, expressed in cubic feet per second (cfs) or cubic meters per second (cms).

**Spillway channel** is an open channel or closed conduit conveying water from the spillway downstream.

**Spillway crest** is the lowest level at which water can flow over or through the spillway.

**Stability** is the condition of a structure or a mass of material when it is able to support the applied stress for a long time without suffering any significant deformation or movement that is not reversed by the release of the stress.

**Standards** are commonly used and accepted as an authority.

**Staff gage or staff recorder** is a graduated scale placed in a position so that the stage (level) of a stream, pond, or reservoir may be read directly.

**Standpipe** is a vertical tube that contains water at the same water pressure as the surrounding soil, also known as an open well piezometer.

**Stilling basin** is a basin constructed to dissipate the energy of rapidly flowing water from a spillway or outlet, and to protect the riverbed from erosion.

**Stone masonry dam** is a dam made of large stone and masonry.

**Strain gauge** is a device which the change in distance between closely spaced points can be measured.

**Strain rosette** is a pattern of intersecting lines on a surface along which linear strains are measured to better define the field of strain about a point.

**Stress meter** is an instrument that measures stress directly, without strain measurement.

**Strong motion accelerometer** is an accelerometer designed to record ground shaking from significant earthquakes while remaining insensitive to smaller micro-seismic events.

**Surveillance** is close visual monitoring of a dam, its foundation, abutments and related facilities for indications of unacceptable performance and /or changing conditions, recording those observations and evaluating their significance to the safety of the dam and its related components.

**Tailings dams** are embankments that contain waste materials, also called slimes, tails, leach residue, or slickens left over after the process of separating the valuable fraction from the uneconomic fraction (gangue) of an ore. Tailings are distinct from overburden or waste rock, which are the materials overlying an ore or mineral body that is displaced during mining without being processed. Mine tailings are usually produced from the mill in slurry form of a mixture of fine mineral particles and water. When applied to coal and oil sands mining, the term 'tailings' refers specifically to fine waste suspended in water.

**Tailwater** is the water immediately downstream from a dam. The water surface elevation varies due to fluctuations in the outflow from the structures of a dam and due to downstream influences of other dams or structures. Tailwater monitoring is an important consideration because a failure of a dam will cause a rapid rise in the level of the tailwater.

**Theodolites** are optical instruments used in surveying which consists of a sighting telescope mounted so that it is free to rotate around horizontal and vertical axes so that the angles can be measured.

**Thermocouple** is a device for measuring temperatures accurately.

**Thermistor** is a resistive circuit component, having a high negative temperature coefficient of resistance, so that its resistance decreases as the temperature increases.

**Threshold Level** for instrument readings represents the value beyond which the reading indicates an unexpected value or unexpected change.

**Timber dams** include all dams that rely on timber for structural support and include timber buttress dams, timber crib dams, and embankment dams with timber cribbing used as reinforcement to steepen the slopes.

**Toe of the dam** is the junction of the downstream slope or face of a dam with the ground surface; also referred to as the downstream toe. The junction of the upstream slope with ground surface is called the heel or the upstream toe.

**Toe Drain** is a section of pervious material and/or pipe placed along the downstream toe of a dam to collect seepage from the dam and its foundation and convey it safely to a free outlet without conveying soil particles.

**Topographic map** is a map with detailed graphic delineation (representation) of natural and man-made features of a region with particular emphasis on relative position and elevation.

**Total head** is the elevation of a point plus the pore pressure at that point expressed in feet or meters of water. Differences in total head indicate flow. Differences in pressure head do not necessarily indicate flow.

**Tributary** is a stream that flows into a larger stream or body of water.

**Tunnel** is a long underground excavation with two or more openings to the surface, usually having a uniform cross section used for access, conveying flows, etc.

**Uncertainty** is the condition of being unsure about some state of nature and results from incomplete or conflicting information.

**Uplift** is the water pressure in the voids of the soil or rock that presses up on the base of a structure. Uplift on a boat causes it to float.

**Upstream blanket** is an impervious blanket of material placed on the reservoir floor and abutments for some distance upstream of the dam toe to help reduce the quantify of seepage through the dam and reduce pore water pressures in the foundation of the dam.

**Volume of dam** is the total space occupied by the materials forming the dam structure computed between abutments and from top to bottom of dam.

**Watershed or river basin** is the area drained by a river or river system or portion thereof. The watershed for a dam is the drainage area upstream of the dam (expressed in square miles or square kilometers).

**Weir** is a notch of regular shape through which water flows. A broad-crested weir is an overflow weir shaped to minimize turbulence of flow over the weir. A measuring weir is a shaped notch through which the height of water flow indicates the flow rate through the weir.

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# APPENDIX A. BIBLIOGRAPHY OF INSTRUMENTATION USE IN DAMS

| NO. | AUTHOR (S) | PERTINENT INFORMATION FROM PUBLICATIONS ON DAM MONITORING | | | | |
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| 1 | Alvarez, A. | **TITLE:** Interpretation of Measurements to Determine the Strength and Deformability of an Arch Dam Foundation | **SOURCE:** *Field Measurements in Rock Mechanics (Proc., Intl. Symp., Zurich)* ri, Rotterdam, Netherlands, 1977 | **PAGE(S)**825-836 | **KEYWORDS:** Hydrostatic thrust, strength limit, deformation | **BRIEF DESCRIPTION:** This article presents the results of an investigates of the strength of the abutment of an important dam. It subsequently presents issues related to strengthening structure. |
| 2 | American Society of Civil Engineers | **TITLE:** Section 6-5: Instrumentation; Appendix E: Description and Use of Instruments during Earth and Rockfill Dam Construction | **SOURCE:** C*onstruction Control for Earth and Rockfill Dams*, Technical Engineering and Design Guides as Adapted from the US Army Corps of Engineers, No. 27, American Society of Civil Engineers, Reston, 1999. | **PAGE(S** 62, 93-96 | **KEYWORDS:** Types of instruments, installation, observations | **BRIEF DESCRIPTION:** This section presents a brief description of instrumentation for earth and rockfill dams. The appendix gives basic descriptions and operating mechanisms of instruments generally installed in embankment dams. |

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| 3 | Anderson, G.R., Chouinard, L.E., Bouvier, C., & Back, W.E. | **TITLE:** Ranking Procedure on Maintenance Tasks for Monitoring of Embankment Dams. | **SOURCE:** *Journal of Geotechnical and Geoenvironmental Engineering,* 125(4), 247-259, American Society of Civil Engineers, Reston, VA, 1999. | **PAGE(S):** 247-259 | **KEYWORDS:** Maintenance, ranking procedure | **BRIEF DESCRIPTION:** This article presents a methodology that can be used to prioritize maintenance and repair tasks for embankment dam monitoring systems. |
| 4 | Armbruster, A., Blinde, A., Brauns, J., Doscher, H.D., Hotzl, H., & Merkler, G.P. | **TITLE:** The Application of Geoelectrical and Thermal Measurements to Locate Dam Leakages. | **SOURCE:** *Detection of Subsurface Flow Phenomena,* Lecture Notes in Earth Sciences, Springer, Berlin/Heidelberg, 1989 | **PAGE(S):** 32-47 | **KEYWORDS:** Geoelectrical measurements, thermal measurements, dam leakage | **BRIEF DESCRIPTION:** This paper focuses on two detection methods to locate dam leakage. These methods are thermal and geoelectrical measurements. |
| 5 | ASCE Task Committee on Instrumentation and Monitoring Dam Performance | **TITLE:** The Purpose of an Instrumentation and Measurement System (Chapter 1) | **SOURCE:** *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance,* Hydropower Committee of the Energy Division, ASCE, Reston, VA, 2000 | **PAGE(S)** 1-1 to 1-13 | **KEYWORDS:** Dam performance, history of monitoring | **BRIEF DESCRIPTION:** This chapter provides a big picture on why it is important to monitor dam behavior. The evaluation of dam performance is compared to design and expectations. A table is provided which summarized specific dam incidents related to instrument monitoring. Also included is a brief |

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| | | | | | | history on dam instrumentation. |
| 6 | ASCE Task Committee on Instrumentation and Monitoring Dam Performance | **TITLE:** Planning and Implementing Measurement Systems (Chapter 5) | **SOURCE:** G*uidelines for Instrumentation and Measurements for Monitoring Dam Performance,* Hydropower Committee of the Energy Division, ASCE, Reston, VA, 2000 | **PAGE(S):** 5-1 to 5-19 | **KEYWORDS:** Planning, organization, training, and maintenance of instrumentation systems | **BRIEF DESCRIPTION:** In this chapter, the key steps in the life cycle of reliable and effective measurement systems for dams are introduced. The planning, design, procurement, installation, operation and maintenance, data management, and abandonments steps are included. |
| 7 | ASCE Task Committee on Instrumentation and Monitoring Dam Performance | **TITLE:** Developing an Instrumentation and Measurement Plan (Chapter 6) | **SOURCE:** *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance,* Hydropower Committee of the Energy Division, ASCE, Reston, VA, 2000 | **PAGE(S):** 6-1 to 6-17 | **KEYWORDS:** Legal issues, documentation of records, training, safety, data collection, analysis, plan modification | **BRIEF DESCRIPTION:** This chapter discusses developing an instrumentation and measurement plan for dam performance monitoring. It touches upon aspects such as legal |

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| | | | | | | considerations, training of personnel,and pre to post construction considerations that need to be addressed. |
| 8 | ASCE Task Committee on Instrumentation and Monitoring Dam Performance | **TITLE:** Data Evaluation and Reporting (Chapter 8) | **SOURCE:** *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance*, Hydropower Committee of the Energy Division, ASCE, Reston, VA, 2000 | **PAGE(S):** 8-1 to 8-62 | **KEYWORDS:** Data evaluation, reporting | **BRIEF DESCRIPTION:** This chapter provides an introduction to data evaluation and the needed connection between the disciplines of dam design, construction, geology, instrument manufacturing, electronics, and data processing. Compacted earth embankment dams, rockfill dams, concrete dams gravity dams, arch dams, and buttress dams were considered. |

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| 9 | ASCE Task Committee on Instrumentation and Monitoring Dam Performance | **TITLE:** Decision Making and Taking Action (Chapter 9) | **SOURCE:** *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance,* Hydropower Committee of the Energy Division, ASCE, Reston, VA, 2000 | **PAGE(S):** 9-1 to 9-6 | **KEYWORDS:** Decision making, emergency | **BRIEF DESCRIPTION:** This chapter describes decisions and actions that result from a monitoring program over the construction and operational life of a project. It discusses decision making through normal conditions, unexpected conditions and emergency conditions. |
| 10 | Aufleger, M. | **TITLE:** Measuring Stress Redistributions In Embankment Dams | **SOURCE:** *Advances in Geotechnical Engineering with Emphasis on Dams (Proc., Geo Jordan Conf., Irbid)*, Ed. A.I.H. Malkawi, M. Alsaleh, & K. Alshibli, American Society of Civil Engineers, Reston, VA, 2004. | **PAGE(S):** 1-14 | **KEYWORDS:** Hydraulic earth pressure cells, earth pressure distribution | **BRIEF DESCRIPTION:** This article presents numerical computations to predict earth pressures and field measurements to verify the predictions. |
| 11 | Baker, D.G. | **TITLE:** Installation of multi-level piezometers in an existing embankment dam | **SOURCE:** *Field Measurements in Geomechanics (Proc., 5th Intl. Symp., Singapore)*, Ed. C.F. Leung, S.A. Tan, & K.K. Phoon, Balkema, Rotterdam, Netherlands, 1999 | **PAGE(S):** 333-338 | **KEYWORDS:** Sinkholes, embankment dam | **BRIEF DESCRIPTION:** This article presents a case history where multi-level piezometer monitoring was necessary in the dam transition zone, immediately |

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| | | | | | | downstream of the impervious core, to investigate the cause of two sinkholes which appeared 30 years after construction. |
| 12 | Bartholomew, C.L., Murray, B.C., & Goins, D.L. | **TITLE:** Embankment Dam Instrumentation Manual | **SOURCE:** Technical Report, Engineering and Research Center, Bureau of Reclamation, Denver, January, 1987. | **PAGE(S):** 250 pages | **KEYWORDS:** Instrumentation systems, data transmission, embankment dams, pressure measuring instruments, seepage, vibration, internal movement, surface movement,dam safety, data handling, data review | **BRIEF DESCRIPTION:** This manual, intended for designers, engineers, instrument readers, dam operators, and dam safety personnel, describes the various instrumentation systems used by the Bureau of Reclamation. |
| 13 | Bernstone, C. | **TITLE:** Dam Crest Measurements Using Differential GPS as a Part of an Integrated Monitoring Program for Small Concrete Dams | **SOURCE:** *Field Measurements in Geomechanics (Proc., 6th Intl. Symp., Oslo)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 2003 | **PAGE(S):** 419-424 | **KEYWORDS:** Global positioning system | **BRIEF DESCRIPTION:** This article presents various aspects of dam crest measurements using differential Global Positioning System. |

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| 14 | Bernstone, C., Westberg, M., & Jeppsson, J. | **TITLE:** Structural Assessment of a Concrete Dam Based on Uplift Pressure Monitoring | **SOURCE:** *Journal of Geotechnical and Geoenvironmental Engineering,* 135(1), 133-142, American Society of Civil Engineers, Reston, VA, 2009 | **PAGE(S):** 133-142 | **KEYWORDS:** Uplift pressure, time-domain reflectometry | **BRIEF DESCRIPTION:** This article discusses a monitoring technique suitable for concrete dams. This technique uses time-domain reflectometry and standard air-dielectric coaxial cable sensors. The signal is interpreted automatically by applying a threshold method to determine the apparent water level, which is then used to calculate the uplift pressure. |
| 15 | Bolt, B.A. and Hudson, D.E. | **TITLE:** Seismic Instrumentation of Dams | **SOURCE:** *Journal of the Geotechnical Engineering Division*, 101(GT11), 1095-1104, American Society of Civil Engineers, Reston, 1975 | **PAGE(S):** 1095-1104 | **KEYWORDS:** Earthquake, seismic, accelerographs, strong ground motion, | **BRIEF DESCRIPTION:** This article presents recommendations for minimum instrumentation requirements to enable engineers to compare behavior with earthquake design conditions and to estimate performance for other, perhaps larger shocks, and also to determine the extent of which local |

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| | | | | | | earthquakes are a results of reservoir impoundment. |
| 16 | Bowles, D.S., Anderson, L.R., & Glover, T.F. | **TITLE:** A Role for Risk Assessment in Dam Safety Management | **SOURCE:** *Hydropower 97 (Proc., 3rd Intl. Conf., Trondheim),* Ed. E. Broch, D. K. Lysne, N. Flatabo, & F. Helland-Hansen, Balkema, Rotterdam, Netherlands, 1997. | **PAGE(S):** 1-9 | **KEYWORDS:** Risk assessment, dam safety | **BRIEF DESCRIPTION:** This paper focuses on various factors that have lead to the use of the risk based approach to support dam safety decision making. |
| 17 | Bridle, R.C., Vaughan, P.R., & Wernek, M.L.G. | **TITLE:** The Trial Embankment of Empingham Dam | **SOURCE:** *Geotechnical Instrumentation in Civil Engineering Projects (Proc., Conf. Organized by the Institution of Civil Engineers, Nottingham)*, Thomas Thelford, London, 1989 | **PAGE(S):** 415-427 | **KEYWORDS:** Embankment dam, dam foundation | **BRIEF DESCRIPTION:** This article presents the case history of a trial embankment in Britain. The properties of the embankment clay foundation were uncertain at the time of design. A large instrumented trial slope was built within the permanent embankment fill to examine and validate the strength of the foundation. |

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| 18 | Brutti,C.M., Perfetti, E. & Zattoni, A. | **TITLE:** Castreccioni Dam: the History and Evolution of the Dam Monitoring system | **SOURCE:** *Field Measurements in Geomechanics (Proc., 6th Intl. Symp., Oslo)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 2003 | **PAGE(S):** 23-30 | **KEYWORDS:** Manual vs. automatic monitoring systems, evolution of monitoring | **BRIEF DESCRIPTION:** This article presents a case history of a dam with emphasis on the history and evolution of its monitoring system. It illustrates the continuous upgrading of the monitoring system at the dam. |
| 19 | Carpenter, L.R., Lytle, J.D., Misterek, D.L., Murray, B.C., & Raphel, J.M. | **TITLE:** Instrumentation (Chapter 25) | **SOURCE:** *Advanced Dam Engineering for Design, Construction, and Rehabilitation,* Ed. R.B. Jansen, Van Nostrand Reinhold, New York, NY, 1988 | **PAGE(S):** 751-776 | **KEYWORDS:** Instrumentation design requirements, installation procedures, monitoring techniques, monitoring schedule, automated data acquisition, data evaluation | **BRIEF DESCRIPTION:** This chapter addresses basic design requirements for measurements and instruments; that is devices, installation procedures, monitoring techniques, schedules, automated data acquisition methodology, and data evaluation. |
| 20 | Choquet, P., Quirion, M., & Juneau, F. | **TITLE:** Advances in Fabry-Perot Fiber Optic Sensors and Instrumentation for Geotechnical Monitoring | **SOURCE:** *Geotechnical News*, 18(1), March, BiTech Publishers, Vanvouver, Canada, 2000. | **PAGE(S):** 35-40 | **KEYWORDS:** Fiber optic sensors, fiber optic instruments, white light interferometry | **BRIEF DESCRIPTION:** This article presents the working principle as well as laboratory and field results of different fiber optic sensors and instruments based in |

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| | | | | | | the Fabry-Perot white light interferometry. |
| 21 | Contreras, I.A., Grosser, A.T., & Ver Strate, R.H. | **TITLE:** The Use of Fully-grouted Method for Piezometer Installation | **SOURCE:** *Field Measurements in Geomechanics, (Proc., 7th Intl. Symp., Boston)* (GSP 175), Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** Piezometer | **KEYWORDS:** Cement-bentonite grout, piezometer, pore pressure, grout mixing, grout permeability requirements | **BRIEF DESCRIPTION:** This article discusses in detail the fully-grouted method, installation procedure, theoretical background, laboratory test results of several cement-bentonite grout mixes, field examples of the application , and a seepage model that evaluates the impact of permeability difference between cement-bentonite grout and the surrounding ground in pore pressure measurements. |

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| 22 | Côté, A., Carrier, B., Leduc, J., Noël, P., Beauchemin, R., Soares, M., Garneau, C., & Gervais, R. | **TITLE:** Water Leakage Detection Using Optical Fiber at the Peribonka Dam | **SOURCE:** *Field Measurements in Geomechanics (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Leakage detection, heat pulse method, temperature monitoring | **BRIEF DESCRIPTION:** This article describes a monitoring system based on temperature readings using fiber optic cables designed for leakage detection through possible defects in the cutoff wall of the Peribonka main dam. The system is based on the heat pulse method to measure the apparent soil thermal resistivity. |
| 23 | Daicho, A. | **TITLE:** Design and Monitoring of Tataragi Dam | **SOURCE:** *Proc., 16th International Congress on Large Dams, San Francisco*, International Commission on Large Dams, Paris, 1988. | **PAGE(S):**227-231 | **KEYWORDS:** Construction control, post-completion security, future revisions in design methods | **BRIEF DESCRIPTION:** This articles presents various aspects of the design and monitoring of a dam in Japan. |

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| 24 | D'Appolonia Engineering | **TITLE:** Chapter 13: Instrumentation and Performance Monitoring | **SOURCE:** *Engineering and Design Manual, Coal Refuse Disposal Facilities*, Mine Safety and Health Administration, U.S. Department of Labor, Pittsburgh, Second Edition, 2009. | **PAGE(S):** 13.1-13A.13 | **KEYWORDS:** Instrumentation program planning, instrument types, measurement techniques, installation methods, maintenance, measurement uncertainty, system reliability | **BRIEF DESCRIPTION:** This chapter discusses the factors that should be considered when planning a site-specific instrumentation program and the types of instruments used for monitoring. It also presents supporting discussions on the uncertainty associated with instrument measurements. |
| 25 | Davidson, D., Dunnicliff, J., Lambert, L., & Walz, A. | **TITLE:** Automated Performance Monitoring of U.S. Dams | **SOURCE:** *Proc., Geotechnical Engineering Congress,* GSP No. 27, Ed. F.G. McLean, D.A. Campbell, & D.W. Harris, American Society of Civil Engineers, Reston, VA, 1991 | **PAGE(S):** 119-137 | **KEYWORDS:** Automatic data acquisition system, data loggers | **BRIEF DESCRIPTION:** This article provides a summary of a comprehensive report prepared by the United States Committee on Large Dams (USCOLD) entitled General Guidelines and Current U.S. Practive in Automated Performance Monitoring of Dams. The reeport was published in 1991. |

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| 26 | DeLoach, S.R. | **TITLE:** Continuous Deformation Monitoring with GPS. | **SOURCE:** *Journal of Surveying Engineering*, 115(1), 93-110, American Society of Civil Engineers, Reston, VA, 1989 | **PAGE(S):**93-110 | **KEYWORDS:** Geodetic surveying, global positioning system | **BRIEF DESCRIPTION:** This paper focuses on the use of modern instrumentation programs (high-precision geodetic surveying) for measuring the behavior of large structures. |
| 27 | De Mello, V. F. B. | **TITLE:** Design Trends on Large Rockfill Dams and Purposeful Monitoring Needs | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 805-826 | **KEYWORDS:** Monitoring trends over time, standard instrumentation on rockfill dams, safety concerns | **BRIEF DESCRIPTION:** The author used two types of rockfill dams to analyze whether current methods and interpretation of monitoring are adequate as they relate to cost benefit analysis, reliability and safety. |
| 28 | der Spuy, J.V., Oosthuizen, C., & Elges, H.F.W.K. | **TITLE:** The Role of Instrumentation in the Detection of Ageing at the Clamwilliam Dam in South Africa | **SOURCE:** *Proc., 17th International Congress on Large Dams, Vienna*, International Commission on Large Dams, Paris, 1991 | **PAGE(S):** 1327-1337 | **KEYWORDS:** Concrete gravity dam, post-tensioned cables, temperature gauges, sliding micrometers, sulphate reaction, risk level | **BRIEF DESCRIPTION:** This article presents a case history of a concrete gravity dam that was strengthened by post-tensioned cables. |

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| 29 | DiBiagio, E. & Myrvoll, F. | **TITLE:** Instrumentation Techniques and Equipment Used to Monitor the Performance of Norwegian Embankment Dams | **SOURCE:** *Publikasjon - Norges Geotekniske Institutt,* 165, 1-14, Norwegian Geotechnical Institute, Oslo, 1986 | **PAGE(S):** 1-14 | **KEYWORDS:** Instrumentation techniques, leakage, surface deformations, internal deformations, internal strain, pore water pressure, total earth pressure | **BRIEF DESCRIPTION:** This article summarizes current instrumentation techniques and equipment used in Norway to monitor the performance of embankment dams. |
| 30 | DiBiagio, E. , Myrvoll, F., Valstad, T., & Hansteen, H. | **TITLE:** Field Instrumentation, Observations, and Performance Evaluations for the Svartevann Dam | **SOURCE:** *Proc., 14th International Congress on Large Dams*, Rio de Janeiro, International Commission on Large Dams, Paris, 1982. | **PAGE(S):** 789-826 | **KEYWORDS:** Extensively instrumented dam | **BRIEF DESCRIPTION:** This article presents a case study which is an example of a new generation Norwegian dam that was extensively instrumented. The dam was extensively instrumented because at the time of its conception (early 1970's), its maximum height was fourty percent more than the highest dam in Norway. |

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| 31 | Dolezajova, M. | **TITLE:** Case History of a Rockfill Dam with Interpretation of the Measurement Results by Computational Model | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 827-838 | **KEYWORDS:** Failure, dam reconstruction, interpretation of field measurements | **BRIEF DESCRIPTION:** A back analysis of field measurements is most commonly used among large civil structures to understand their performance, especially in the occurrence of a failure. Large non-uniform settlement were observed and analyzed in a Western Bohemian Rockfill Dam. |
| 32 | Dowding, C.H. & O'Connor, K.M. | **TITLE:** Comparison of TDR and Inclinometers for Slope Monitoring | **SOURCE:** *Geotechnical Measurements, Lab and Field (Proc. of Sessions of Geo-Denver, Denver)*, Ed. W.A. Marr, American Society of Civil Engineers, 2000. | **PAGE(S):** 80-90 | **KEYWORDS:** Radar, slope movements, coaxial cable, shear strain, incremental displacement | **BRIEF DESCRIPTION:** This article presents a comparison between time-domain reflectometry (TDR) and slope inclinometer technologies in the detection and measurement of subsurface deformation in slopes. It also presents case histories involving monitoring of movements in soil and rock slopes and |

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| | | | | | | embankments. |
| 33 | Duffy, M.A., Hill, C., Whitaker, C., Chrzanowski, A., Lutes, J., & Bastin, G. | **TITLE:** An Automated and Integrated Monitoring Program for Diamond Valley Lake in California. | **SOURCE:** *Proc., 10th Intl. Symp. on Deformation Measurements, Orange, CA*, International Federation of Surveyors, Copenhagen, Denmark, 2001 | **PAGE(S):** 1-23 | **KEYWORDS:** Automated monitoring | **BRIEF DESCRIPTION:** This paper focuses on a program to monitor the effects of reservoir and dam loads on the dam itself and its foundation. In addition to the monitoring program a deformation monitoring program was also implemented due to the seismic active area where the dam is located. |
| 34 | Dunnicliff, J. | **TITLE:** Instrumentation of the Plover Cove Main Dam | **SOURCE:** *Geotechnique,* 18, 283-300, Thomas Telford, London, 1968 | **PAGE(S):** 283-300 | **KEYWORDS:** Instrumentation, seepage pattern | **BRIEF DESCRIPTION:** This article describes the instrumentation at a dam in Hong Kong and provides some recommendations forplanning future instrumentation. |

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| 35 | Dunicliff, J. | **TITLE:** Long-Term Performance of Embankment Dam Instrumentation | **SOURCE:** *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | **PAGE(S):** 1-22 | **KEYWORDS:** Instrument selection | **BRIEF DESCRIPTION:** This paper provides guidelines for use of instrumentation to monitor long term performance of embankment dams. General criteria for reliable long term instrumentation are given. |
| 36 | Dunnicliff, J. | **TITLE:** Contract Practices for Geotechnical Instrumentation | **SOURCE:** *Geotechnical News,* 12(3),32-38 , BiTech Publishers, Richmond, British Columbia, 1991 | **PAGE(S):** 32-38 | **KEYWORDS:** Contract practices, specifications, procurement | **BRIEF DESCRIPTION:** This article covers issues pertaining to contract practices such as where do contract practices fit into the big picture of an instrumentation program, the goals of specification writing, types of specifications, and procurement of materials,. |

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| 37 | Dunnicliff, J. | **TITLE:** Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation - An Update | **SOURCE:** *Geotechnical News*, 15(3), September, BiTech Publishers, Vanvouver, Canada, 1997. | **PAGE(S):** 36-46 | **KEYWORDS:** Planning instrumentation programs, instrumentation system design report | **BRIEF DESCRIPTION:** This article presents an update to a chapter in the author's book entitled Geotechnical Instrumentation for Monitoring Field Performance (John Wiley & Sons, New York, NY, 1988). The update is for Chapter 4: Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation. The significant change in this update is the addition of a step on preparing instrumentation system design reports. The article also includes a checklist for planning steps. |

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| 38 | Dunnicliff, J.<br>Davidson, D. | **TITLE:** Lessons Learned From Automating Instrumentation at Some U.S. Dams | **SOURCE:** *Geotechnical News*, 9(2), 46-51, BiTech Publishers, Richmond, British Columbia, 1991 | **PAGE(S):** 46-51 | **KEYWORDS:** Automation, Instrumentation, Automatic Data Acquisition Systems (ADAS) | **BRIEF DESCRIPTION:** This article presents the experience and knowledge gained from the automation of instrumentation at several U.S. dams. It discusses the importance of automation and the issues that imfluence the decision on automating dam instrumentation . |
| 39 | Dunnicliff, J. & Green, G.E. | **TITLE:** Geotechnical Instrumentation: An Overview (Chapter 1) | **SOURCE:** *Geotechnical Instrumentation for Monitoring Field Performance,* John Wiley & Sons, New York, NY, 1988 | **PAGE(S):** 3-11 | **KEYWORDS:** Geotechnical instrumentation overview | **BRIEF DESCRIPTION:** This chapter provides a broad overview of what geotechnical investigation is and why field performance is monitored. The chapter addresses the past,present and future of geotechnical instrumentation. |
| 40 | Dunnicliff, J. & Green, G.E. | **TITLE:** Benefits of Using Geotechnical Instrumentation (Chapter 3) | **SOURCE:** *Geotechnical Instrumentation for Monitoring Field Performance,* John Wiley & Sons, New York, NY, 1988 | **PAGE(S):** 33-36 | **KEYWORDS:** Instrumentation, safety | **BRIEF DESCRIPTION:** Benefits of using geotechnical instrumentation are described in this chapter with |

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| | | | | | | examples of instrumentation applications for various project types. This chapter aims at displaying that the value added to safety and avoidance of failures make instrumentation programs cost effective. |
| 41 | Dunnicliff, J. & Green, G.E. | **TITLE:** Systematic Approach to Planning Monitoring Programs using Geotechnical Instrumentation (Chapter 4) | **SOURCE:** *Geotechnical Instrumentation for Monitoring Field Performance,* John Wiley & Sons, New York, NY, 1988 | **PAGE(S):** 37-44 | **KEYWORDS:** Monitoring program, organization, planning monitoring system | **BRIEF DESCRIPTION:** This chapter presents a logical and systematic approach for dam monitoring programs, beginning with defining the objective and ending with planning how the measurement data will be implemented. |
| 42 | Duscha, L.A. & Jansen, R.B. | **TITLE:** Surveillance (Chapter 26) | **SOURCE:** *Advanced Dam Engineering for Design, Construction, and Rehabilitation,* Ed. R.B. Jansen, Van Nostrand Reinhold, New York, NY, 1988 | **PAGE(S):** 777-798 | **KEYWORDS:** Dam surveillance | **BRIEF DESCRIPTION:** This paper focuses on the six essential elements of dam surveillance: (1) Knowledge of the project and its records. (2) Risk assesment based on the performances of |

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| | | | | | | other dams in similar settings. (3) Inspection of the dam, the reservoir, and their environment. (4) Measurement of changes. (5) Prompt analysis fo deviations from normal behavior. (6) Readiness for quick corrective action. |
| 43 | Espinoza, B.C. & Brylawski E. | **TITLE:** Structural and Geotechnical Instrumentation of the Pichi Picún Leufú Hydroelectric Dam, Argentina: A 54-m (177 ft) Compacted Gravel Embankment Dam with an Upstream Concrete Slab and Cutoff Wall | **SOURCE:** *Field Measurements in Geomechanics (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Monitoring, successful monitoring plan | **BRIEF DESCRIPTION:** This paper presents the performance of the geotechnical and structural instrumentation up to the current time with emphasis on the structural performance since reservoir filling. |
| 44 | Fanelli, M. | **TITLE:** Influence of Rock Behavior on Foundation of Concrete Dams | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 839-864 | **KEYWORDS:** Rock foundation for dams, rock foundation instrumentation | **BRIEF DESCRIPTION:** This article presents the influence of rock foundations on concrete dams. It emphasizes the need of understanding the behavior of underlying rock foundations when |

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| | | | | | | dealing with dams. |
| 45 | Federal Energy Regulatory Commission | **TITLE:**Instrumentation and Monitoring (Chapter 9) | **SOURCE:** *Engineering Guidelines for the Evaluation of Hydropower Projects*, Office of Energy Projects, Federal Energy Regulatory Commission, Washington, D.C., 1991. | **PAGE(S):** 9.9-9.59 | **KEYWORDS:** Minimum instrumentation requirements, water level, water pressure, seepage and leakage, movement, visual observation, instrumentation system design, low-hazard dams, high-hazard dams, uplift, procurements, monitoring schedules, automated data acquisition | **BRIEF DESCRIPTION:** This chapter provides engineers with recommended guidelines to for reviewing and evaluating the adequacy of instrumentation and monitoring programs. It also lists the most common causes of embankment dam failures as well as advantages and disadvantages of instruments. Minimum recommended instrumentation requirements for existing and proposed dams are also given. |

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| 46 | Federal Energy Regulatory Commission | **TITLE:**Dam Safety Performance Monitoring Program (Chapter 14) | **SOURCE:** *Engineering Guidelines for the Evaluation of Hydropower Projects*, Office of Energy Projects, Federal Energy Regulatory Commission, Washington, D.C., 2005. | **PAGE(S):** 14.1-14.46 | **KEYWORDS:** Potential failure mode analysis, surveillance and monitoring program, static loading, normal operating water level, floods, earthquakes | **BRIEF DESCRIPTION:** This chapter presents recommendations on procedures and criteria to develop a dam safety performance monitoring program based upon "failure mode thinking" to assist in the review and evaluation of safety and performance of water retaining project works regulated by the Federal Energy Regulatory Commission (FERC). |
| 47 | Federal Highway Administration | **TITLE:** Geotechnical Instrumentation Reference Manual | **SOURCE:** *Training Course in Geotechnical and Foundation Engineering*, National Highway Institute Course No. 12431 - Module 11, Publication No. FHWA HI-98-034, National Highway Institute, 1998 | **PAGE(S):** 238 pages | **KEYWORDS:** Instrumentation, planning of instrumentation systems, calibration, installation, data processing, presentation , interpretation | **BRIEF DESCRIPTION:** This manual provides the practicing geotechnical engineer detailued information on the use of geotechnical instrumention in highway construction. Many of the concepts are applicable to the instrumentation and monitoring of dams. The manual presents |

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| | | | | | | an overview of measurement methods and tools, and provides recommendations on systematic and complete approach to planning monitoring programs. It also gives guidelines for tasks like calibration, maintenance and installation of instruments, data collection, data processing and presentation, data interpretation and reporting of results. |
| 48 | Feldman, A.I., Ellis, H.L., Davis, W.L., & McRae, J. | **TITLE:** Plumb Line System for Double Arch Dams | **SOURCE:** *Field Measurements in Geomechanics, (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Plumb line systems, double arch dams | **BRIEF DESCRIPTION:** This article presents an "innovative" plumb line installed on the face of a double curvature concrete arch dam to measure horizontal movements to 0.1 mm accuracy. |

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| 49 | Fishman, Y.A. & Shangin, V. S. | **TITLE:** Analysis of Displacements of Concrete Shear Blocks and Concrete Dams on Rock Foundation by the Field Measurements Results | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 865-874 | **KEYWORDS:** Displacement values, acceptable safety criteria | **BRIEF DESCRIPTION:** This article aims at determining a proper criteria of limiting displacements on the basis of the interrelations between displacements and failure. |
| 50 | Fujii, H. & Watanabe, T. | **TITLE:** Pore Pressure on Small Fill Dams | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 875-884 | **KEYWORDS:** Pore pressure, small fill dams | **BRIEF DESCRIPTION:** The results of pore pressure measurements using piezometers were analyzed and presented in this article |
| 51 | Galiev, E. G., Lomov, I. E., Tildel, P. P., & Khakimova, G. H. | **TITLE:** Vertical Settlement of Rock Foundation at Ingouri Arch Dam During First Stage Filling of Reservoir | **SOURCE:** *Field Measurements in Geomechanics(Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 885-890 | **KEYWORDS:** Vertical settlement, settlement during construction | **BRIEF DESCRIPTION:** The two stage arch dam construction was monitored for vertical settlement due to variables such as weight of the dam, weight of the water in the reservoir, uplift action of the water in the fissures and hydrodynamic effect of percolating flow. |

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| 52 | Goad, C.C. | **TITLE:** Kinematic Survey of Clinton Lake Dam | **SOURCE:** *Journal of Surveying Engineering*, 115(1), 67-77, American Society of Civil Engineers, Reston, VA, 1989 | **PAGE(S):** 66-77 | **KEYWORDS:** Kinematic survey, global positioning system | **BRIEF DESCRIPTION:** This paper focuses on the use of global positioning system (GPS) to perform kinematic surveys on dams. |
| 53 | Hanna, T.H. | **TITLE:** Instrument Use in Embankment Dam Monitoring (Section 7.19) | **SOURCE:** *Field Instrumentation in Geotechnical Engineering,* Trans Tech Publications, Clausthal-Zellerfeld, Federal Republic of Germany, 1985 | **PAGE(S):** 640-684 | **KEYWORDS:** Performance monitoring, embankment dam | **BRIEF DESCRIPTION:** This section covers the instrumentation, measurements taken and how the data was used for several different dams. |
| 54 | Haug, W., Miesseler, H.-J., & Wolff, R. | **TITLE:** Permanent Monitoring of Concrete Dams with the Aid of Innovative Optical Fiber Sensors | **SOURCE:** *Proc., 17th International Congress on Large Dams, Vienna*, International Commission on Large Dams, Paris, 1991 | **PAGE(S):** 1269-1284 | **KEYWORDS:** Permanent monitoring, concrete dams,measurements using light, optical fiber sensors | **BRIEF DESCRIPTION:** This article describes the use of optical fiber sensors in dam monitoring. It addresses how light can be used as a measurement tool. |
| 55 | International Atomic Energy Agency | **TITLE:** Thematic Plan Isotope Hydrology in Dam Safety and Sustainability. | **SOURCE:** International Atomic Energy Agency, Vienna, 1999 | **PAGE(S):** 31 pages | **KEYWORDS:** Isotope techniques, sustainability, safety | **BRIEF DESCRIPTION:** The objective of this paper is to promote the use of safe isotope techniques for the sustainability and safety of dams. |

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| 56 | International Commission on Large Dams (ICOLD) | **TITLE:** Dam Monitoring - General Considerations | **SOURCE:** *Dam Monitoring - General Considerations*, Bulletin 60, International Commission on Large Dams, Paris, 1988 | **PAGE(S):** 1-69 | **KEYWORDS:** Purpose of instrumentation, instrumentation system planning, accuracy of measurements, reliability of measurements, basic instrumentation requirements, design considerations | **BRIEF DESCRIPTION:** This bulletin outlines the reasons for installing instruments, describes basic considerations in instrumentation system planning, examines the factors influencing the accuracy of measurements, and discusses the realibility of measurements. |
| 57 | International Commission on Large Dams (ICOLD) | **TITLE:** Monitoring of Dams and Their Foundations - State of the Art | **SOURCE:** *Monitoring of Dams and Their Foundations - State of the Art*, Bulletin 68, International Commission on Large Dams, Paris, 1989 | **PAGE(S):** | **KEYWORDS:** State-of-the art monitoring of dams, monitoring of dam foundations, general specifications for instrumentation | **BRIEF DESCRIPTION:** This report presents a summary of state-of-the-art reports on dam and foundation monitoring submitted by member countries of the ICOLD Committee on Monitoring of Dams and Their Foundations. These reports presented the state-of-the art of dam foundation monitoring in the countries of the members which are |

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| | | | | | | Australia, Austria, France, Italy, Japan, Norway, Portugal, South Africa, Switzerland, and the United States. Included in the appendices are the reports submitted by the member countries. |
| 58 | International Commission on Large Dams (ICOLD) | **TITLE:** Automated Observation for the Safety Control of Dams | **SOURCE:** Bulletin No. 41, International Commission on Large Dams, Paris, 1982. | **PAGE(S):** | **KEYWORDS:** Automation schemes, dam safety, purpose of monitoring, risk conditions evaluation, data processing, data storage, data interpretation, statistical behavior models, deterministic behavior models, hybrid behavior models, tolerance limits, abnormal performance | **BRIEF DESCRIPTION:** This bulletin presents a synthesis of what emerged from recent publications, especially those of ICOLD , on the topic. |

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| 59 | Jamshid Sadrekarimi, Mohammad Kia, and Abouzar Sadrekarimi | **TITLE:** Performance of Foundation Ground of a Large Dam during First Filling | **SOURCE:** *Field Measurements in Geomechanics (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Seepage trends, pore pressure, water levels | **BRIEF DESCRIPTION:** This article presents a study of the response of the foundation of a large dam to reservoir first filling. It presents a study on seepage trends with differing site conditions (soil and rock type, water levels) |
| 60 | Kaloustian, E. S. | **TITLE:** Results of Field Studies of the Inguri Arch Dam Rock Foundation Behavior with Use of Rock Strain Gauges | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 901-906 | **KEYWORDS:** Dam foundations, reliability, geographical differences | **BRIEF DESCRIPTION:** This article presents the results of field measurements at an arch dam rock foundation. |
| 61 | Keefer, T.N. | **TITLE:** Use of Goes Satellite Transmission in Dam Monitoring | **SOURCE:** www.sutron.com (Downloaded September 2009), Sutron Corporation, Sterling, VA | **PAGE(S):** | **KEYWORDS:** GOES system, piezometers | **BRIEF DESCRIPTION:** This article describes alternative telemetry networks to combine line-of-site radio, hard wire, and GOES (Geostationary Operational Environmental Satellite) messaging to replace hand or ground based collection of piezometer levels. |

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| 62 | Knight, D.J. | **TITLE:** The Proven Usefulness of Instrumentation Systems on Varied Dam Projects | **SOURCE:** *Geotechnical Instrumentation in Civil Engineering Projects (Proc., Conf. Organized by the Institution of Civil Engineers, Nottingham)*, Thomas Thelford, London, 1989 | **PAGE(S):** 401-414 | **KEYWORDS:** Uses of instruments, performance and interpretation of measurements | **BRIEF DESCRIPTION:** This paper refers to nine dam projects of greatly varying magnitude, geotechnical conditions and designs throughout the world. It describes the purpose, performance and interpretation of the instrumentation systems of the dams. A concluding section assesses the performance and usefulness of the various types of instruments. |
| 63 | Kogovsek, B. & Pirc, H. | **TITLE:** Dam on the Sava River for Nuclear Power Plant Krsko Monitoring and Maintenance | **SOURCE:** *Proc., 19th International Congress on Large Dams, Florence,* International Commission on Large Dams, Paris, 1997 | **PAGE(S):** 67-74 | **KEYWORDS:** Observation points, concrete contraction, hydration heat, cracks, erosion, nuclear power plant | **BRIEF DESCRIPTION:** This article discusses the monitoring and maintenance a dam located near a nuclear facility. The dam was constructed to increase the river water level required to pump cooling water to the power plant. The dam experienced cracks |

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| | | | | | | due to concrete contraction and hydration heat as well as erosion of concrete surfaces caused by the suspended load in the river flow. |
| 64 | Kollgaard, E.B. & Chadwick, W.L. | **TITLE:** Development of Dam Engineering in the United States | **SOURCE:** *Development of Dam Engineering in the United States*, Prepared in Commemoration of the 16th ICOLD Congress, San Francisco, Ed. Kollgaard, E.B. & Chadwick, W.L., Pergamon Press, NY, 1988 | **PAGE(S):** | **KEYWORDS:** Instrumentstion systems, seismic instrumentation, state-of-the-art of dam instrumentation, case histories | **BRIEF DESCRIPTION:** This book presents the development of dam engineering in the United States from its earliest beginning date in the 19th century to the present day . It discusses the state-of-the art of dam engineering. It also presents case histories of 100 dams in the United States. |
| 65 | Kotzias, P.C., Stamatopo ulos, A.C., & Kountouris , P.J. | **TITLE:** Field Quality Control on Earth Dam: Statistical Graphics for Gauging | **SOURCE:** *Journal of Geotechnical Engineering,* 119(5), 957-964, American Society of Civil Engineers, Reston, VA, 1993 | **PAGE(S):** 957-964 | **KEYWORDS:** Quality control, statistical graphics | **BRIEF DESCRIPTION:** This article focuses on the second operation (gauging) of field quality control on earth dam. Gauging consists of sampling, testing, and recording. It |

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| | | | | | | illustrates how modern statistical graphics can compile, differentiate, and succinctly communicate extensive field information from recorded data. |
| 66 | Kulhawy, F.H. & Duncan, J.M. | **TITLE:** Stresses and Movements in Oroville Dam | **SOURCE:** *Journal of the Soil Mechanics and Foundations Division ASCE*, 98(SM7), American Society of Civil Engineers, Reston, 1972. | **PAGE(S):** 653-665 | **KEYWORDS:** Extensively instrumentated dam, finite element analysis, calculated versus measured behavior | **BRIEF DESCRIPTION:** This article presents a case history of an embankment dam that was instrumented extensively. The authors compared the measured stresses and movements against results of finite element analyses. |
| 67 | Lambe, T.W., Marr, W.A. & Silva, F. | **TITLE:** Safety of a Constructed Facility: Geotechnical Aspects | **SOURCE:** *Journal of the Geotechnical Engineering Division,* 107(GT3), American Society of Civil Engineers, Reston, VA, 1981 | **PAGE(S):** 339-352 | **KEYWORDS:** Safety program, safety assessment, design assessment, performance evaluation, risk analysis | **BRIEF DESCRIPTION:** This article presents a comprehensive safety program based on geotechnical engineering fundamentals to help ensure that a geotehcnical facility meets performance criteria. This paper also touches upon |

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| | | | | | | risk analysis in safety assessment. |
| 68 | Little, A. L. | **TITLE:** Experiences With Instrumentation for Embankment Dam Performance | **SOURCE:** *Field Instrumentation in Geotechnical Engineering (Symp., British Geotechnical Society, London)*, Halsted Press, 1973 | **PAGE(S):** 229-239 | **KEYWORDS:** Piezometers, embankment dam | **BRIEF DESCRIPTION:** Different types of piezometers used to monitor dams are discussed in this article. |
| 69 | Lollino, P., Cotecchia, F., Zdravkovic, L., & Potts, D.M. | **TITLE:** Numerical Analysis and Monitoring of Pappadai Dam | **SOURCE:** *Canadian Geotechnical Journal,* 42, 1631-1643, National Research Council, Canada, 2005 | **PAGE(S):** 1631-1643 | **KEYWORDS:** Rockfill dam, impoundment, numerical analysis, deformation, pore pressure changes | **BRIEF DESCRIPTION:** This article presents a case history for the construction of the Pappadai dam in Italy. The dam and its foundation was monitored during construction and susbequent impoundment. |

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| 70 | Londe, P. | **TITLE:** Concepts and Instruments for Improved Monitoring | **SOURCE:** *Journal of the Geotechnical Engineering Division ASCE*, 108(GT6), American Society of Civil Engineers, Reston, 1982. | **PAGE(S):** 820-834 | **KEYWORDS:** Instrumentation approach, instrumentation requirements | **BRIEF DESCRIPTION:** This article presents the author's personal views on what he considers to be the best approach for instrumentation. It discusses instrumentation for both construction and operation phases of a project. The opinions presented in this article are based on the author's experience from numerous civil works projects throughout the world. |
| 71 | Lovenbury, M.T. | **TITLE:** The Detection of Leakage Through the Core of an Existing Dam | **SOURCE:** *Field Instrumentation in Geotechnical Engineering (Symp., British Geotechnical Society, London)*, Halsted Press, 1973 | **PAGE(S):** 240-248 | **KEYWORDS:** Prevention of failure, standing piezometers, leakage through core | **BRIEF DESCRIPTION:** This article presents a case history involving the detection of leakage through a core of an existing dam. The detection was performed using a group of standing piezometers. |

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| 72 | Lytle, J. D. | **TITLE:** Precise Mensuration with Electronic Distance Measurement Equipment to Assure Dam Safety | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 917-926 | **KEYWORDS:** Maintenance of dams, continuous monitoring, dam safety plan | **BRIEF DESCRIPTION:** This article presents one aspect of the instrumentation program which was developed by the St. Louis district of the United States Army Corps of Engineers. |
| 73 | Lytle, J.D. | **TITLE:** Dam Safety Instrumentation; Automation of Data Observations, Processing and Evaluation | **SOURCE:** *Proc., 14th International Congress on Large Dams*, Rio de Janeiro, International Commission on Large Dams, Paris, 1982. | **PAGE(S):** 493-511 | **KEYWORDS:** Periodic inspection and evaluation, automated data acquisition, automated data processing | **BRIEF DESCRIPTION:** This article presents the instrumentation and evaluation programs at the US Army Corps of Engineer's St. Louis District, located in the mid-Mississippi valley. It discusses the implementation of periodic inspection and evaluation, automated data acquisition and processing, instrumentation observation and data evaluation. |

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| 74 | Madrid, A. | **TITLE:** Using IR Thermography for Detecting and Diagnosing Cracking in Concrete Dams. | **SOURCE:** *Infrared Technology XVI (Proc., Society of Photo-Optical Instrumentation Engineers, San Diego)*, Ed. I.J. Spiro, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1990 | **PAGE(S):** 110-126 | **KEYWORDS:** IR-thermography, crack, thermal imaging | **BRIEF DESCRIPTION:** This paper focuses on analytical and experimental research on detecting and diagnosing deep cracks in concrete dams by means of IR thermography measurements. |
| 75 | Mahasandana, T. & Pinrode, J. | **TITLE:** Monitoring of Reservoir Induced Seismicity in the Region of Western Thailand | **SOURCE:** *Proc., 19th International Congress on Large Dams, Florence,* International Commission on Large Dams, Paris, 1997 | **PAGE(S):** 153-161 | **KEYWORDS:** Seismic station, seismograph, reservoir induced seismicity, residual stress release | **BRIEF DESCRIPTION:** This article presents case histories of two dams in Thailand that were installed with seismic stations to monitor seismic activity at their respective locations. |
| 76 | Marr, W.A. | **TITLE:** Why Monitor Geotechnical Performance? | **SOURCE:** *Field Measurements in Geomechanics (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Risk, delay, monetary benefit, decision theory, reasons for instrumentation | **BRIEF DESCRIPTION:** This article discusses the reasons for monitoring geotechnical performance to help engineers develop justifications for geotechnical instrumentation programs for their projects. It also presents an approximate method |

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| | | | | | | to quatify savings from the use of geotechnical instrumentation. |
| 77 | Martin, J.H., Davies, J.P., & Blockley, D.I. | **TITLE:** Inference of Embankment Dam Safety by Combining Processed Geotechnical Instrument data with Stored Engineering Knowledge | **SOURCE:** *Geotechnical Instrumentation in Civil Engineering Projects (Proc., Conf. Organized by the Institution of Civil Engineers, Nottingham)*, Thomas Thelford, London, 1989 | **PAGE(S):** 429-437 | **KEYWORDS:** Dam safety management, analysis of instrument measurement, engineering judgment, knowledge acquisition | **BRIEF DESCRIPTION:** The paper describes methods for analyzing instrument measurements to help with the management of safety. The method involves characterizing the time patterns of data from instruments and then applying stored engineering knowledge to interpret the characterizations. |
| 78 | McKellar, D.C.R., Nunn, D.J., & Pells, P.J.N. | **TITLE:** Instrumentation of Some Embankment Dams in Southern Africa | **SOURCE:** Field Instrumentation in Geotechnical Engineering *(Symp., British Geotechnical Society, London)*, Halsted Press, 1973 | **PAGE(S):** 249-261 | **KEYWORDS:** Data collection, settlement, piezometers, performance | **BRIEF DESCRIPTION:** This paper concentrates on the instrumentation of five dams and the value of the resulting data in evaluating their performance. |

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| 79 | McKenna, G. | **TITLE:** Rules of Thumb for Geotechnical Instrumentation Costs | **SOURCE:** *Geotechnical News,* 24(2), June, BiTech Publishers, Vanvouver, Canada, 2006. | **PAGE(S):** 46-47 | **KEYWORDS:** Life-cycle of instrument, decommissioning, instrumentation cost | **BRIEF DESCRIPTION:** This article presents rules of thumb for geotechnical instrumentation costs based on a hypothetical example of a small embankment dam located about half a day away from a major center. The hypothetical dam is instrumented with a few inclinometers and a dozen piezometers to confirm design assumptions by construction performance monitoring. |
| 80 | Melvill, A.L. | **TITLE:** Monitoring the Performance of Elandsjagt Dam During Construction and First Filling | **SOURCE:** *Trans., 15th ICOLD, Laussane,* International Commission on Large Dams, Paris, 1985 | **PAGE(S):** 1021-1038 | **KEYWORDS:** Rapid reservoir filling, inexpensive monitoring methods, load transfer | **BRIEF DESCRIPTION:** This article presents some of the results of the instrument readings taken during the dam construction, period of no filling, extremely rapid first filling of the reservoir, and the one-year period after |

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| | | | | | | first filling. |
| 81 | Mikkelsen, P.E. | **TITLE:** Cement-Bentonite Grout Backfill for Borehole Instruments | **SOURCE:** *Geotechnical News*, 20(4), December, BiTech Publishers, Vanvouver, Canada, 2002. | **PAGE(S):** 38-42 | **KEYWORDS:** Bentonite grout, cement-bentonite grouts, grout strength, grout deformation, grout permeability, mix design, mixing procedure | **BRIEF DESCRIPTION:** This article presents a review of current bentonite backfill and sealing products to illustrate why their use should be limited. |
| 82 | Mikkelsen, P.E. & Wilson, S.D. | **TITLE:** Field Instrumentation: Accuract, Performance, Automation, and Procurement | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 251-272 | **KEYWORDS:** Systematic error correction, distribution of instruments, primary planes, instrument clusters | **BRIEF DESCRIPTION:** This article discusses five aspects of field instrumentation. The five aspects are: (1) inclinometer accuracy for various modes of operation (2) use of piezometers and porous filter elements (3) automation of field instruments (4) problems resulting from concentration of too many instruments in one |

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| | | | | | | location (5) adverse effects of "low bid" procurement for instruments and installation services. |
| 83 | Muller,G. & Muller, L. | **TITLE:** Monitoring of Dams with Measuring Instruments | **SOURCE:** *Proc., 10th International Congress on Large Dams*, Montreal, International Commission on Large Dams, Paris, 1970. | **PAGE(S):** 1033-1046 | **KEYWORDS:** Rock foundation, elastic moduli, rock mass | **BRIEF DESCRIPTION:** This article describes two instruments, i.e. extensometers and chain deflectometers. It also persents methods to determine the static and dynamic elastic moduli. The article also emphasizes the need for measurement in the foundation rock. |
| 84 | Myers, B. | **TITLE:** Optimization of Dam Monitoring Systems: Review of the Available Technology and Case Studies. | **SOURCE:** *Trans., 20th ICOLD,* Beijing, International Commission on Large Dams, Paris, 2000 | **PAGE(S):** | **KEYWORDS:** Optimization of monitoring systems | **BRIEF DESCRIPTION:** This paper discusses the tools that are currently availble for monitoring dams, and how dam owners can apply them. |

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| 85 | Myers, B. & Stateler, J. | **TITLE:** Why Include Instrumentation in Dam Monitoring Programs? | **SOURCE:** White Paper, Version 1.00, United States Society on Dams, Denver, CO, 2008. | **PAGE(S):** | **KEYWORDS:** PFMA (potential failure modes analysis), monitoring phases | **BRIEF DESCRIPTION:** This paper addresses instrumentation techniques and approaches, and their benefits. It walks through the instrumentation concerns through different dam life phases and other monitoring needs. PFMA (Potential failure modes analysis) is outlined. |
| 86 | Myers, B.K., Duston, G., & Sherman, T. | **TITLE:** Utilizing Automated Monitoring for the Franzen Reservoir Dam Safety Program | **SOURCE:** *Advanced Technical Seminar on Structural Behavior Monitoring*, Albuquerque, Association of State Dam Safety Officials, Lexington, KY and Federal Emergency Management Agency, Hyattsville, MD, 2009 | **PAGE(S):** | **KEYWORDS:** Dam safety program | **BRIEF DESCRIPTION:** This paper describes the short and long term plan to monitor the Franzen Reservoir Dam. |
| 87 | Myers K.B. & Scofield H.D. | **TITLE:** Providing Improved Dam Safety Monitoring Using Existing Staff Resources: Fern Ridge Dam Case Study | **SOURCE:** www.engineeredmonitoringsolutions.com (Downloaded February 2010), Engineered Monitoring Solutions, LLC, Newberg, OR | **PAGE(S):** | **KEYWORDS:** Staff resources, manpower reduction | **BRIEF DESCRIPTION:** This paper discusses the important role that instrumentation plays in long-term dam monitoring and a reduction in manpower for monitoring. |

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| 88 | O'Connor, K.M. & Dowding, C.H. | **TITLE:** GeoMeasurements by Pulsing TDR Cables and Probes | **SOURCE:** CRC Press, Boca Raton, Florida, 1999. | **PAGE(S):** 402 pages | **KEYWORDS:** Radar, remote sensing electrical measurement technique, coaxial cable, soil moisture, localized deformation in rock, soil deformation, structural deformation, air-liquid interfaces, cable-grout | **BRIEF DESCRIPTION:** This book presents the basics of time domain reflectometry (TDR) as well as other aspects of TDR technology including the monitoring of soil moisture, deformation in rock and soil, and structural deformation. It also discusses the electronics and software associated with TDR applications. The main aim of the book is to consolidate the similarities among the seemingly divergent specialities employing TDR in geomaterials. |
| 89 | Oosthuizen, C. | **TITLE:** The Use of Field Instrumentation as an Aid to Determine the Behavior of Roller Compacted Concrete in an Arch Gravity Dam | **SOURCE:** *Field Measurements in Geomechanics (Proc., 3rd Intl. Symp., Oslo)*, Ed. G. Sørum, Balkema, Rotterdam, Netherlands, 1991 | **PAGE(S):** 783-798 | **KEYWORDS:** Arch gravity dam, monitoring techniques | **BRIEF DESCRIPTION:** This article discusses the use of field instrumentation to improve understanding of the behavior of arch gravity dams. It presents two dam case histories, one of |

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| | | | | | | which had been extensively instrumented to monitor the behavior of the structure and materials. |
| 90 | Oosthuizen, C., Goldie, R.H., & Dorfling, C.J. | **TITLE:** An Attempt to Explain the Complex Behavior of a 'Simple' Cylindrical Arch Dam | **SOURCE:** *Field Measurements in Geomechanics (Proc., 6th Intl. Symp., Oslo)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 2003 | **PAGE(S):** 261-266 | **KEYWORDS:** Crack width gauges, crack width tilt gauges | **BRIEF DESCRIPTION:** A rational behavioral hypothesis is formed and presented for the dam based on data obtained from crack width gauge measurements, geodetic survey records, in situ stress measurements, and on site observation. |
| 91 | Oosthuizen, C., Naude, P.A., Pretorius, C.J., Mota, V.F., & Müller, F.P.J. | **TITLE:** Geodetic Surveying & TRIVEC Monitoring Systems at Katse Dam: Value Added or Waste? | **SOURCE:** *Field Measurements in Geomechanics (Proc., 6th Intl. Symp., Oslo)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 2003 | **PAGE(S):** 267-272 | **KEYWORDS:** TRIVEC, pendulums | **BRIEF DESCRIPTION:** This article discusses the monitoring system at the dam from a reliability and cost benefit perspective. |

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| 92 | O'Rourke, J.E. | **TITLE:** Performance Instrumentation Installed in Orville Dam | **SOURCE:** *Journal of the Geotechnical Engineering Division*, 100(GT2), 157-174, American Society of Civil Engineers, Reston, 1975 | **PAGE(S):** 157-174 | **KEYWORDS:** Sophisticated instruments, extensive dam monitoring, seepage, earthquake, movements, pore pressures, soil stresses | **BRIEF DESCRIPTION:** This article describes the comprehensive performance-instrumentation program implemented at Orville Dam in California where many standard earth-dam instrumentation systems were used, as well as new specially-designed systems. It covers the instrumentation equipment, installation methods, and operational response during the construction period as well as the current operational status (as of 1973). |
| 93 | Peck, R.B. | **TITLE:** Observation and Instrumentation - Some Elementary Considerations | **SOURCE:** *Judgement in Geotechnical Engineering, The Professional Legacy of Ralph B. Peck,* Ed. J. Dunnicliff & D.U. Deere, BiTech Publishers Ltd., Vancouver, Canada, 1991 | **PAGE(S):** 128-130 | **KEYWORDS:** Observations, measurements | **BRIEF DESCRIPTION:** This article is a synopsis of opening remarks made at a Metropolitan Section of the ASCE seminar on the use of field observations in foundation design and construction. |

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| 94 | Penman, A.D.M. | **TITLE:** On the Embankment Dam | **SOURCE:** *Geotechnique,* 36(3),303-348, Thomas Telford, London, 1986 | **PAGE(S):** 303-348 | **KEYWORDS:** Embankment dam, movement measurements, leakage, effective stress analysis | **BRIEF DESCRIPTION:** This article describes and discusses significant engineering issues pertaining to the embankment dam. These discussions are accompanied by relevant case histories. |
| 95 | Penman, A.D.M. | **TITLE:** Instrumentation Requirements for Earth and Rockfill Dams | **SOURCE:** *Problems and Practice of Dam Engineering (Proc., Intl. Symp., Bangkok)*, Ed. A.S. Balasubramaniam, Taylor Francis, London, 1980 | **PAGE(S):** 184-209 | **KEYWORDS:** Instrument types, instrument position, dam safety | **BRIEF DESCRIPTION:** This artile discusses the instrumentation requirements for dams mainly through case histories. It also discuss the dam safety guidelines developed in Britain, the United States, and by ICOLD. |
| 96 | Penman, A.D.M. & Charles, J.A. | **TITLE:** Measuring Movements of Embankment Dams | **SOURCE:** *Field Instrumentation in Geotechnical Engineering (Symp., British Geotechnical Society, London)*, Halsted Press, 1973 | **PAGE(S):** 341-358 | **KEYWORDS:** Horizontal plate gauges, monitoring of embankment dams, precision level | **BRIEF DESCRIPTION:** The purpose of this papeThis article gives brief review of some of the earlier instrumentation methods and describes recent work by the Geotechnics Division of the Building Research |

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| | | | | | | Station in measuring the deformations of two of Britain's highest dams. |
| 97 | Penman, A. & Charles, A. | **TITLE:** Constructional Deformations in Rockfill Dam | **SOURCE:** *Journal of the Soil Mechanics and Foundations Division ASCE*, 99(SM2), American Society of Civil Engineers, Reston, 1973. | **PAGE(S):** 139-163 | **KEYWORDS:** Measured versus calculated deformation, finite element method | **BRIEF DESCRIPTION:** This article describes the movement that occurred in the downstream rockfill shoulder of Llyn Brianne Dam during construction. The movements are compared with those calculated from finite element analysis using parameters derived from large-scale laboratory tests. |
| 98 | Penman, A.D.M. & Kennard, M.F. | **TITLE:** Long-Term Monitoring of Embankment Dams in Britain. | **SOURCE:** *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | **PAGE(S):** 46-67 | **KEYWORDS:** Dam failure, development of monitoring techniques | **BRIEF DESCRIPTION:** This article presents settlement and pore pressure observations made at several British dams. It also discusses the development of various types of instruments. |

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| 99 | Penman, A .D. M., Rocha Filho P., Torniatti, N. B. & Gusmao, L. A. P. | TITLE: Horizontal Pate Gauges Used in Large Dams | SOURCE: *Field Measurements in Geomechanics (Proc., 3rd Intl. Symp., Oslo)*, Ed. G. Sørum, Balkema, Rotterdam, Netherlands, 1991 | PAGE(S): 251-260 | KEYWORDS: Horizontal plate gauges, monitoring of embankment dams | BRIEF DESCRIPTION: This article presents latest types of horizontal plate gauges and gives a few case histories to illustrate how horizontal plate gauges have been used in dams. |
| 100 | Peters, N. & Long, W.C. | TITLE: Performance Monitoring of Dams in Western Canada. | SOURCE: *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | PAGE(S): 23-45 | KEYWORDS: Visual inspection, instrumentation programs | BRIEF DESCRIPTION: This article presents the case history of performance monitoring at Gardiner Dam in Canada. It demonstrates the value of instrumentation in providing information for design changes during construction and the need for permanent monitoring for safe operation of the dam. |

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| 101 | Potchana, P., Vavassori, M., & Zattoni, A. | **TITLE:** Automatic Data Acquisition System (ADAS): Monitoring System of Khao Laem Dam, Thailand | **SOURCE:** *Field Measurements in Geomechanics, (Proc., 5th Intl. Symp., Singapore)*, Ed. C.F. Leung, S.A. Tan, & K.K. Phoon, Balkema, Rotterdam, Netherlands, 1999 | **PAGE(S):** 145-150 | **KEYWORDS:** Monitoring system, remote data acquisition units, rockfill dam | **BRIEF DESCRIPTION:** This article presents a case history in Thailand . The geotechnical monitoring system of the dam comprised a hundred sensors connected to eleven remote data acquisition units located in the dam area to analyze the behavior of the dam. |
| 102 | Quaranta, J.D., Banta, L.E., & Altobello, J.A. | **TITLE:** Remote Monitoring of a High Hazard Coal Waste Impoundment in Mounteneous Terrain Case Study | **SOURCE:** *Tailings and Mine Waste (Proc., 12th Tailings and Mine Waste Conf., Vail, Colorado),* CRC Press/Balkema, Leiden, Netherlands, 2008. | **PAGE(S):** 125-136 | **KEYWORDS:** Remote monitoring, data logger, radio equipment | **BRIEF DESCRIPTION:** This article discusses a case history of the application of a wireless system to collect and analyze data for monitoring waste impoundment performance and environmental indicators. The system monitored weather data, piezometric water levels, pH, and specific conductance. The article also presents data results along with discussions on the |

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| | | | | | | long-term performance, advantages, and challenges of the system. |
| 103 | Regan, P.J. | **TITLE:** An Examination of dam Failures vs. Age of Dams | **SOURCE:** *Managing Our Water Retention Systems (Proc., 29th United States Society on Dams Annual Meeting and Conference, Nashville)*, United States Society on Dams, Denver, CO, 2009 | **PAGE(S):** | **KEYWORDS:** Dam safety, safety over time, failure modes | **BRIEF DESCRIPTION:** This paper examines the distribution of failures over time for the aggregate body of dams as well as the distribution over time for specific types of dam failure modes, and explores the reasons that some failures occur in the dams earliest years while others occur after an extended period of operation. |
| 104 | Regan, P.J., Nettle, J.D., & Zygaj, J.A. | **TITLE:** Managing Dam Safety Risks Through Surveillance and Monitoring Plans and Surveillance and Monitoring Reports. | **SOURCE:** *The Sustainability of Experience – Investing in the Human Factor (Proc., 28th United States Society on Dams Annual Conference, Portland)*, United States Society on Dams, Denver, CO, 2008 | **PAGE(S):** 951-966 | **KEYWORDS:** Surveillance Monitoring Plan (SMP) | **BRIEF DESCRIPTION:** This paper discusses the importance of surveillance and monitoring plans and reports in managing the risks associated |

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| | | | | | | with dams. |
| 105 | Rosati, E. & Esquivel, R.F. | **TITLE:** Instrumentation Performance for El Infernillo Dam after 18 Years of Observation | **SOURCE:** *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | **PAGE(S):** 104-124 | **KEYWORDS:** Rockfill dam monitoring, scope of instrumentation | **BRIEF DESCRIPTION:** This article presents a case history involving instrumentation installed on a dam located at one of the most seismically active zones in Mexico. The dam was monitored for 18 years. |
| 106 | Sadrekarimi, J., Sadrekarimi, A., & Kia, M.A. | **TITLE:** A Comparison Between Predicted and Observed Behavior of Alavian Dam, Iran | **SOURCE:** *Field Measurements in Geomechanics, (Proc., 6th Intl. Symp., Oslo)*, Ed. F. Myrvoll, Balkema, Lisse, Netherlands, 2003 | **PAGE(S):** 313-320 | **KEYWORDS:** Settlement, rock deformation, foundation failure | **BRIEF DESCRIPTION:** This article presents a comparison between predicted and measured behavior of a dam in Iran. The observed settlement of the foundation was approximately five times larger than the predicted value. |

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| 107 | Salembier, M. | **TITLE:** Some Applications of Distofor Extensometer to Large Dam Foundations | **SOURCE:** *Field Measurements in Geomechanics (Proc., 1st Intl. Symp., Zurich)*, Ed. K. Kovari, Balkema, Lisse, Netherlands, 1983 | **PAGE(S):** 927-934 | **KEYWORDS:** Extensometer, dam foundations | **BRIEF DESCRIPTION:** This article describes the Distofor extensometer and its uses. Several case histories were also presented. |
| 108 | Sartori, M. | **TITLE:** Application of Thermal IR-techniques for Reconnaissance of Dam and Barrage Defects in an Early State, Analysis of Dump Sites and Tunnel Condition Surveys. | **SOURCE:** *Detection of Subsurface Flow Phenomena*, Lecture Notes in Earth Sciences, Springer, Berlin/Heidelberg, 1989 | **PAGE(S):** 359-369 | **KEYWORDS:** Infrared techniques, dam reconnaissance | **BRIEF DESCRIPTION:** This paper focuses on the application of infrared (IR) techniques to examine dams and barrage defects. |
| 109 | Schenk, V. | **TITLE:** Monitoring Aspects of Two Embankment Dams with Bituminous Impervious Elements in the Federal Republic of Germany | **SOURCE:** *Proc., 16th International Congress on Large Dams, San Francisco*, International Commission on Large Dams, Paris, 1988. | **PAGE(S):** 759-777 | **KEYWORDS:** Rockfill dam, test impoundment, asphaltic concrete face, asphaltic concrete membrane | **BRIEF DESCRIPTION:** This article presents the monitoring aspects of two embankment dams with bituminous impervious elements. One of the specific issues discussed is the monitoring during test impoundment. |

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| 110 | Scott, M. D., Lo, R. C., & Thavaraj, T. | **TITLE:** Use of Instrumentation to Safeguard Stability of a Tailings Dam | **SOURCE:** *Field Measurements in Geomechanics, (Proc., 7th Intl. Symp., Boston) (GSP 175)*, Ed. J. DiMaggio & P. Osborn, ASCE, Reston, VA, 2007 | **PAGE(S):** | **KEYWORDS:** Observational approach, tailings dam | **BRIEF DESCRIPTION:** This article presents a case history of a tailings dam that was instrumented to monitor its response to new construction work aimed at raising the dam. It also addresses the monitoring advancements made in the previous decade for inclinometers and piezometers. |
| 111 | Sherard, J.L. | **TITLE:** Piezometers in Earth Dam Impervious Sections | **SOURCE:** *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | **PAGE(S):** 125-165 | **KEYWORDS:** Piezometers, impervious section | **BRIEF DESCRIPTION:** This paper presents experience and opinions regarding remote reading piezometers, with tips placed during construction in the impervious sections of earth dams and tubes or cables leading to measuring points outside of the dam. It also addresses which type of piezometer is appropriate for different cases. |

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| 112 | Silvestri, T. | **TITLE:** Rockmeter Measurements and Other Checks on Dam Foundation | **SOURCE:** *Field Measurements in Rock Mechanics (Proc., Intl. Symp., Zurich)* ri, , Rotterdam, Netherlands, 1977 | **PAGE(S):** 811-823 | **KEYWORDS:** Settlement, rock deformation, seismic waves | **BRIEF DESCRIPTION:** This article examines the settlement, rock deformation, and seismic wave velocity of dam foundation and subsequently explains the monitoring results. |
| 113 | Song, C.R. & Yeoh, Y.H. | **TITLE:** Assessment of Dam Body Safety From Field Monitoring Results | **SOURCE:** *Advances in Geotechnical Engineering with Emphasis on Dams (Proc., Geo Jordan Conf., Irbid), E*d. A.I.H. Malkawi, M. Alsaleh, & K. Alshibli, American Society of Civil Engineers, Reston, VA, 2004. | **PAGE(S):** 86-93 | **KEYWORDS:** Settlement, surface cracks, seepage | **BRIEF DESCRIPTION:** This study presents the behavior analysis of a pumped power storage dam body that showed longitudinal cracks on its crest. The analysis is based on the field monitoring results. |
| 114 | Sossenkina, E., Glunt, M., Mann, A.J., Newhouse, G.S., & Rizzo, P.C. | **TITLE:** Listening to the Dam-Instrumentation and Monitoring Program Saluda Dam Remediation | **SOURCE:** www.rizzoassoc.com (Downloaded January 2010), Paul C. Rizzo Associates, Inc., Pittsburgh, PA | **PAGE(S):** | **KEYWORDS:** Instrumentation, water pressure, excavation | **BRIEF DESCRIPTION:** This paper focuses on the application of geotechnical instruments to monitor the Saluda Dam during a major renovation. |

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| 115 | Straubhaar, R. & Hageli, H. | **TITLE:** A Monitoring System to Detect Ageing of Fill Dams | **SOURCE:** *Proc., 17th International Congress on Large Dams, Vienna*, International Commission on Large Dams, Paris, 1991 | **PAGE(S):** 235-245 | **KEYWORDS:** Rockfill dam, low alteration resistance, local materials as fill | **BRIEF DESCRIPTION:** This article presents the monitoring system of a constructed at a site consisting essentially of lithic tuff with low alteration resistance. |
| 116 | Szalay, K. & Marino, M. | **TITLE:** Instrumentation of Tarbela Dam | **SOURCE:** *Recent Developments in Geotechnical Engineering for Hydro Projects,* Ed. F.H. Kulhawy, ASCE, New York, NY, 1981 | **PAGE(S):** 68-103 | **KEYWORDS:** Instrumentation, problems during reservoir filling, corrective action | **BRIEF DESCRIPTION:** This article a case history of a dam in Pakistan. This dam project consisted of an embankment dam, tunnels, tunnel intake, outlet gate operation, spillways and excavated slopes. Instrumentation systems were used to monitor the performance of remedial work carried out at the dam. |
| 117 | Tachell, G.E. | **TITLE:** Automatic Data Acquisition Systems for Monitoring Dams and Landslides | **SOURCE:** *Field Measurements in Geomechanics (Proc., 3rd Intl. Symp., Oslo)*, Ed. G. Sørum, Balkema, Rotterdam, Netherlands, 1991 | **PAGE(S):** 249-260 | **KEYWORDS:** Automated data collection | **BRIEF DESCRIPTION:** This article discusses the benefits of automated data collection from geotechnical instruments. |

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| 118 | Taylor, H. and Chow, Y.M. | **TITLE:** Design, Monitoring and Maintaining Drainage System for a High Earthfill Dam | **SOURCE:** *Proc., 12th International Congress on Large Dams,*Mexico City, International Commission on Large Dams, Paris, 1976. | **PAGE(S):** 146-167 | **KEYWORDS:** Drainage system, dam safety | **BRIEF DESCRIPTION:** This article presents a case history of a high earthfill dam founded on sedimentary rock. It describes the design, monitoring, and maintenance of drainage facilities in the dam and its foundation, and how these factors relate to dam safety. |
| 119 | Tedd, P., Price, G., Wilson, A. C. & Evans, J. D. | **TITLE:** Use of the BRE Electro-level System to Measure Deflections of the Upstream Asphaltic Membrane of Roadford Dam | **SOURCE:** *Field Measurements in Geomechanics (Proc., 3rd Intl. Symp., Oslo)*, Ed. G. Sørum, Balkema, Rotterdam, Netherlands, 1991 | **PAGE(S):** 261-272 | **KEYWORDS:** BRE system, deflections | **BRIEF DESCRIPTION:** This article presents a case history where an electro-level system was successfully used to measure membrane deflection close to the dam toe for 15 months during the first filling of the reservoir. |
| 120 | Tronstad, K., Johansen, D.I., Eugene, B., & Myrset, O. | **TITLE:** Instrumentation and Monitoring of the Virdnejavri Arch Dam - Alta | **SOURCE:** *Geotechnical Instrumentation in Civil Engineering Projects (Proc., Conf. Organized by the Institution of Civil Engineers, Nottingham)*, Thomas Thelford, London, 1989 | **PAGE(S):** 439-446 | **KEYWORDS:** Arch dam, data acquisition system, rate of impoundment | **BRIEF DESCRIPTION:** The paper describes the instrumentation and monitoring of a dam in Norway. It describes the measuring systems and data acquisition system used. A |

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| | | | | | | summary of the performance of the dam is given. |
| 121 | United States Army Corps of Engineers | **TITLE:** Instrumentation of Embankment Dams and Levees | **SOURCE:** *Engineering and Design - Instrumentation of Embankment Dams and Levees,* Engineer Manual No. 1110-2-1908, Dept. of the Army, United States Army Corps of Engineers, Washington, D.C., 1995 | **PAGE(S):** 1.1-9.5, A.1-B.8 | **KEYWORDS:** Instrumentation objectives, instrumentation systems planning, automation, data analysis, data management, dam safety, instrumentation maintenance | **BRIEF DESCRIPTION:** This manual provides guidance to Corps of Engineers (COE) personnel who are responsible for monitoring and analyzing embankment dams and levees. It addresses all aspects of instrumentation including traditional monitoring methods, important geotechnical concetps, and the growing concerns of rehabilitation, replacement, and maintenance. The manual also addresses automation considerations, installation as well as data management, analysis , and |

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| | | | | | | reporting. |
| 122 | United States Army Corps of Engineers | **TITLE:** Instrumentation for Concrete Structures | **SOURCE:** *Instrumentation for Concrete Structures*, Engineer Manual 1110-2-4300, Department of the Army, United States Army Corps of Engineers, Washington, D.C., 1987 | **PAGE(S):** | **KEYWORDS:** Instrumentation, concrete structures, instrumentation planning, instrumentation installation, data collection | **BRIEF DESCRIPTION:** This manual provides guidance and information related to the instrumentation of concrete structures and the measurement of structural behavior. More specifically, it is meant to guide individuals and organizations in the Corps of Engineers engaged in the planning of instrumentation programs, and in the preparation, installation, and collection of data |

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| | | | | | | from instruments and devices for measuring srtuctural behavior within concrete gravity structures for civil works. |
| 123 | United States Army Corps of Engineers | **TITLE:** Interim Risk Reduction Measures for Dam Safety <u>**NOTE:**</u> *This EC expired on June 30, 2009 and the information may not be current and should not be referenced in an official document.* | **SOURCE:** *Interim Risk Reduction Measures for Dam Safety*, Engineering Circular EC-1110-2-6064, United States Army Corps of Engineers, Washington, D.C., 2007 | **PAGE(S):** | **KEYWORDS:** Dam safety, risk reduction measures | **BRIEF DESCRIPTION:** The purpose of this circular is to establish policy for the development, preparation, and implementation of interim risk reduction measures for dam safety. The main objective is to reduce the probability and consequences of catastrophic failure to the maximum extent that is reasonable from a practical standpoint, while long term corrective measures are being undertaken. |

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| 124 | United States Bureau of Reclamation | **TITLE:** Dam safety Performance Monitoring for High- and Significant-hazard Dams | **SOURCE:** *Reclamation Manual* FAC 01-08, Relese No. 91, United States Bureau of Reclamation, Washington, D.C., 1999 | **PAGE(S):** 6 pages | **KEYWORDS:** Dam safety, hazard | **BRIEF DESCRIPTION:** This purpose of this paper is to establish roles, responsibilities and procedures for performance monitoring to provide continuing surveillance of dams. |
| 125 | United States Bureau of Reclamation | **TITLE:** Concrete Dam Instrumentation Manual | **SOURCE:** *Concrete Dam Instrumentation Manual.* Water Resources Technical Publication, United States Departtment of the Interior, Bureau of Reclamation, Denver, 1987. | **PAGE(S):** 153 pages | **KEYWORDS:** Instrumentation systems, data handling, concrete dams, pressure measuring devices, seepage, vibration, stress, strain, movements, monitoring, dam safety | **BRIEF DESCRIPTION:** This manual provedes information needed for the installation, operation, and analysis of instrumentation systems for dam instrumentation systems. |
| 126 | United States Society on Dams | **TITLE:** General Guidelines for Automated Performance Monitoring of Dams | **SOURCE:** *General Guidelines for Automated Performance Monitoring of Dams,*Committee on Monitoring of Dams and Their Foundations, United States Society on Dams, Denver, 2002 | **PAGE(S):** 70 pages (excluding appendices) | **KEYWORDS:** Automated monitoring, planning, procurement, and installation of automated instrumentation systems, automatic data acquisition systems | **BRIEF DESCRIPTION:** This guidelines address all general aspects of automated monitoring of dams including planning, procurement, installation, operation, and maintenance of automated data acquisition systems. It attempts to bridge |

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| | | | | | | the gap between these different areas. |
| 127 | URS Corp. | **TITLE:** The Dam Seepage Monitoring System for the National Dam Safety Program | **SOURCE:** www.damsafety.com (Downloaded February 2010) | **PAGE(S):** | **KEYWORDS:** Seepage monitoring, National Dam Fafety Program | **BRIEF DESCRIPTION:** This article is on a dam seepage monitoring tool that was designed to assist dam safety engineers and owners of small to medium sized dams in their long-term performance monitoring effort. |
| 128 | van der Veen, R. | **TITLE:** Automatic Data Acquisition Systems and Databases | **SOURCE:** *Geotechnical News*, 20(1), March, BiTech Publishers, Vanvouver, Canada, 2002. | **PAGE(S):** 24-28 | **KEYWORDS:** Data acquisition system, communication methods, on-line control, data evaluation, power supply | **BRIEF DESCRIPTION:** This article gives a brief overview of the current possibilities of monitoring systems in geotechnical applications. |

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| 129 | Welch, L.R. & Paul, D.B. | **TITLE:** Performance of the New Waddell Dam Seepage Control Features | **SOURCE:** *Field Measurements in Geomechanics (Proc., 5th Intl. Symp., Singapore)*, Ed. C.F. Leung, S.A. Tan, & K.K. Phoon, Balklema, Rotterdam, Netherlands, 1999 | **PAGE(S):** 345-354 | **KEYWORDS:** Fragile foundation, continuous monitoring | **BRIEF DESCRIPTION:** This article presents a case history of a dam that was evaluated for the efficiency of its seepage control measures. |
| 130 | Williams, D.R., Balanko, L.A., and Martin, R.L. | **TITLE:** Monitoring and performance of an earth-fill dam in central Alberta | **SOURCE:** *Canadian Geotechnical Journal*, 20, 570-586, National Research Council, Canada, 1983 | **PAGE(S):** 570-586 | **KEYWORDS:** Earth-fill dam, landsliding, instrumentation, ground movements, pore pressures, slope stability | **BRIEF DESCRIPTION:** This article presents a case history involving the monitoring and performance of a 30-m high earth-fill dam in Canada. A large landslide had occurred at one of the dam's abutments. The large size of the slide rendered remediation impractical and uneconomic. A monitoring program was initiated one year after the slide to assess the performance of the dam and ensure continued safe operation. |

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| 131 | Wilson, S.D. | **TITLE:** Deformation of Earth and Rockfill Dams | **SOURCE:** *Embankment-Dam Engineering - Casagrande Volume*, Ed. R.C. Hirschfeld & S.J. Poulos, John Wiley & Sons, New York, 1973 | **PAGE(S):** 366-417 | **KEYWORDS:** Earth and rockfill dams, deformation measurements | **BRIEF DESCRIPTION:** This article covers the types of dam deformation, instrumentation, significant findings based on deformation measurements, and several case histories. |
| 132 | Wilson, S.D. & Mikkelsen, P.E. | **TITLE:** Instrumentation for Embankments and Embankment Dams | **SOURCE:** *Construction Practices and Instrumentation in Geotechnical Engineering (Proc., Conf., Surat, India)*, Indian Geotechnical Society, 1982 | **PAGE(S):** 3-10 | **KEYWORDS:** Embankment dam, movement measurements, leakage, effective stress analysis | **BRIEF DESCRIPTION:** This article discusses key issues pertaning to instrumentation of embankments including planning, procurement, and number of instruments. It provides detailed discussions on piezometers, settlement instruments, soil pressure cells, surface monitoring devices, and seepage monitoring devices. |

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| 133 | Yanmaz, A.M. & Sezgin, O.I. | **TITLE:** Evaluation Study on Instrumentation System of Cindere Dam | **SOURCE:** *Journal of Performance of Constructed Facilities*, 23(6), 415-422, American Society of Civil Engineers, Reston, VA, 2009 | **PAGE(S):** 415-422 | **KEYWORDS:** Dams, dam safety, instrumentation, monitoring | **BRIEF DESCRIPTION:** This article reviews the capability of the instrumentation installed at Cindere Dam and studies the feasibility of possible instrumentation systems. It then compares the current and alternative instrumentation system in terms of technical and economical aspects. |

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# APPENDIX B. PURPOSE AND USE OF INSTRUMENTATION DEVICES & DATA MANAGEMENT SYSTEMS

This appendix provides a listing of the most commonly used instruments for performance monitoring of dams. Each listing gives a brief description of the instrumentation, how it works and where it is used along with a schematic of the instrument and a photograph. Further information can be found on the web sites of instrumentation vendors. The following lists some of the sources of instrumentation:

- www.geokon.com
- www.geomechanics.com
- www.geonor.com
- www.oyo.com
- www.roctest.com
- www.rst-inst.com
- www.solinst.com
- www.slopeindicator.com
- www.campbellcsi.com
- www.geotech.co.uk
- www.interfels.com
- www.omega.com
- www.measurementsgroup.com
- www.soilmoisture.com
- www.durhamgeo.com
- www.westbay.com
- www.borros.se
- www.geocomp.com
- www.sisgeo.com
- www.soil.co.uk
- www.solexperts.com

The following list summarizes the instruments described in this appendix:

Acoustic Emissions Testing
Automated Total Station (Robotic Total Station)
Convergence Gage
Crackmeter – Electronic
Crackmeter – Grid
Deep Benchmark
Digital Camera
Earth Pressure Cell
Extensometer (Probe type)
Extensometer (Rod type)
Fiber Optic Sensors
Flowmeter
Flowmeter (Heat pulse type)
Global Positioning System
Inclinometer
Inverted Pendulum
In-Place Inclinometer (IPI)
Light Detection and Ranging (LiDAR)
Liquid Level Gage
Load Cell
Observation Well
Piezometer (electronic)

Plumb line
Seismograph
Settlement Plate
Strain Gauge
Stress Cell
Strong Motion Accelerometer
Survey Monuments
Synthetic Aperture Radar (InSAR, PsInSAR, GbInSAR)
Temperature SensorTilt Beam
Tiltmeters
Time Domain Reflectometry (TDR)Turbidity MeterWeather Station

## Acoustic Emissions Testing

### Description:

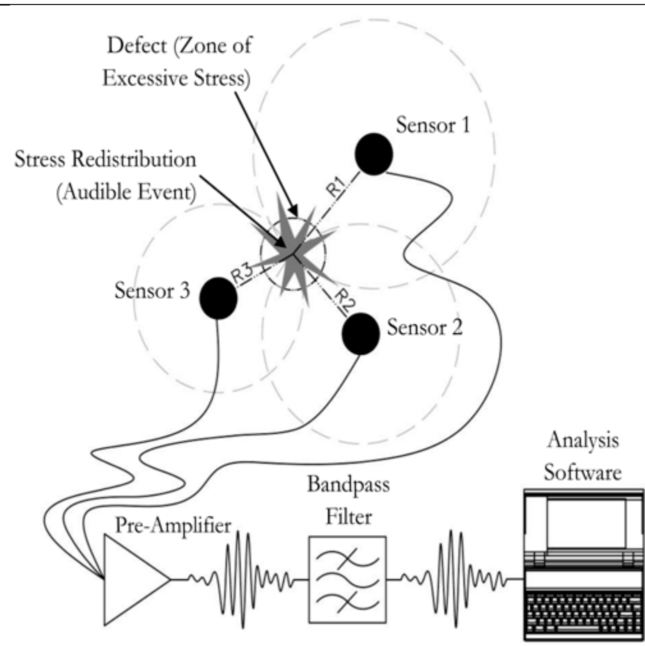
Acoustic Emission Testing (AET) records the sound characteristics emitted by the release of energy due to sudden stress redistribution within a material. The rate of sound emission, the magnitude and the frequency may indicate the formation of a rupture within the material.

### How it works:

Sensitive microphones are strategically fixed to the structure in question so as to minimize the influences from background noise. As the structure is sheared, elastic and plastic deformation occurs. This deformation, caused by redistribution of stress within the material, releases an instantaneous burst of sound energy. This audible event then propagates through the material and is collected by the sensors. The waveform may be channeled through a pre-amp to increase the gain, through a bandpass filter to remove background noise, and finally to the analysis software. By comparing the time it takes for the waveform to reach each sensor, a location of the defect can be determined.

### Where it is used:

AET is commonly used to inspect pressure vessels, pipelines, welds, bridges, dams and also used for geological seismic research. Several researchers have explored the use of AET to detect developing distress within dams.




Acoustic Emission Concept

## Automated Total Station (Robotic Total Station)

### Description:

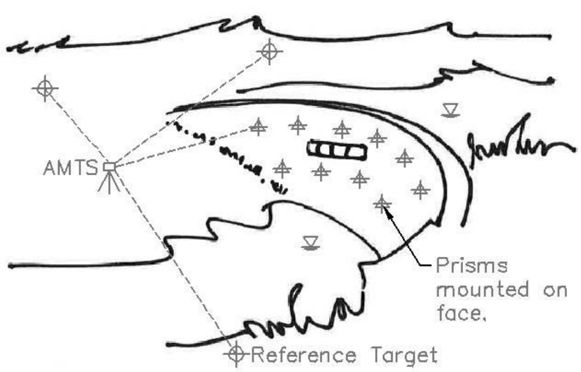
The automated or robotic total station is a motorized total station with laser distance meter to precisely measure distance, azimuth and zenith to a reflecting target. It is used to precisely measure change in position of reflecting targets placed on the dam or other structure components relative to a set of fixed reference targets over time. Can measure x, y, z movements to ± 1 mm.

### How it works:

With the measurements of distance, azimuth and zenith to a reflecting target and to several reference targets, the total station calculates the x, y, and z location of each reflecting target (prism). The total station is electronically controlled either locally or remotely to periodically take a set of readings of the targets within its field and the reference targets. Automated total stations are quite accurate at measuring change in x, y and z position of a target relative to fixed targets to about ±1 mm (one standard deviation). The total station must be mounted to a base that remains firmly fixed for the duration of the measuring sequence; however by using reference targets outside the zone of expected movement, the total station can slowly move over time and still give accurate measurements of the target's change in position.

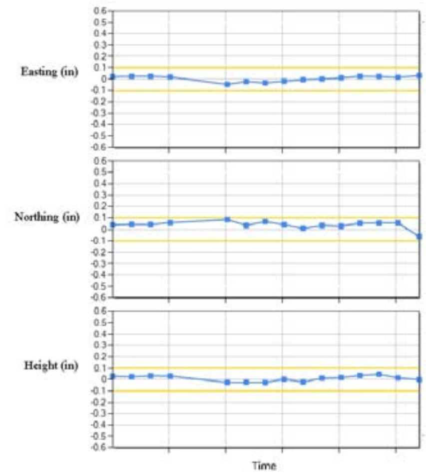
### Where it is used:

An automatic total station is used whenever measurements of deformation on the exposed surface are required on an hourly to daily basis. Reflecting prisms can be installed at any location which is considered to be critical and expected to move.




AMTS Concept

Automated Total Station Setup




AMTS Graph

## Convergence Gage

### Description:

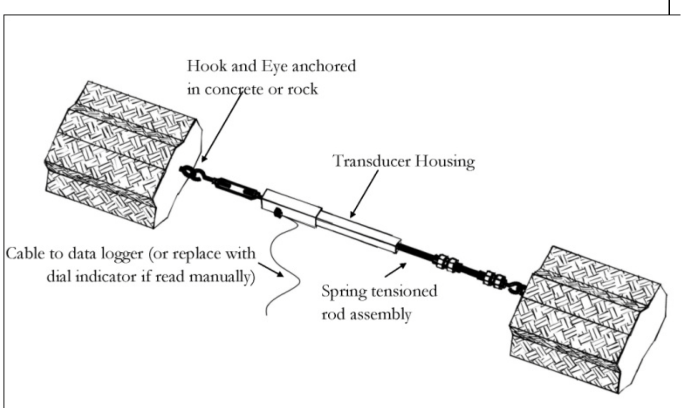
A convergence gage measures the change of distance between two anchor points to determine whether those points are converging or separating.

### How it works:

The convergence gage consists of a calibrated tape, a spring mechanism to tension the tape to a constant value and connectors on each end to hook into eye bolts. The connectors are positioned into the eye bolts at the same position each time and the tape is tensioned to a force recommended by the manufacturer. Modern versions have a digital readout and can be read to 0.001 inch. Where movements are only a few thousands of an inch, the technician must be careful to perform the measurements with the same technique each time.

### Where it is used:

Convergence gages are typically used to measure small amounts of convergence or divergence between two points where precise readings are required and other techniques cannot be used. Its most common application in dams would be in tunnels and underground openings to measure dimensional changes over time.




Schematic of Convergence gage (Not to Scale)


Measurement head of Convergence gage

## Crackmeter – Electronic

### Description:

A crackmeter indicates the change in width of a crack. It is used to determine whether the crack is widening, closing or not changing.

### How it works:

A crackmeters consists of two anchors, two ball joints, and a high resolution displacement sensor, arranged in the configuration shown below. Holes are drilled on either side of an existing crack. The holes are filled with grout, and the anchors are inserted into each hole. The displacement sensor is then attached, and initial readings are taken. The initial reading serves as the datum from which to compare all future readings in order to determine whether the crack is expanding or contracting.

### Where it is used:

A crackmeters is used to monitor a crack in a structure, or a joint in rock. They are frequently installed on structures adjacent to construction activities, or structures most likely to be affected by seismic activity. They are also used to determine the behavior of structural members during loading or unloading. A Crackmeter may also be used to monitor a tension crack in an earthen slope.

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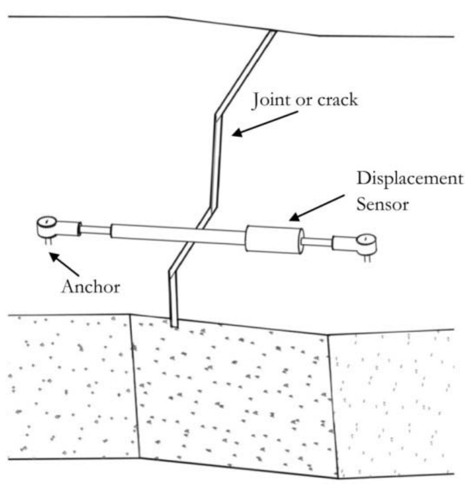
|  |  |
| Crackmeter Configuration | Crackmeter (from www.Geokon.com) |

## Crackmeter – Grid:

### Description:

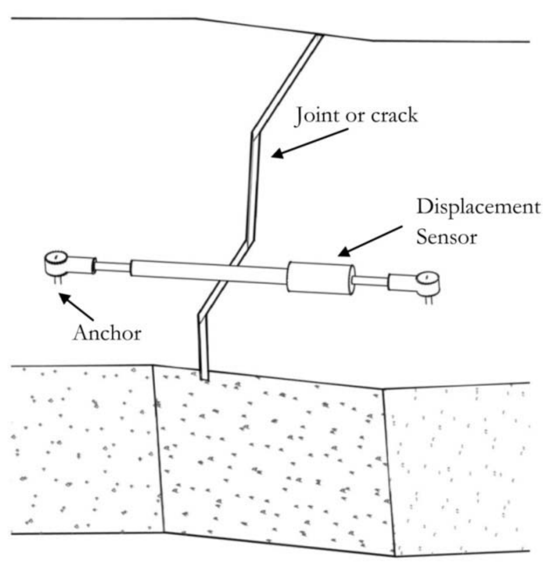
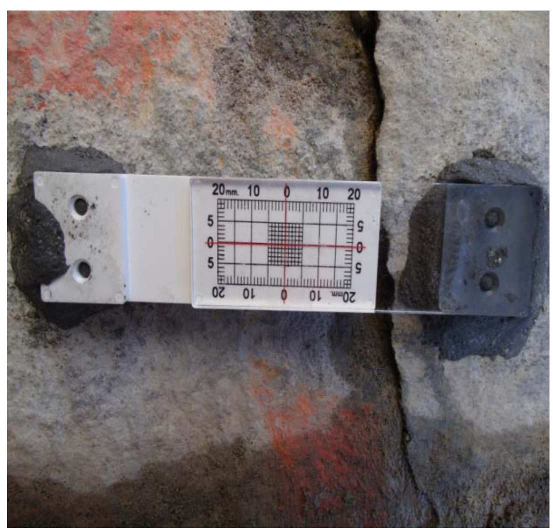
A crackmeter measures the change in width of a crack. It is used to determine whether the crack is expanding, contracting, or not changing.

### How it works:

A manual crackmeter consists of two plastic plates, each fixed on either side of an existing crack. A cursor on one plate overlaps a grid on the other, so that any change in width of the crack can be read manually using the scales marked on the face of the gage. Once the gage is installed, initial readings are taken. The initial readings serve as the datum from which to compare all future readings in order to determine whether the crack is expanding or contracting. Current practice is to photograph the crack gage when taking the reading so that the value can be seen in the photo and provide a permanent record of the reading. For applications where remote monitoring of very small movements is required, crackmeters with electronic differential or vibrating wire displacement sensors should be used.

### Where it is used:

A crackmeter is used to monitor a crack in a structure, or a joint in rock. They are frequently installed on structures adjacent to construction activities, or structures most likely to be affected by seismic activity. They are also used to monitor the behavior of structural members during loading or unloading. A crackmeter may also be used to monitor a tension crack in an earthen slope.

|  |  |
|---|---|
| Crackmeter Configuration | Grid Crackmeter |

## Deep Benchmark

### Description:

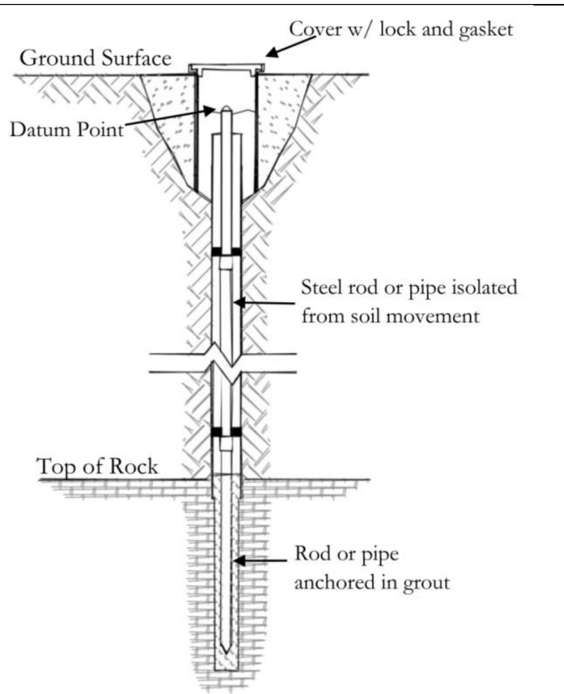
Deep benchmarks are survey control points that provide a vertical reference datum for surveying.

### How it Works:

A deep benchmark consists of a steel pipe or stainless steel rod set into firm bedrock. The rod or pipe is surrounded by an outer protective casing which isolates it from the surrounding soil movement. Centralizers are placed between the inner rod and outer casing to keep the rod free from downdrag by the casing. The annulus between the inner rod and outer casing may be filled with grease. The benchmark is protected at the surface with an outer casing cast into concrete and ideally a locking top. Benchmarks should be labeled with a unique indelible mark.

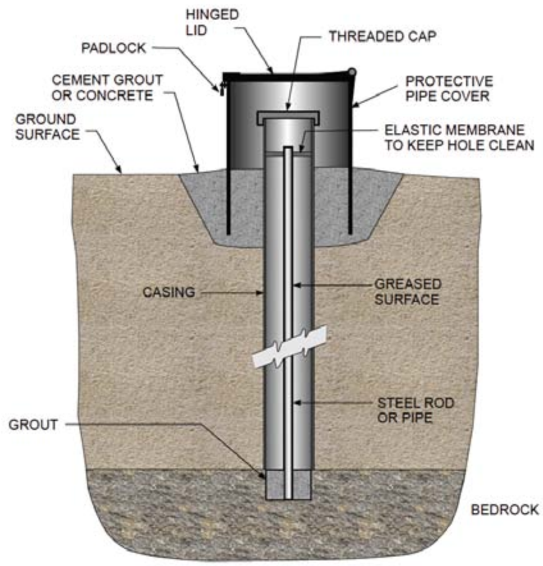
### Where it is used:

Deep benchmarks are used when stable ground level benchmarks are not available and when survey level precision of the highest order is desired. Deep benchmarks reduce the effects of ground movements and temperature on measured elevations.




Deep Benchmark Detail (Not to Scale)

Installed Deep Benchmark




Alternate schematic adopted from D'Appolonia (2009) and Dunnicliff (1993)

## Digital Camera

### Description:

Digital images can be used with proper software to estimate the horizontal and vertical movements of targets located at distances away from the camera such as one located along the crest of the dam to indicate settlement and horizontal translation of the top of the dam.

### How it works:

Fixed targets which are clearly visible by a digital camera are installed along the face of a dam or embankment. Using a two or more fixed digital cameras, pictures are taken periodically, capturing a group of defined targets in any one image with a scale included or a known elevation. This process allows tracking to be implemented in three dimensions, creating tracked pixel coordinates for each camera. The software uses the tracked pixel coordinates from each camera to compute the direction from each to a given target, and is able to determine a target position that best suits the pixel coordinates. The use of a scale or known elevation within the pictures allows the software to accurately determine these target positions. Over any duration of time the software can determine if any of the points are moving vertically or horizontally by comparing initial target positions to current target positions.

### Where is it used:

The digital camera is an excellent cost effective instrument to monitor dams and embankments. However, the accuracy of measurement is not as good as those from AMTS and GPS instruments. It is most commonly used for short-term monitoring of full-scale load tests where the displacements are expected to be large.

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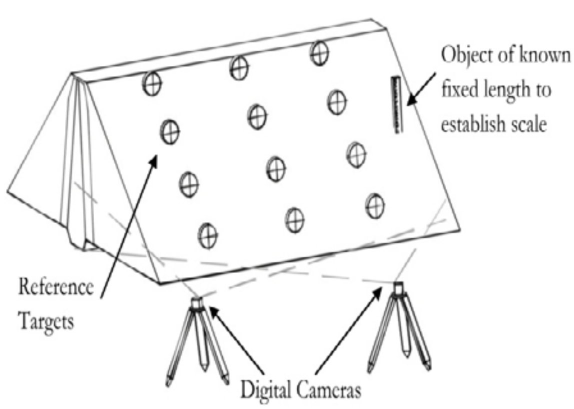
|   |  |
| Digital Camera Setup | Digital Camera Reference Targets (Photo from of IJKdijk Project in Netherland) |

## Earth Pressure Cell

### Description:

An earth pressure cell measures the normal stress across a plane within soil.

### How it works:

An earth pressure cell consists of two circular stainless steel plates that are welded along the edge and separated by a narrow void filled with de-aired oil. Changes in earth pressure normal to the plates force the two plates to squeeze together causing the fluid pressure to increase. The pressure of the fluid within the earth pressure cell is then measured by a pressure transducer. A calibration factor is applied to convert the readings from the pressure sensor to earth/contact pressure. Ideally the earth pressure cell should have the same stiffness as the surrounding ground so as not to change the soil stresses. However the measurement principles used require the cell to have a stiff plate which leads to irregular pressure distributions on the face of the cell. This can cause over registration or under registration of the stress. Earth pressure cells measure total stress normal to the face of the cell.

### Where it is used:

Earth pressure cells might be installed at the contact of a dam and its foundation to measure normal stresses. They have also been used in a vertical orientation to measure horizontal stresses within an earthen dam. Due to difficulties of installing the instrument without affecting the reading, earth pressure cells not commonly used in dams.

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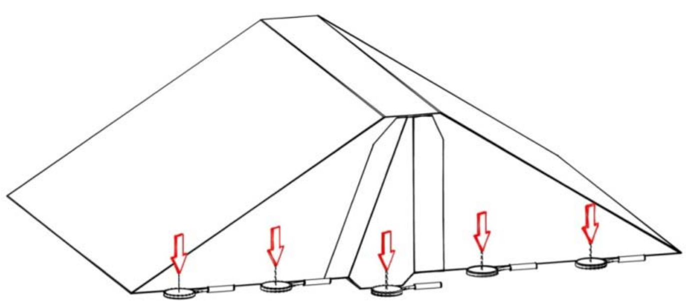
|  |  |
| Earth Pressure Cells monitoring the total stress distribution beneath an embankment dam | Earth Pressure Cells (photo from www. sisgeozemin.com) |

## Extensometer (Probe type)

### Description:

A probe extensometer measures change of vertical distance between two or more points along a common vertical axis.

### How it works:

Magnets are spaced along a length of casing and the casing is positioned into a borehole. The annulus between the casing and the wall of the borehole is grouted with a weak grout. Vertical movement of the soil around the magnets will raise or lower them with each magnet moving independently of the others. A probe fastened to a calibrated tape is lowered into the casing. Some indication (sound, flashing light, gage movement) is given each time the probe passes by a magnet. The reading on the tape at each magnet location is recorded. The difference in movement between two magnets indicates the compression or expansion of soil between those two levels. An alternate method replaces the magnets with steel plates and the probe consists of an induction coil that indicates the position of a plate as the coil passes by. When vertical displacements of inches are expected the casing must include collapsible sections to avoid buckling of the casing. Inclinometer casing may be used together with a probe extensometer.

### Where it is used:

Extensometers are typically installed vertically to measure settlement or heave in excavations, foundations, dams and embankments. They can also be installed horizontally to measure lateral deformation or formed into concrete to measure deformation between two magnets and compute average strain. See Dunnicliff (1993) for a complete summary of probe extensometer types, their accuracy together with their advantages and limitations.

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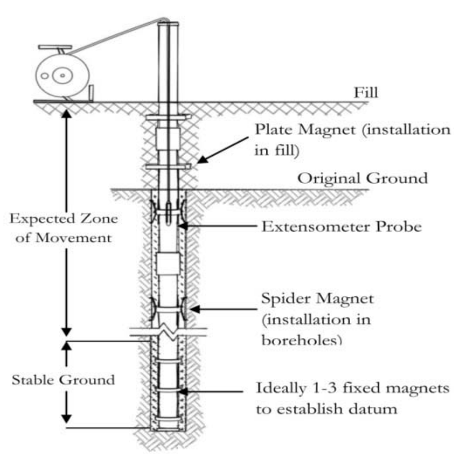
|   |  |
| Schematic of Probe Extensometer (Not to Scale) | Magnetic Probe Extensometer (photo from www.Geokon.com) |

## Extensometer (Rod type)

### Description:

A rod extensometer measures change of vertical distance between two or more points along a common vertical axis using rods anchored at various depths that extend to the surface of a casing.

### How it works:

Stiff rods are anchored to soil or rock selected depths in a borehole with the rod extending to the top of the casing. Up to eight rods may be placed in a borehole. The movement of the end of an exposed rod is measured relative to an established reference. Each rod is encased in a plastic tube that contains grease to minimize friction between the rod and the tube. The annulus between the tubes and the wall of the borehole is grouted with a weak grout. The tops of the rods are collected in a cap that provides the established reference. Vertical movement of the soil around the rod anchor will raise or lower each rod. The difference in movement between two rods indicates the compression or expansion of soil or rock between those two levels. When displacements of inches are expected the tubes must include collapsible sections to avoid buckling.

### Where it is used:

Rod extensometers are typically installed settlement or heave in excavations, foundations, dams and embankments. They can also be installed at any angle including upward as in the crown of a chamber. See Dunnicliff (1993) for a complete summary of extensometer types, their accuracy together with their advantages and limitations.

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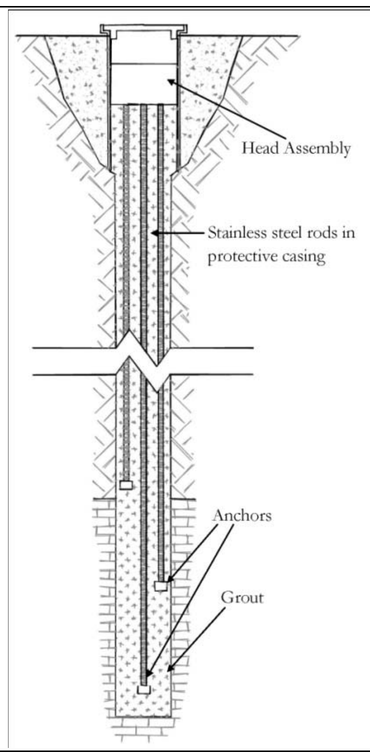
|  |  |
| Schematic of Rod Extensometer (Not to Scale) | Head containing four rod extensometers |

## Fiber Optic Sensors

### Description:

A fiber optic sensor uses changes in light reflection at a point along a fiber or at its end to measure a change in the physical environment. Sensors have been developed to measure temperature, strain, pore pressure, tilt and acceleration.

### How it works:

Fiber optic sensing involves sending a light pulse through a fiber optic cable. Changing temperatures, strains and pressures affect the characteristics of light transmission through the fiber optic cable. When the pulse encounters a change in these characteristics, some light is "scattered" back to the source. Examination of the scattered light spectrum and the time it takes to make the round trip allows for the determination of location, temperature, pressure and strain information. Fiber optic sensors for geotechnical applications can be divided into two categories, point sensors or distributed sensors. Point sensors use Fiber Bragg Gratings (FBG) which are alterations in the density of the glass core produced by exposing the fiber to intense ultraviolet light in a controlled environment. These gratings are tuned to respond to a particular frequency during the manufacturing process and are placed at regular intervals along the fiber cable. The result is a series of points along a single fiber line each responding to a unique frequency allowing for measurements with high spatial resolution to be acquired. Distributed sensors use the actual fiber as the sensor and are based on the principles of Raman and Brillouin scattering, both a function of the instantaneous acoustic velocity of the fiber. Since the acoustic velocity of a medium is dependent on strain and temperature, changing acoustic velocities along the fiber result in a small amount of scattered light back to the source. Spectral and time of flight analysis of the scattered signal can produce temperature and strain data with a spatial resolution of about 1 meter making distributed sensors ideal for projects involving large areas and long distances.

### Where it is used:

Fiber optic sensors may be buried within a dam or fastened to the surface of components of a dam. Temperature and strain sensors can be mounted on the surface of existing structures. Temperature, strain, pore pressure and seepage rate can be monitored on sensors placed within the dam. Fiber optic sensing is a relatively new technology that is beginning to see applications in dams. A particularly useful feature of fiber optic sensors is that they can, if required, provide distributed sensing over very large distances. Data from point sensors can be transmitted over fiber for miles without changing the reading. Fiber optic sensors can be cast into concrete portions of dams to monitor the temperature change during curing.

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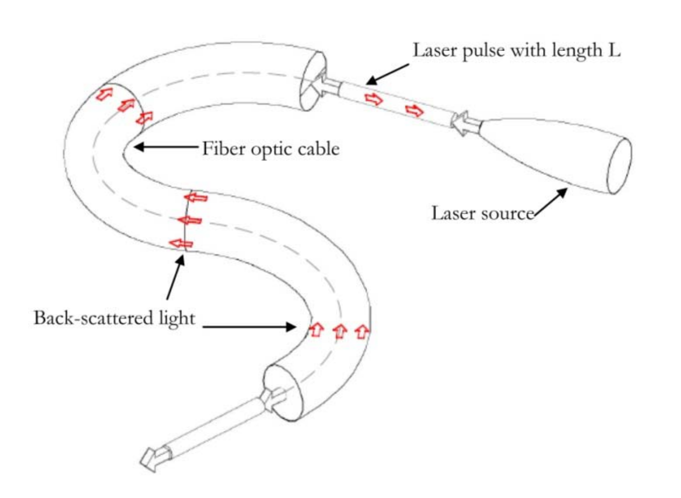
|   |  |
| Schematic of Fiber Optic Sensor Configuration | Combined strain and temperature fiber optic sensor (photo from SMARTEC) |

# Flowmeter

## Description:

Flowmeters are used to measure the rate of flow in an open channel or full pipe.

## How it works:

Flow meters are of two types. An open channel flowmeter forces flow to pass through a shaped outlet. Common types include the Sharp-Crested Weir, the V-Notch Weir, the Cipolletti weir, the Rectangular-Notch Weir, and the Parshall Flume or Venturi Flume. The depth of flow through the outlet is measured and converted to flow rate using a calibration curve for the outlet. The height of flow may be measured with a scale, a pressure transducer positioned at the bottom of the opening, a float with a sensor to measure its position, or an ultrasonic sensor positioned above the channel to measure the distance to the water surface. The other type uses an electric sensor within a filled pipe where the electrical output is proportional to flow rate. Different sensor types measure pressure loss through a constriction in the pipe, velocity, mass flow rate or rate of heat loss from an electrical coil positioned in the flow stream.

## Where it is used:

Flow meters are used in dams primarily to measure the discharge from seeps, springs and drains. For dams most flow measurements are made using the open channel method. Of most interest is detecting unexpected changes in rate of flow. Flow rates may vary so much that measurements within a closed pipe are not practical, except on some dewatering systems. The challenge is to collect all water discharging from seeps, springs, and drains so it flows through one or more channels. Periodic maintenance is required to clean the channel and measuring system of sedimented soil particles and plant growth, including algae. The readings may be affected by surface water inflow from weather events.

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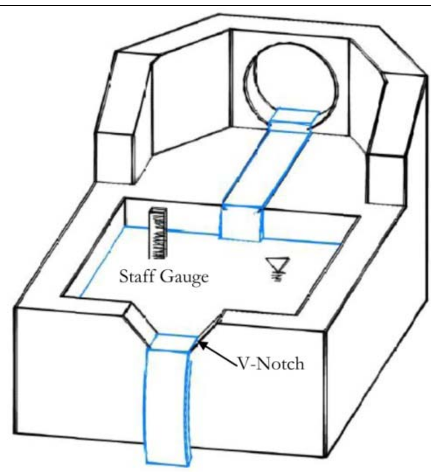
|   |  |
| Flow Weir Concept | Flow Weir (photo from www.magryn.com) |

## Flowmeter (Heat Pulse type)

### Description:

The rate of heat loss from a sensor is related to the flow rate of water across the sensor positioned at the bottom of a borehole.

### How it works:

The heat-pulse flowmeter contains a heating grid and two thermistors located on either side of the grid. The flow meter is positioned in the borehole so that it is exposed to water flowing by the borehole. In one type of sensor, the grid is heated, and the temperatures of the thermistors are recorded. Changes in temperature with time are used to compute the flow rate and estimate the direction of flow. In another type, the amount of current required to maintain the sensor at a set temperature is proportional to the rate of flow.

### Where it is used:

A heat-pulse flowmeter is typically used for measuring flow in low-yield wells, but may also be used to measure flows upwards of 100 gpm. A borehole flowmeter such as a heat-pulse flowmeter may be used to identify fractured, highly permeable zones beneath or near a dam in order to identify areas of potential excessive water leakage.

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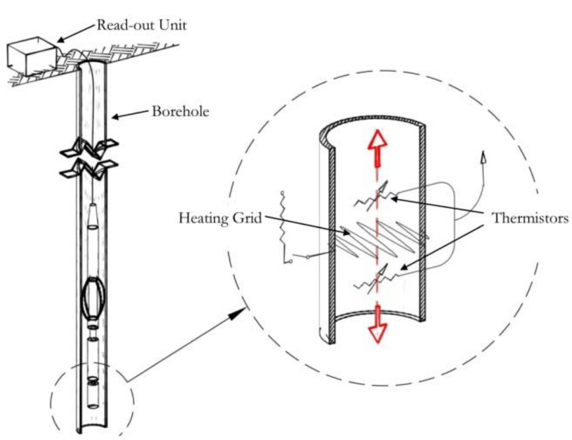
|  |  |
| Heat-Pulse Borehole Flowmeter Configuration (Not to Scale) | Heat-Pulse Flowmeter (photo from http://water.usgs.gov/ogw/bgas/flowmeter) |

## Global Positioning System (GPS)

### Description:

Global positioning systems use ground receivers which to capture timing signals from multiple satellites to determine their latitude, longitude and elevation.

### How it works:

The GPS constellation consists of satellites orbiting the earth that broadcast precise timing signals. A GPS receiver calculates its position using the timing signals from at least four satellites. A reference receiver can be used to determine the change in the position of other receivers relative to the reference. This differential GPS approach together with averaging of readings over a 24 hour time interval provides readings precise to a standard deviation of 1 mm. One or more reference receivers can be located within approximately 30 kilometers of the project, ideally situated on rock. GPS receivers operate around the clock and in most weather conditions. They require line of sight to at least four satellites. A typical receiver station consists of an antenna, a power supply, an electronics pack and a radio to transmit readings to a central computer.

### Where it is used:

GPS receivers can be used to monitor changes in x, y and z position of points on the ground surface or the top of a structure. Readings rates of up to 10 per second are possible but the accuracy at this high rate is only about 10 mm.

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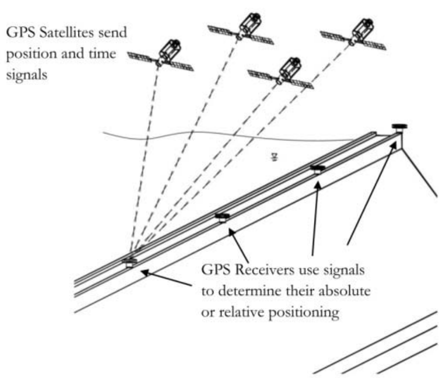
|  |  |
| GPS Concept | GPS Receiver with Antenna |

# Inclinometer

## Description:

An inclinometer is used to measure subsurface lateral movement away from the axis of a near vertical casing installed within a borehole. Inclinometers may also be used to measure the settlement of a casing laid horizontally across the foundation of a dam.

## How it works:

Plastic inclinometer casing is assembled and inserted into a borehole to a depth at least 10 feet below the bottom of any expected horizontal displacement of the ground. The casing is grouted into the borehole with weak grout. The inner part of the casing has four orthogonal grooves that run continuously over the length of the casing. One pair of grooves is aligned with the expected direction of maximum horizontal movement. The inclinometer probe has spring loaded wheels that ride within the grooves to keep the probe aligned with a known direction. The probe is lowered to the bottom of the casing using a cable that has a calibrated length. It is then raised in increments of length L and readings are taken at each increment. L is typically 2 ft or 1 m. The probe contains a tilt sensor that produces a voltage proportional to the angle of tilt $\theta$ with respect to true vertical. Since the distance between measurements L is known, the horizontal distance $L\sin\theta$ can be calculated. By summing readings from the bottom to a certain depth, the horizontal position of the casing at that point can be determined. By comparing subsequent readings to the initial readings, horizontal displacement is computed at the depth of each reading. Probe inclinometers can be accurate to within ±¼ inch per 100 ft.

## Where is it used?

Inclinometers are typically used in dams to monitor subsurface horizontal movement of slopes and horizontal movements of deep excavation support systems. They may also be used to detect slip between the dam and its foundation or along a horizontal plane of weakness.

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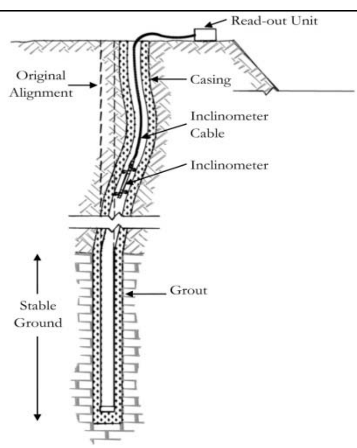
|  |  |
| Inclinometer Detail (Not to Scale) | Inclinometer Casing Installation |

## Inverted Pendulum

### Description:

An inverted pendulum is used to precisely measure the horizontal movement of a point within the dam relative to its base.

### How it works:

A vertical hole is drilled from the top measuring point to the base reference point, which may be in the foundation of the dam. An anchor is installed at the bottom of the hole. A float tank sits atop a support frame which is anchored to the dam. A wire connects a float in the tank to the anchor at the bottom of the hole. Gravity keeps the wire aligned vertically. The position of the float in the float tank indicates horizontal movement of the tank relative to the bottom anchor.

### Where it is used:

An inverted pendulum are used to monitor horizontal movements of tall concrete structures.

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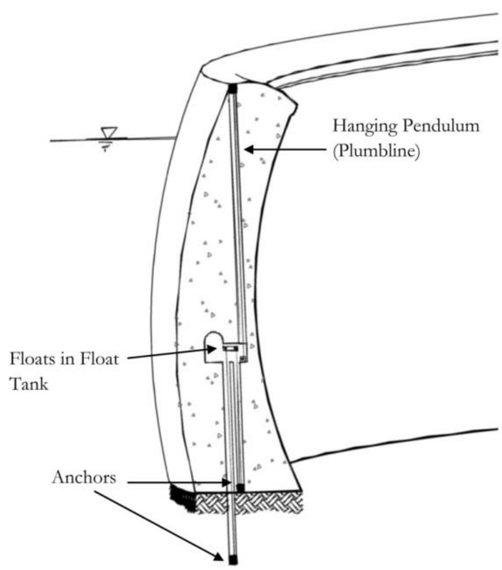
|  |  |
| Inverted Pendulum and Hanging Pendulum Arrangement | Inverted Pendulum (photo from of RST Instruments Ltd.) |

## In-Place Inclinometer (IPI)

### Description:

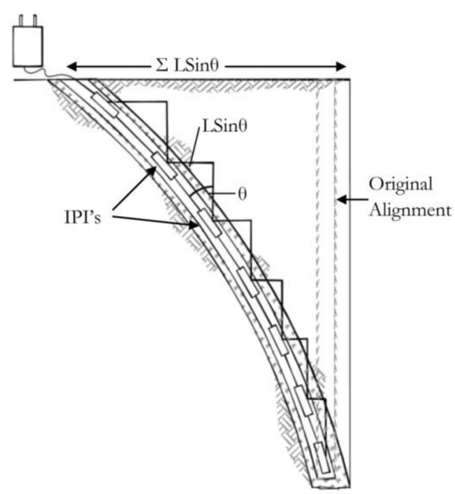
An in-place inclinometer is a string of tilt sensors connected by stiff rods that is positioned in a vertical casing to measure horizontal movement of the casing at each sensor location over time.

### How it works:

In-place inclinometers are typically installed in standard grooved inclinometer casings within boreholes and utilize tilt sensors to make accurate measurements of inclination. The tilt sensors are connected with stiff rods of known lengths. The output of the tilt sensor is proportional to the angle of tilt $\theta$ with respect to true vertical. Since the gage length between pivot points L is known, the horizontal position of the sensor relative to the end of its rod can be calculated as $L\sin(\theta)$. By comparing subsequent readings to the initial readings, lateral deflection of points along the casing is determined. The sensors are left in the casing to collect readings of horizontal movement over time. The string can be installed to be temporarily removed for maintenance and for independent verification of the readings with an inclinometer probe.

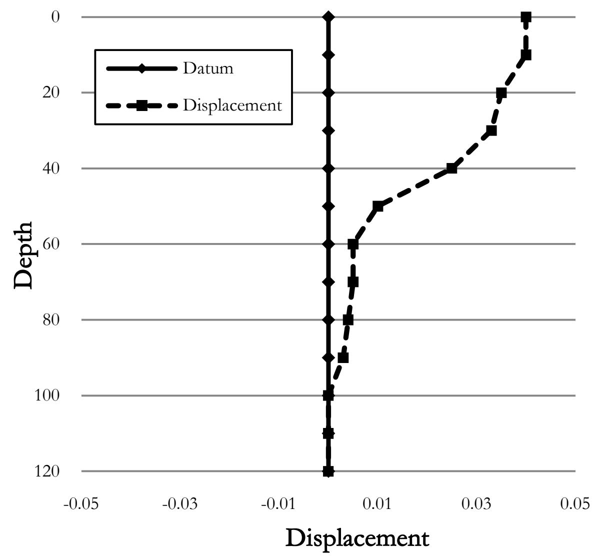
### Where it is used:

In-place inclinometers are utilized on structures that require real time monitoring for deformations and locations that are difficult or time consuming to access. Inclinometers are typically used in dams to monitor subsurface horizontal movement within the dam, its foundation and the abutment areas. They may be used during construction to verify design assumptions or they may be monitored over the life of the dam to help ensure that the dam and surrounding slopes remain stable. Versions are available that can be read hundreds of times per second and indicate horizontal movement of a dam during and following an earthquake.




IPI Configuration Showing Exaggerated Deformation (Not to Scale)

Installed In-Place Inclinometer




Example IPI data plot

## Light Detection and Ranging (LiDAR)

### Description:

LiDAR is airborne equipment that uses satellite positioning and light reflection to develop precise contour maps of the surface of the earth, it may be used to detect movements on the surface of a dam to a resolution of about a ½ inch.

### How it works:

LiDAR equipment use the time for light to travel to an object and back to measure distance. GPS and Inertial navigation equipment are used to precisely locate the aircraft so that the ground surface can be accurately measured. The combined information yields s precise digital elevation model. The intensity of the reflected beam is a measure of the reflectance of the surface and can also be used to gain knowledge of surface material characteristics.

### Where it is used:

LiDAR can be used in conjunction with GPS to detect movements on the surface of a dam to a resolution of about ½ inch. It can be used to locate potential dam sites, identify areas at risk for flooding and for the development of evacuation plans. LiDAR is also a valuable tool for the 3D visualization of projects. In monitoring applications the change in elevation with time may indicate the development of a large landslide.

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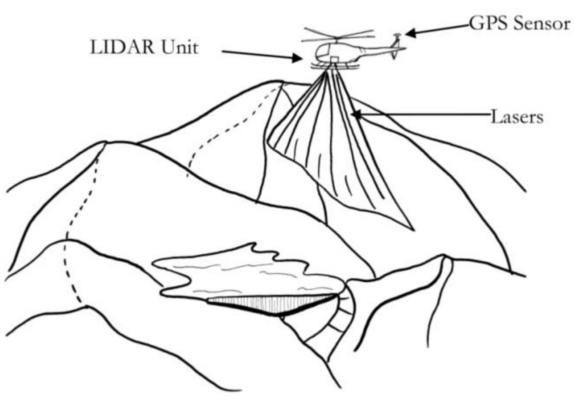
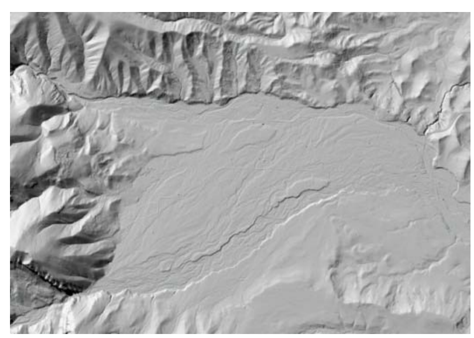
|  |  |
| LIDAR Concept | Example map produced using LiDAR technology (photo from National Geospatial Management Center website http://www.ncgc.nrcs.usda.gov/programs/watershed-protection.html) |

## Liquid Level Gage

### Description:

A sensor that gives precise measurements of the change in elevation of point located along a horizontal liquid filled pipe, used for precise measurements of settlement.

### How it works:

A settlement gage can be constructed by attaching a pressure sensor to a plate and connecting it to an external fixed reference point with a tube filled with water. The pressure on the transducer will increase as the plate settles. Provided the fluid level in the reference point does not change, the change in reading of the pressure transducer will be proportional to change in elevation of the plate. A "liquid level system" consists of string of very precise pressure sensors connected to a common tube or pipe that contains liquid. Gravity keeps the fluid at the same level all along the pipe and provides a reference. Each sensor is fixed to a point that may settle or heave which causes a change in the reading of the sensor.

### Where it is used:

Liquid level gages are used for precise measurements of settlement or heave. They are alternatives to settlement plates and extensometers, their advantage being higher resolution and precision and the ability for automated reading.

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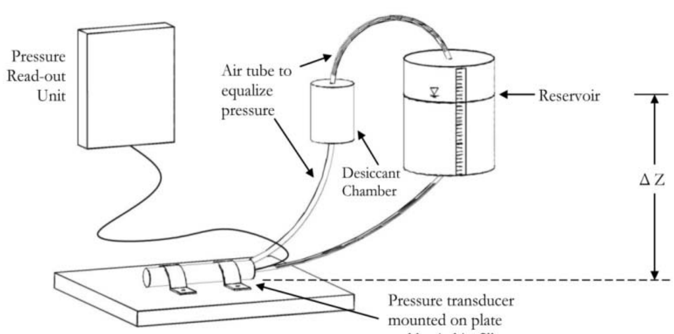
|  |  |
| Liquid Level Gage Configuration | Liquid Level Gage (photo from www.Geokon.com) |

# Load Cell

## Description:

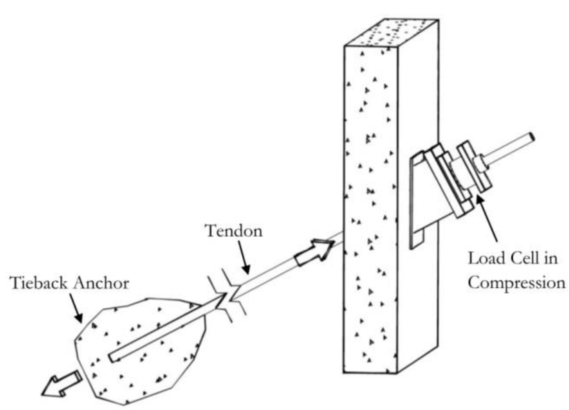
A load cell is used to measure force in a structural member such as a tie down anchor or a compression member.

## How it works:

A load cell is fitted into the member for which the load is to be measured so that it experiences the same compressive or tensile force as the member. As the force changes the load cell is compressed or extended and gives a reading that is linearly proportional to force. A load cell might be positioned on top of a pile and a force applied to the pile to measure its capacity. Other load cells are manufactured with a hole in the center so that tension elements such as rock anchors can pass through the middle of the cell and the cell becomes the seat of the anchor head. The compressive force measured in the load cell equals the tension applied to the anchor. Most load cells contain 3 to 6 strain gages the readings of which are averaged to obtain a single value of axial load. This averaging removes the effects of any bending that may develop in the sensor from uneven loading. The strain gages may be vibrating wire or resistive type.

## Where it is used:

Load cells are frequently to measure forces in tiebacks, rock anchors, tie down anchors or other structural members. During proof testing for tiebacks and rock bolts, load cells confirm the load designated by the hydraulic pressure applied to the jack at that point in time. Throughout the life of the project, a load cell to demonstrate that the required force is maintained in the anchor. Load cells provide an electronic output for automatic data gathering.




Tieback Configuration with Load Cell

Load Cell used in a static pile load test

# Observation Well

## Description:

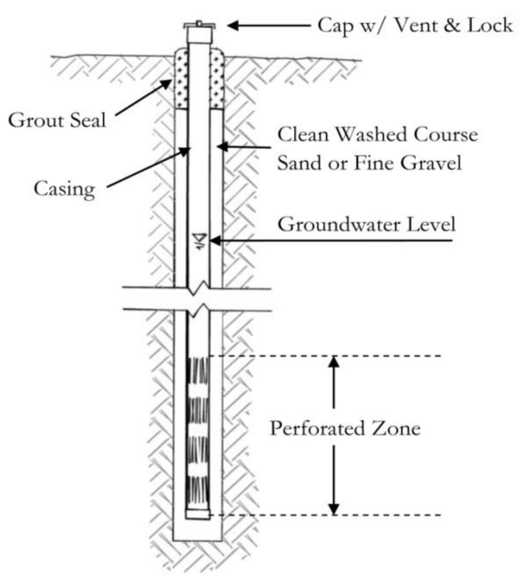
Observation well is a vertical conduit (usually a plastic pipe) into the ground that is used to measure the depth to groundwater from the surface of the ground.

## How it works:

An observation well provides an internal space within a pipe for water to flow into or out until the level in the pipe equals the groundwater level outside the pipe. Various methods are used to measure the depth to the water surface in the pipe. This surface rises and falls with the groundwater. An observation well consists of a perforated section of pipe attached to a riser pipe, installed in a sand- or gravel-filled borehole. A surface seal made of cement or other material is needed to prevent surface water from entering the borehole. Also a vent is required in the pipe cape to allow water to freely flow through the perforated section of pipe or wellpoint. The elevation of the water surface in the observation well is determined by sounding an open standpipe piezometer.

## Where it is used

In current practice, observation wells are frequently used to determine the depth to the top ground water surface and monitor how that changes with seasons. They are also used to collect samples of groundwater for chemical testing. Observation wells that cross through layers of soil with differing permeability should not be used. For this reason, use of observation wells for monitoring of dams is declining in favor of piezometers. Observation wells are frequently used to measure drawdown for pump tests to measure soil permeability and quantify of flow.




Observation Well Detail (Not to Scale)


Installed Observation Well

## <u>Piezometer (electronic)</u>

### Description:

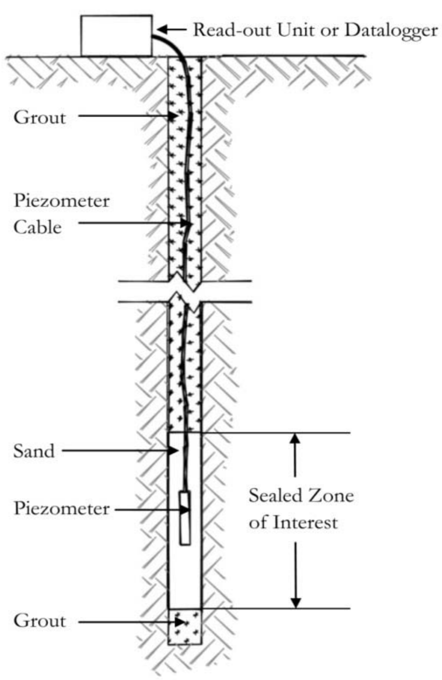
Piezometers are used to measure pressure of the pore water in the voids of soil and rock, also used to determine how water pressures change within a dam and its foundation.

### How it works (vibrating wire piezometers):

A transducer is lowered by a cable down a borehole to the desired elevation and sealed An impermeable zone is created above the sensor with bentonite or cement-bentonite grout to isolate the sensor so it reads the pore water pressure at its depth. Water pressure acts on transducer to create an electrical output proportional to the water pressure. Most piezometer sensors also include a thermistor allowing for the measurement of temperature. Piezometer transducers may be of the vibrating wire type or piezo-resistive type.

### Where it is used

Piezometers are installed in boreholes or existing standpipes into the foundation, embankment and abutments of a dam. Piezometers beneath a concrete dam monitor uplift pressures on the dam. Piezometers installed in the embankment portion of an earth dam indicate construction induced pore pressures that may lower soil strength. They are also used to determine the effectiveness of the dam's core at controlling pore water pressures in the downstream portion of the dam. Clusters of piezometers can be used to establish of the pattern of water flow through the dam and its foundation to help isolate locations with unacceptable performance.




Piezometer Detail (Not to Scale)

Vibrating Wire Peizometers

## Plumb line:

### Description:

A plumb line is fastened to the dam at one elevation and hung to another point directly below it to measure relative change in horizontal position of the two points which gives a measure of the rotation of the structure between those two points.

### How it works:

A weight (plumb) is suspended on a wire which is fixed to the structure. Gravity holds the wire vertical. A reference frame at the level of the plumb is used to indicate changes in the horizontal position of the plumb over time. The plumb may be suspended in an oil tank to minimize oscillations. Measurements can be taken at more than one location along the wire.

### Where it is used:

Plumblines are used to precisely monitor rotations of concrete dams.

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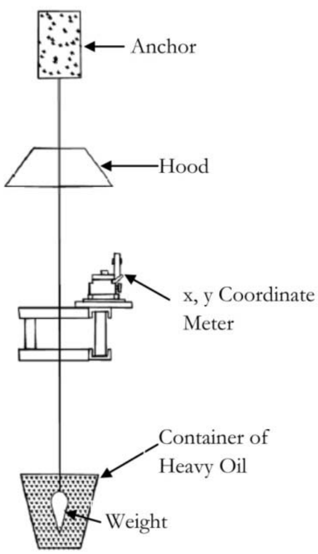
|  |  |
| Plumbline Monitor Configuration | Installed Plumbline Displacement Monitor (photo from Soil Instruments Ltd.) |

## Seismograph:

### Description:

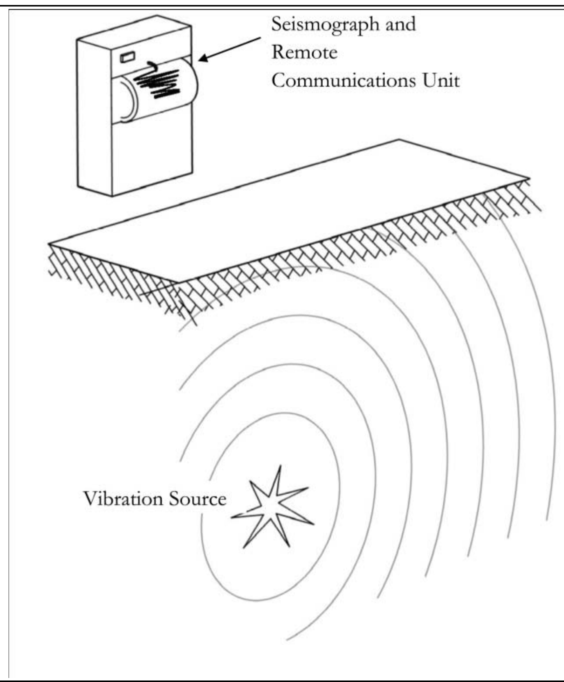
A seismograph measures the velocity of ground motion during shaking. It is used to determine the level of vibrations induced in a structure from impact equipment, blasting, or seismic activity.

### How it works:

A seismograph consists of a case with a suspended mass that is free to move independently of the case. The case is anchored to the ground or to a structure. During shaking, the mass moves relative to its casing, producing an electrical signal which is proportional to the velocity of the motion.

### Where it is used:

Seismographs are primarily used to monitor the level of shaking caused by blasting or heavy impact loads from construction equipment. In dams they are primarily used to help limit the level of shaking of an existing dam structure during other construction activities that cause vibrations.




Seismograph Setup

## Settlement Plate

### Description

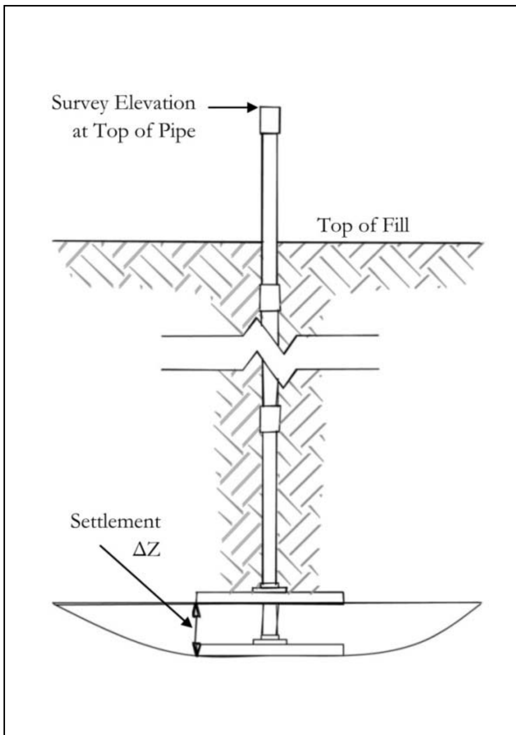
A settlement plate consists of a square plate 3 to 4 ft in dimension with a riser pipe attached. The plate is positioned at the bottom of a fill and the riser pipe extends up to above the ground surface.

### How it works:

A settlement platform consists of a square plate or anchorage to which a riser is attached. Fill is placed over the plate. If the fill height exceeds about 25 feet, the riser should be isolated from the surrounding fill by an outer pipe within which the riser can move freely. As the height of fill increases, the riser and outer pipe are raised by adding additional pipe lengths. Movements of the settlement platform can be monitored by optical survey of elevation of the top of the riser. Measurements of change in elevation of the plate and fill height are monitored over time to determine the vertical consolidation of the materials below the settlement plate.

### Where it is used:

Settlement plates are used to monitor magnitude and rate settlement of a compressible foundation during and after construction of an embankment. The data may also be used to limit the rate of embankment construction relative to the rate of soil consolidation so that the shear strength of the foundation soil is not exceeded




Settlement Plate Configuration

Installed Settlement Plates

## Strain Gauge

### Description:

A sensor used to measure elongation or contraction of a small reference length on a portion of a structural element. It is commonly used to compute change in normal stress indicated by the measured change in strain in the structural element.

### How it works:

Different types of strain gauges use different techniques to measure strain. Most commonly used types of strain gauges for dam monitoring are:

1) Mechanical strain gauge – Changes in length between two points fastened to the structure are measured with a scale or micrometer to determine strain.

2) Electrical resistance strain gauges – a foil gage fastened to the structure changes length with strain which causes a change in resistance of the small copper wire on the gage. Change in resistance is measured with an electronic readout to get an analog or a digital reading. Resistance strain gages may be fastened to a short length of #4 rebar, called a sister bar, and buried in concrete to measure change in stress in the structure.

3) Vibrating wire strain gauges – a gage containing a stretched wire is fastened to the structure. Changes in length of the gage changes the tension in the wire causes its vibrating frequency to change. The wire is vibrated and the frequency read with an electronic readout to get a digital reading. Gages may be placed on the exterior surface or buried within concrete.

4) Fiber optic based strain gauges - Changes in the length of the fiber at a specific location changes the wavelength of the reflected light. Changes are read with an electronic readout to give a digital reading.

### Where it is used

Strain gauges can be installed on structural members where changes in stress are required. They are typically mounted on the surface of the structure but certain gages can be buried within concrete. Sister bars may be buried at critical sections within concrete to measure stress as the dam is constructed. Others may be placed on structural elements to measure change in stress during the operation of the equipment.

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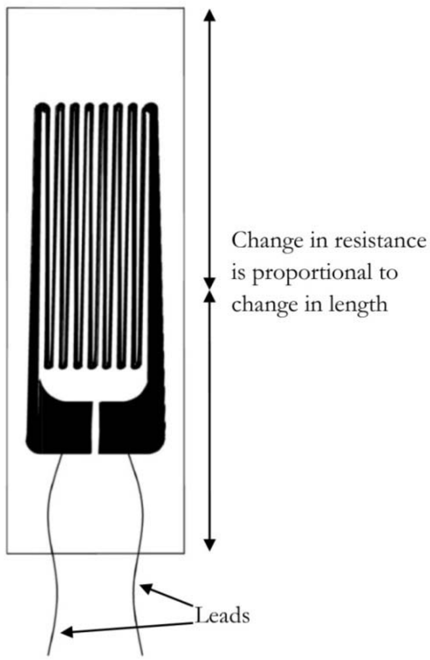
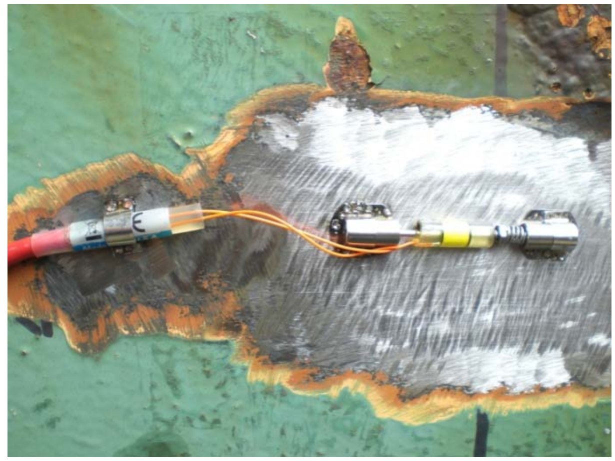
|---|---|
|  |  |
| Schematic of Resistance Strain Gauge | Vibrating Wire Strain Gauge |

## Stress Cell

### Description:

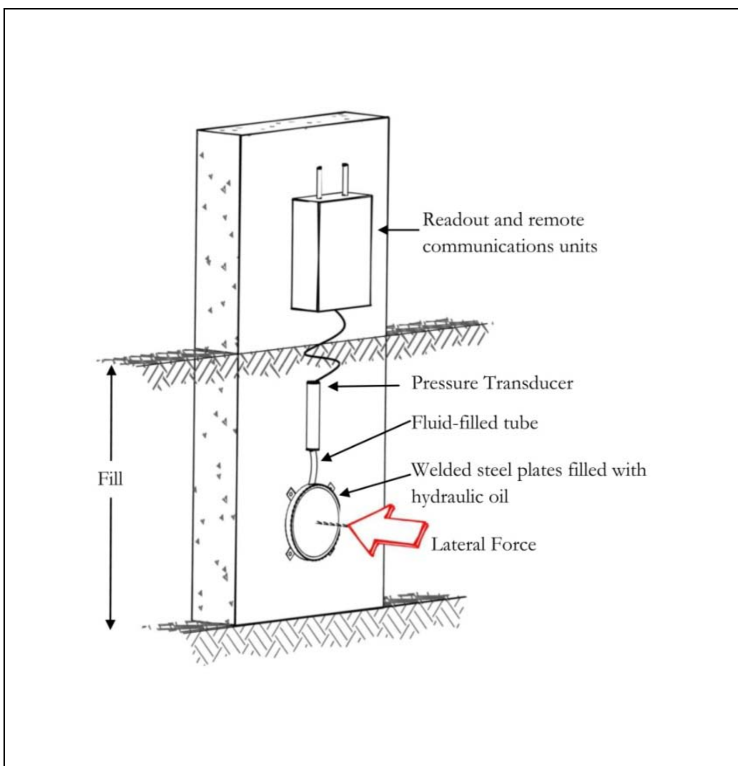
Stress cells are instruments that measure stress normal to a plane.

### How it works:

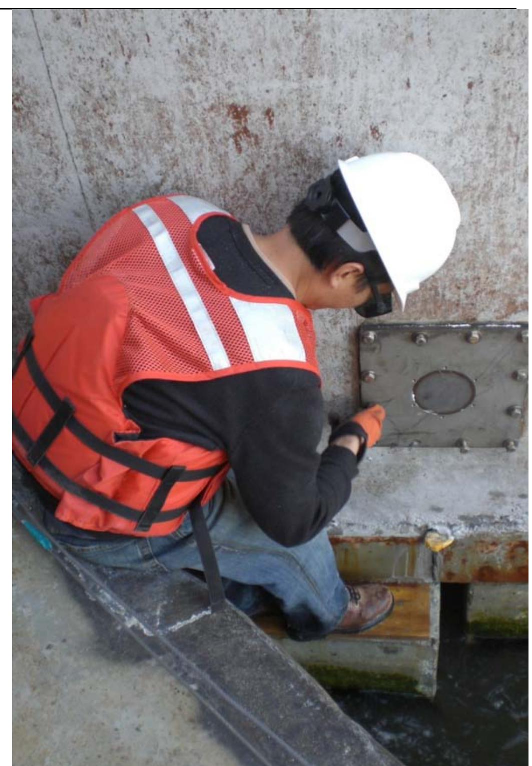
There are various different designs and applications for stress cells. They typically consist of two plates welded together and filled between with hydraulic oil. As the pressure acts on the plates, it is transferred to the oil and measured by an attached pressure transducer. Stress cells are typically split into two groups, earth pressure cells and contact pressure cells. The main difference being that the former is designed to measure normal stress on a plane in soil and the latter is designed to measure normal stress applied to the face of a structural element. In each case the "sensitive plate" of the instrument is placed facing the direction of the expected forces.

### Where it is used:

Pressure cells can be placed in the clay core and on the foundation beneath embankment dams. When placed in fill, numerous stress cells can be used to determining the magnitude, orientation and distribution of the stresses present. They can also be used for stress measurements under building slabs, against slurry walls, retaining walls and piles. Their purpose is to verify design assumptions and to monitor for stresses that exceed design limits. If used in conjunction with a piezometer, effective stress can be calculated in soils.




Stress Cell Configuration (Not to Scale)



Stress Cell

## Strong Motion Accelerometer

### Description:

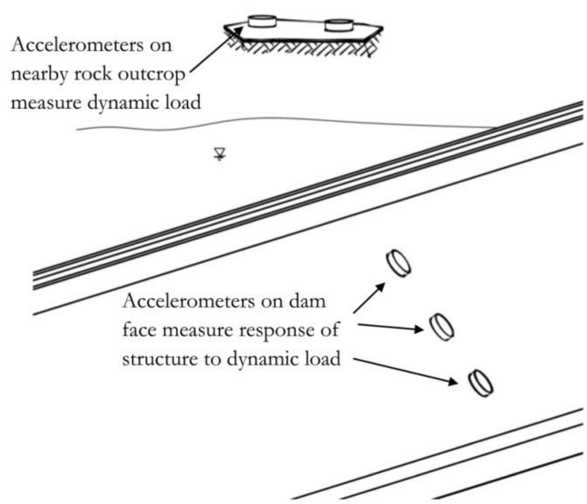
A strong motion accelerometer measures the acceleration of ground motion or structure during shaking. It is primarily used to determine if dynamic forces from impact equipment, blasting, or seismic activity that might damage the structure.

### How it works:

An accelerometer consists of a case with a suspended mass that is free to move independently of the case. The case is anchored to the ground or to a structure. During shaking, the mass moves relative to its casing, producing an electrical signal that is proportional to the acceleration of the sensor. A strong motion instrument usually contains three accelerometers to indicate acceleration in three perpendicular directions. The sensors are read several hundred times per second to obtain a complete time history of the event causing the shaking.

### Where it is used:

Accelerometers are used to monitor structures such as dams and embankments in areas where seismic activity or reservoir-induced seismicity may occur. Sensors may be placed at different levels within the dam and its foundation to determine how the level of shaking varies with depth.




Accelerometer Locations for Dam Monitoring

Strong Motion Accelerometer (photo from REF TEK)

## Survey Monuments

### Description:

A survey monument indicates horizontal and vertical change in position of a fixed point. They are used to monitor settlement and horizontal movement on a structure.

### How it works:

A survey monument can be installed either at the surface of the dam structure or into the ground along an adjacent embankment and protrudes above the grounds surface. A survey monument is typically installed into a dam by installing a casing with a smaller hollow metal pipe centered within it, pouring concrete in the void between the metal pipe and the casing, and fixing a short stainless steel stud into the top of the hollow metal pipe by filling it with grout. A survey monument is typically installed into a dam's embankment by drilling a hole, centering a hollow metal pipe within it, filling the space between the pipe and edge of the hole with concrete, and then centering and grouting a stainless steel threaded rod that is as long as the hole is deep within the metal pipe. Once in place, a reading on a survey monument is measured using a prism rod and an AMTS unit to obtain a baseline reading. The baseline reading is used to compare future periodic readings against for vertical and horizontal movement. By utilizing numerous survey monuments within the dam and its adjacent embankments, analysis of what areas are experiencing horizontal and vertical movements can be performed.

### Where it is used:

A survey monument is used throughout the surface of the infrastructure of a dam to monitor if the dam is experiencing vertical and horizontal changes in its position throughout its life. This functionality of a survey monument is particularly useful if altercations or expansions are made to a dam's infrastructure since these activities can compromise the stability of the existing dam.

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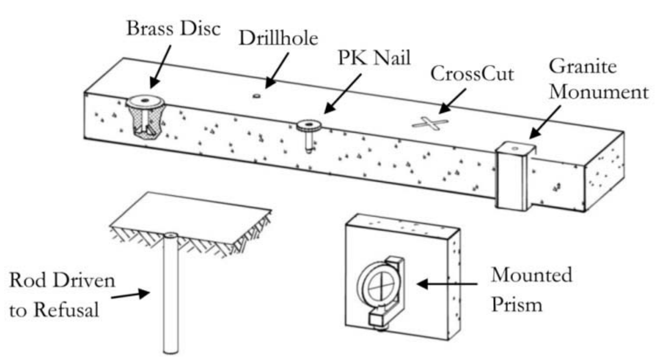

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<tr>
<td>Varieties of Survey Prisms</td>
<td>Mounted Prism</td>
</tr>
</table>

## Synthetic Aperture Radar (InSAR, PsInSAR)

### Description:

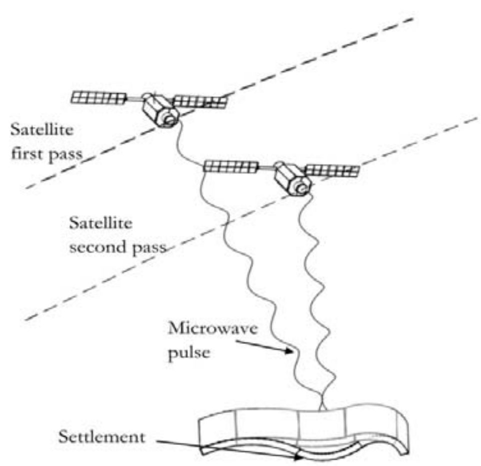
Synthetic Aperture Radar is a form of radar which uses relative motion between an antenna and its target region to provide distinctive long-term coherent-signal variations that are used to obtain finer spatial resolution than is possible with conventional beam-scanning means. It originated as an advanced form of side-looking airborne radar.

### How it works:

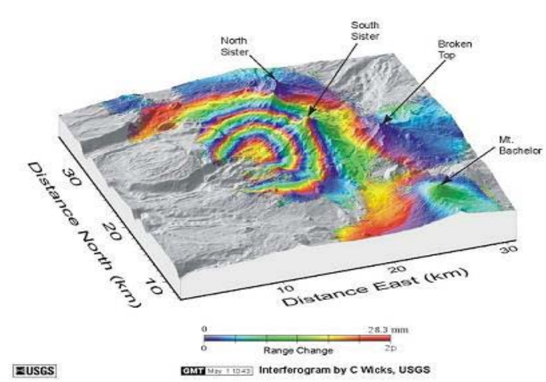
An orbiting satellite transmits a microwave pulse with known wavelength to the earth's surface. When the pulse contacts the earth surface it is only partially through its period. As it bounces back the period starts over again, therefore the returning "backscattered" waveform is of a different phase than the original signal. This phase difference combined with the time it takes to make the round trip yields a distance and therefore a digital elevation model can be generated. "Interferometry" refers to the process of comparing two SAR readings taken at separate times from nearly the same satellite position while filtering out other factors that contribute to phase shifting. These factors include atmospheric noise such as air temperature and water vapor pressure, excessive distance between the two positions, and the severity of the topography. InSAR is advantageous in that it can provide a complete elevation model of an area with each pass of the satellite in a cost effective manner. By placing reflectors at desired points on the ground surface, the change in elevation of that point can be measured as small as a centimeter. PsInSAR uses Persistent or Permanent Scatter techniques to identify and remove inconsistencies from the data set, especially those caused by structures in urban areas.

### Where it is used:

InSAR can be used to monitor the rate of ground surface subsidence of a dam and the slopes above its reservoir over time. This can help identify zones of movement and establish the rate of change in elevation.




InSAR Concept




Example Interferogram (from USGS http://volcanoes.usgs.gov/insar/)

## Temperature Sensor

### Description:

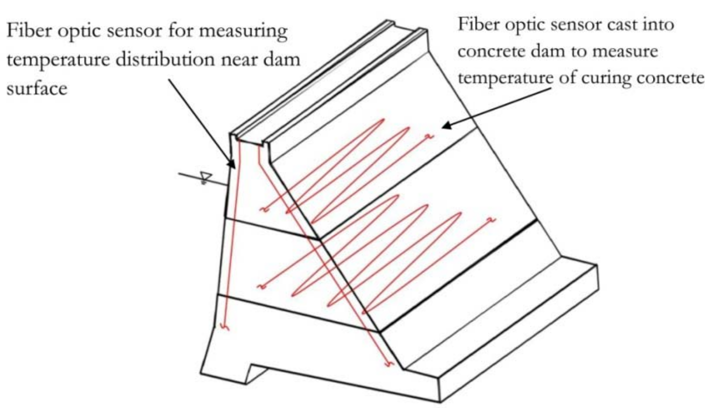
A temperature sensor is a small device that gives an electrical output that is proportional to temperature. There are several types.

### How it works:

*Resistance Temperature Devices (RTDs)* are usually made from copper, platinum or nickel. Their resistance changes with changes in temperature. *Thermistors* are similar to RTDs except they are made from semi-conductors. *Thermocouples* take advantage of the voltage created when two dissimilar metals come into contact. This voltage is proportional to temperature. A *Fiber Optic Temperature Sensor* scatters light in proportion to its temperature. Many sensors may be positioned along a single fiber that can be miles long. Each of these devices can be electronically.

### Where it is used:

Temperature sensors are used to measure temperature changes in curing concrete, temperature differences in groundwater to indicate potential flow sources, and thermal gradients in soil and rock. Temperature sensors may also placed in other electronic sensors so that temperature effects on the sensor can be removed by calibration.




One Example Application of DTS

Thermistor

## Tilt Beam

### Description:

A tilt beam is a tilt sensor attached to a stiff length of metal channel, called a beam, that is used to measure rotation of one end of the channel relative to the other.

### How it works:

Tilt beams are used to measure average rotation between the two ends of the beam. The length of the beam times sin (change in tilt angle) indicates the movement of one end of the beam relative to the other. Tilt beams may be mounted vertically to indicate rotation of a vertical member, or horizontal movement of one end of the beam relative to the other, or they may be mounted horizontally to indicate change in vertical position of one end of the beam relative to the other. Multiple tilt beams may be combined end to end vertically to provide a profile of horizontal movement at the ends of the beams or horizontally end to end to measure differential settlement along the string of beam sensors. Once installed, a baseline set of readings is taken which will be subtracted from all future readings taken, providing the overall change in differential movement. One end of tilt beam string must be chosen as the datum from which the movement of the tilt beams is determined. This datum should be carefully determined by choosing a secure unmoving point or a point for which the position can be determined by another means.

### Where it is used:

Tilt beams are used on dams to determine differential settlements on horizontal portions of the dam or in vertical alignments to measure horizontal movement along the height of the dam.

| | |
|---|---|
| (1994), |   |
| Tilt Beam Configuration | Tilt Beam installation in a tunnel |

## Tiltmeters

### Description:

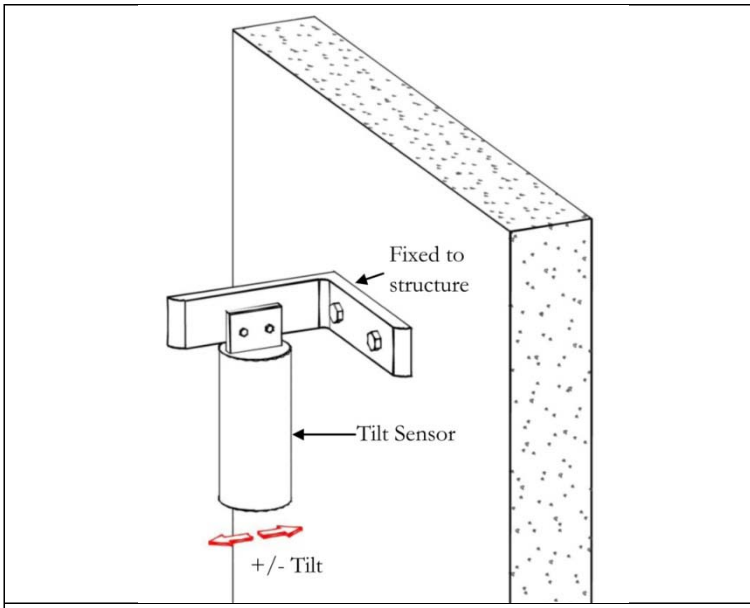
Tiltmeters indicate change in angle of the sensor relative to the direction of gravity. They are used to measure rotation of a structure.

### How it works:

Tiltmeters are typically anchored to a structure to monitor the rotation of the structure over time. The tiltmeter uses the force of gravity as its datum. They are liquid tilt sensors that work like a carpenter's level but give an electronic output that is proportional to the orientation of the sensor to vertical. A vibrating wire tilt sensor measures the deviation of the sensor away from vertical. MEMS tilt sensors contain tiny masses that give an electrical output proportional to their orientation. Tilt meters are available in both uniaxial and biaxial models.

### Where it is used:

Tiltmeters are typically used to precisely monitor rotation of structures Tiltmeters can measure small rotation as low as 1 micro-radian, providing a higher precision than geodetic surveying techniques. Most tilt sensors are very sensitive to changes in temperature as are the structures to which they are mounted. Practical use of tilt meters requires considerations of these temperature effects.




Tiltmeter Configuration

Installed Tiltmeter

## Time Domain Reflectometry (TDR)

### Description:

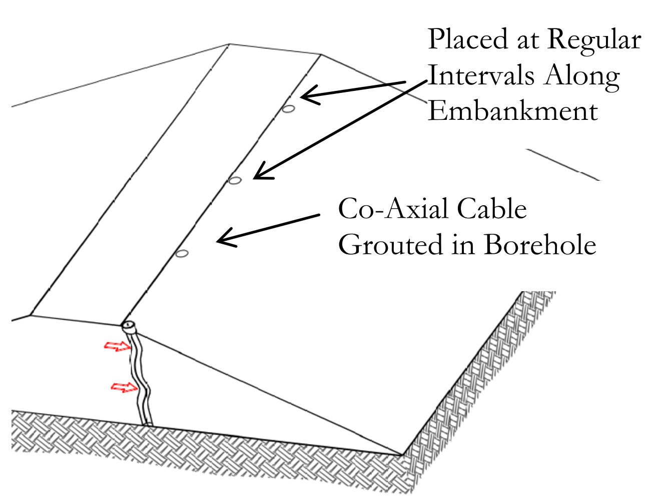
Time Domain Reflectometry uses the reflection of an electronic signal from a crimp in a coaxial cable to indicate the distance to the crimp that is caused by excessive deformation. It is most commonly used to detect locations of large shear distortions below the ground surface.

### How it works:

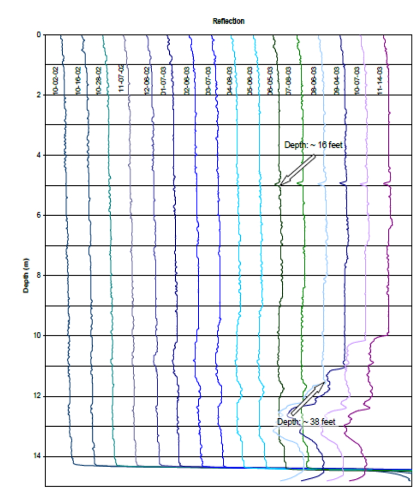
TDR exploits the phenomena of electromagnetic signals partially reflecting back to their source each time a change in the characteristic impedance of the conductor material is encountered. These "impedance boundaries" are caused by deformations in the cable caused by ground shear around the cable. A distance is calculated by measuring the time it takes for a part of the signal to be reflected to the detector. The location of a shear plane will appear as a spike on the TDR trace. As the shearing increases over time, the spike will increase in magnitude but reliable measurements of displacement magnitude are difficult to obtain. The TDR cable may be crimped at regular intervals to provide a reference points. This is a qualitative approach that does not measure the direction or magnitude of the shearing; only the location and magnitude of impedance changes over time.

### Where it is used:

TDR can be used for non-destructive testing of bar or cable anchors embedded in concrete dams to determine if there is a significant change in area of the bar over its length. It is also used to monitor the development of slide planes and shear zones within earth and rock slopes as an alternative or complement to slope inclinometers. Readings can be read remotely and automatically.




TDR Schematic




TDR Trace (from Ohio DOT)

## Turbidity Meter

### Description:

A turbidity meter is used to measure the quantity of soil particles contained in seepage discharge.

### How it works:

A turbidity meter measures the amount of suspended particles in a water sample by assessing the degree to which light is scattered by the particles. The meter emits a constant beam of light through the water sample. A sensor situated at 90 degrees from the transmitted light beam detects scattered light. Another sensor situated 180 degrees from the transmitted light beam detects the unscattered light that passes through the sample. Based on the amount of light that reaches both sensors, the turbidity of the water sample can be calculated and correlated with quantity of solids suspended in the water.

### Where it is used:

A turbidity meter may be used to detect the presence of soil particles in the flow from a spring or seep.  An increase in the turbidity can indicate the development of piping or internal erosion within the dam or its foundation.

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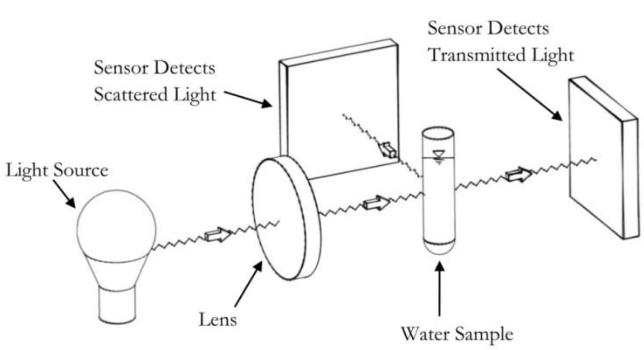
|  |  |
| Schematic of Turbidity Meter Concept | Turbidity Meter (photo from Cole-Parmer http://www.coleparmer.com/catalog/product_view.asp?sku=0556322) |

## Weather Station

### Description:

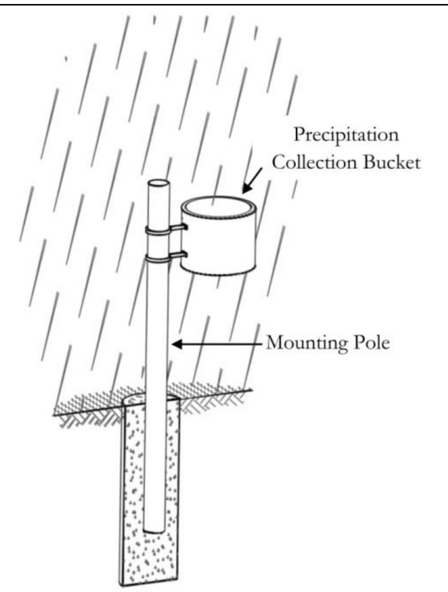
A weather station consists of sensors to measure air temperature, humidity, wind speed and direction, and precipitation.

### How it works:

A rain collector gathers and guides precipitation into a location for measurement. Some use a bucket that tips when full and the number of tips per unit of time are counted to measure rainfall. A datalogger counts the number of times the switch is activated. A *balance precipitation gauge* computes the amount and intensity of precipitation using a weighing system. Heaters may be added to convert snowfall to water for measurement. Wind speed and direction are measured with an anemometer. Temperature and humidity sensors are also added.

### Where it is used:

Weather stations are used to record environmental conditions which may affect the performance of a site and/or the instruments used to measure that performance. Since performance of many civil works are affected by rainfall, weather stations provide valuable data to help quantify the effects of rainfall on the instrumented structure. They may also be used in hydrology to track precipitation as it relates to surface or groundwater flow. Precipitation data is valuable for dam monitoring, as it relates to changes in pore water pressure within the ground and may also influence measurements of flow from springs and seeps.




| | |
|---|---|
| Weather Station Setup | Precipitation Gauge (photo from http://www.novalynx.com/260-2501.html) |

# APPENDIX C. CASE STUDIES

## Case Study 1 - Uplift Pressure Monitoring

Uplift pressure monitoring is necessary for concrete gravity dams since hydrostatic uplift is a prominent factor in initial design and subsequent stability analyses. Uplift reduction produced by drains must be substantiated where it is used in stability calculations. Careful monitoring and comparison of actual uplift readings with values assumed in stability analysis allows Dam Owners to verify the margin of safety of their dams.

If measurements of pressure beneath a dam indicate uplift is greater than assumed in the most current stability analysis, some action is required. One option is to reanalyze the dam to evaluate its stability with the measured uplift. If the stability is found to be inadequate based on current measurements, an effort can be made to improve the degree of drainage beneath the dam to match or exceed the values assumed in the most recent stability analysis. This can be done by adding new drains or by cleaning existing ones. Another option is to improve stability by structural means such as post-tensioned anchors. Drainage improvement is often less expensive, but the results cannot be guaranteed beforehand. Anchors are often more expensive than drainage improvements, but the benefits can typically be predicted more confidently.

Uplift pressure monitoring and relief strategies were incorporated at two concrete gravity dams on the Columbia River in the state of Washington by Chelan County Public Utility District from 1981 through 1991. (Yow and Christman, 1994) The full paper can be found in ICOLD Proceedings of the 14$^{th}$ Congress, June 1994.

## Rocky Reach Dam

About 80 piezometers were installed in the spillway, center dam, and powerhouse, post-tensioned anchors were installed, and several new drains were added. These were mostly typical standpipe piezometers with packers and grouted in place. They were installed to measure pressures in a zone of several feet at the base of the dam. Most of the spillway and powerhouse piezometers are located in areas normally underwater and had closed standpipes with pressure gages. Readings were infrequent and difficult to obtain. The results required conservative interpretation because of the possible influence of un-watering on the pressure readings. Pressure was found to decrease with distance downstream of the foundation drains.

During this period, the piezometers were equipped temporarily with pressure transducers and a strip chart recorder to evaluate their response to changes in headwater and tailwater. All piezometers were downstream of the drain curtain. Since headwater is maintained at a fairly constant level, the piezometers all responded to tailwater variations rather than headwater. Uplift forces included in the stability analysis were based on assumed drainage efficiencies of about 10% less than those indicated by the piezometers to allow for possible future changes in drainage efficiency. In general, the piezometers indicated very effective drainage of the dam foundation.

In 1984 and 1985, post-tensioned anchors were installed in the center dam, service bay, and other parts of the dam, to bring those structures in line with upgraded stability criteria. The anchors in the center dam and service bay were designed assuming a straight line pressure distribution from headwater to tailwater.

In 1988 a program of piezometer repair and modification was undertaken. It was noted that a few of the open-standpipe piezometers were damaged by the installation of anchors nearby. Some of these were repaired by flushing or surging while others had to be drilled out and replaced.

Piezometers in the powerhouse and spillway which could be read only when a unit or the fish ladder was drained (once per year), were equipped with pressure transducers to allow monitoring bi-weekly under normal load conditions. These bi-weekly readings allowed the Owner to accumulate a substantial database of readings over a period of a few months. If this was not possible, the Owner would have been required to use the historic data to reanalyze the project's structural stability. Quite possibly this would have led to remedial structural modifications.

The program of uplift data collection, piezometer repair, and drainage improvement, enabled the Owner to show that the stability analysis performed in the early 1980s was still applicable and structural improvements were shown to be unnecessary.

### Rock Island Dam

The original piezometers at Rock Island Dam were installed in the early 1970s. They were steel standpipes with mechanical packers to isolate the concrete/rock interface and a segment of voids in the basalt or tuff bedrock. The packers and standpipes were not grouted in place. In 1984 one piezometer in the spillway began to exhibit water levels above the level used in the design calculations. After a carefully planned investigation, it was discovered that several corrosion induced pinholes had formed in the steel standpipe, allowing water from the deck and the annulus outside the standpipe to flow into the pipe. The problem standpipe was replaced and an additional standpipe piezometer was added nearby. After a period of close monitoring, it became apparent that there was no significant trend of increase in the uplift pressure.

As a result of this work at Rock Island Dam, it became clear that it is worthwhile to know how each piezometer responds to changes in uplift and that some care needs to be taken in evaluating readings from a piezometer that responds slowly to changing uplift conditions. Two approaches to avoiding this problem seemed to work equally well. One is to calculate an average "drainage efficiency" based on the instantaneous efficiencies from a large number of readings. The other approach is to calculate drainage efficiency based on "inflection points" in a plot of the readings. This works because an inflection point, one where the slope of the curve changes form positive to negative, or vice versa, represents a time when the piezometer level is momentarily in equilibrium with uplift pressure, headwater, and tailwater. For either approach, a series of frequent readings, such as each half-hour, is helpful in understanding how the piezometer actually behaves.

### Lessons Learned

The Owner and its Consultants describe the main points from their experiences at these two dams in the following summary.

1. Uplift pressure and piezometer readings both responded to changes in headwater and tailwater levels, but not necessarily with the same speed. Closed, pressurized piezometers responded immediately while open standpipe piezometers took time to fill or drain to reflect changes in uplift pressure.

2. Water level measurements from standpipes that respond slowly must be interpreted carefully so that a false impression of uplift conditions is avoided. The water level can be the result of average headwater and tailwater conditions over the last few hours or even days. A series of closely spaced readings is most helpful in evaluating how the piezometer responds and how to interpret the data, particularly until a trend or baseline is established.

3. Automatically recorded readings are often preferable to manually obtained readings. They introduce less human error and are less expensive in the long run, particularly where frequent readings are required. For the same reason, digitally recorded readings are preferable to those from a strip chart recorder.

4. Changes in uplift pressure or drainage efficiency may be caused by construction or repair activity at a dam and uplift may change seasonally. It is not safe to assume that all foundation drainage takes place through the foundation drains or other obvious routes or to assume that drainage efficiency is the same year round.

5. Uplift pressures can often be decreased by the addition or cleaning of drains. The feasibility of this must be evaluated for the particular situation, but anchors should not be assumed to be the only remedy for high uplift pressures.

## Case Study 2 – Observation Well Evaluations

A 50-year unnamed high hazard potential reservoir dam was selected for this case study because several adjustments to the overall monitoring program were required over time to keep the program effective. This case illustrates the importance of periodic critical review of existing dam safety performance monitoring and data analysis management program, especially in regard to reevaluation of the purpose of the instrument and the quality and timeliness of the data being retrieved.

### Background

In order to monitor internal pressures and seepage, a system of observation wells, flumes, and piezometers were installed in this reservoir embankment dam the early 1960's prior to first filling. The embankment dam is a rockfill type with central impervious earth core. It is about 6.5 miles long with crest width of 41 feet, 2H:1V upstream and downstream slopes, and a maximum height of about 55 feet. The storage capacity is about 60,000 acre-feet. The downstream portion of the core and rockfill were placed on bedrock. The upstream portion of the core and rockfill was constructed on natural soil over the bedrock. Filter transition zones are constructed adjacent to the impervious core for protection against internal erosion. Extensive grouting was done in the bedrock under the central core to reduce the permeability of the foundation.

Eighty-one (81) wells were drilled into the foundation rock at various depths to intercept aquifers in certain strata of the bedrock. Some wells extended thousands of feet from the toe of the dam. These were intended to measure the impact of the reservoir on the area ground water regime. Twenty-two (22) wells were drilled to the top of rock to measue the groundwater in the embankment. Five (5) flumes were located near the toe of the embankment to measure cumulative seepage flows.

The original dam safety monitoring program was established by the design engineer. It has been periodically evaluated by the federal dam safety regulator through an approved independent dam safety consultant.

The monitoring program was basically unchanged during the first 30 years. There were no written operational procedures for instrumentation calibration, protection, maintenance, data collection, data analysis, and data management. Traditionally, data on observation wells, piezometers, and flumes were taken on a semi-annual basis by the operartional staff. Actually, this pumped storage upper reservoir operates on a weekly pump and generation cycle. Since there was no guidance on when measurements should be collected, the state of the reservoir water surface elevation was not factored in to the timing of earlier data collection.

Data was collected by operation personnel and then turned over to a maintenance engineer for manual plotting and evaluation. There were no hard and fast data collection and data evaluation commitment due dates. The data was evaluated on a time available basis and was summarized and evaluated by the independent dam safety consultant on a five-year interval. Because of normal staff turnover, the O&M personnel assigned to data collection had little knowledge of the intent and purpose of the monitoring program. Clear threshold and limit action levels were not established.

Since original construction, regular visual inspections of the embankment dam revealed no significant settlement, sliding, or erosion that was not being effectively managed by routine maintenance, i.e. vegetation control, rip rap repairs, etc. Based on the available record, most water level measurements remained relatively unchanged since construction. The functionality of some observation wells had been affected by normal attrition due to such things as vandalism, siltation, and well casing deterioration. Piezometers located in the embankment were abandoned in 1973 due to vandalism. The flumes were abandoned in 1983 since they had shown no significant changes for over 20 years after first filling and were also subject to continuing vandalism.

There was no evidence of unusual conditions which would cause concern about the safety of the reservoir dike. However, because of all these factors, it became clear that the effectiveness of the original monitoring program should be reviewed and updated.

### Dam Safety Monitoring Program Evaluation and Upgrades

During 1989 and 1990, about 30 years after construction, a review of all instrumentation and monitoring was initiated for the observation wells and a supplemental embankment dam stability analysis was performed as well. The study included:

- Baseline elevation checks of top of casing to verify the accuracy of past water level readings;
- Hydraulic response tests (rising and falling head) on selected wells;
- Evaluation of protection and security of instruments;
- Decommissioning of inactive wells by grouting and capping;
- Uplift stability analyses of the embankment; and,
- Supplemental slope stability analyses of the embankment.

Of the 103 wells originally installed, there were still about 87 wells "in service" at the time of this evaluation. After the evaluation, it was determined that 46 well should remain in service. The balance were abandoned because they either gave unreliable water level readings, had accumulated too much sediment, or were too far downstream of the embankment toe to be useful for dam safety monitoring during the operational life of the reservoir. Almost all of the free-field wells were abandoned because access was difficult and time consuming. These well were located on private commercial and residential property. Access required permission from owners and resulted in the occasional restoration claims after field crew access. Since an earlier study of reservoir operational impacts on the surrounding groundwater was shown to be negligible, the original purpose of these far-field wells was no longer necessary. Seventeen (17) new wells were installed at selected locations around the reservoir to provide adequate performance monitoring coverage. The total number of active wells at the end of this program was sixty-three (63).

New wells and existing wells were provided with protective steel casings with covers and locks. Where appropriate, ballards were installed to protect the instruments from mowing equipment and vehicles.

Hydraulic response tests were performed to find reasons for anomalies observed in the historical data record and to evaluate the long-term functionality of existing wells. As a result of these tests some non-functioning wells were abandoned, lag-time response of the wells to reservoir elevations was established, and a protocol was established to collect readings on the same day of the week for each well and for each time it is monitored. Later on, data collection devices were installed in order to collect more frequent and timely data and to reduce manual reading work hours. Prompt notification procedures were established for any data exceeding threshold or limit levels.

The effectiveness of the impermeable core and foundation grout curtain were confirmed.

An area in one portion of the dike was investigated in order to evaluate the significance of overflowing observation wells at the embankment toe. The wells were extended to obtain the hydraulic uplift pressure. An uplift stability analysis confirmed that the factor of safety is greater than 1.5, which was deemed adequate. The piezometric levels in this area have been steady for many years with no indication of increasing trends. Visual and probing inspection of the area near the dike toe indicates the ground is firm except at the immediate overflowing well location. This area has been flagged for continued close inspection and monitoring.

Supplemental slope stability analyses were also performed using the critical dike cross section using phreatic surfaces from the monitoring data. The safety factor for the critical circular surface significantly exceeds regulatory criteria. Threshold and limit levels have been established based on the stability analysis results.

Dam safety training programs were established for operations, maintenance, security, and engineering staff.

### Lessons Learned

The key points to consider are that:

1. periodic training is required for all personnel associated with the dam safety program;
2. the focus of an instrumentation program must change with the life cycle of the dam;
3. instruments need to be maintained in good working order for the data to be useful;
4. frequency of data collection may need to be adjusted from time to time; and,
5. the potential failure modes need to be considered in deciding what and how to monitor.

Evaluation of the effectiveness of existing dam safety monitoring programs should be a continuous process. The authors recommend in-depth reviews for high hazard potential dams at 5-year intervals, and for intermediate and low hazard potential dams at 10-year intervals.

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# APPENDIX D. POTENTIAL FAILURE MODE ANALYSIS TOOL

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | USUAL | Overtopping | Concrete arch dam with central gated spillway. | Overtopping of the dam will occur at high flow events. Accumulated debris could block the spillway and increase the overtopping. Erosion of fill material would compromise the left abutment integrity for the arch dam and reduce or eliminate the lateral resistance at the left abutment parapet wall. Loss of the parapet wall or abutment support would redistribute stresses in the arch dam and could lead to eventual failure of the arch dam. | Evaluate the risk of erosion on the left abutment through geologic investigations and stability assessments. Develop a robust early warning system. Evaluate the IDF if the PMF cannot be passed. Raise the parapet wall at the left abutment, and lower the right parapet wall. Provide slope protection at left abutment. Increase spillway capacity. | Potential for debris accumulation. Operator access is required to operate the gates. Overtopping during the PMF could last up to 65 hours. | No indications of abutment rock deterioration. Would take time to develop significant erosion. |
| CONCRETE ARCH | USUAL | Landslide | Concrete thick arch dam with spillway at the central portion of the arch containing slide gates. | A large landslide flows onto the arch dam, blocks the overflow section, and gate hoists are destroyed. | Continue monitoring the abutment slide prone areas. | Overtopping could trigger a slide by undermining the toe. Activation of this slide could trigger additional slides from farther up the slope. | Landslide is unlikely to lead to an uncontrolled release of the reservoir. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | USUAL | Spillway Gate | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment. Powerhouse is located at the base of the arch dam. | Increased friction at the trunnion hub causes high bending moments in one or more radial arms during raising of the spillway gates. Combined bending and axial loads cause buckling of the gate arm and collapse of the gate leading to an uncontrolled release. | Consider using laser level measurements to track gate arm deflections. Amperage draw measurements have uncertainties related to other sources of friction. | Failure mode has occurred at other projects with similar gates. Difficult to inspect trunnion bearings. Top radial arm is lightest and most highly stressed. | Gate sections have been strengthened by adding additional steel members between radial arms. Gates have been analyzed for friction values up to 0.4. Lubrite bearings do not require lubrication. There have been no problems with gate operation, regular maintenance and testing is performed. Amperage readings indicate draw is within the capacity. |
| CONCRETE ARCH | USUAL | Structural | Double curvature thin arch dam with a central overflow section with flashboards. One abutment has a gravity wing dam with rock anchors. | Under normal and flood loading segregation at lift joints and poor concrete quality lead to structural failure of the arch dam. | Continue alignment survey program and resolve uncertainty about trends. Update analyses. | Apparent movement trend in upstream and to the left indicated by alignment survey. Lift joints show segregation. Uncertainty in concrete quality due to age and era of dam construction. | Left abutment upgraded with anchors and provides stability for arch dam. Left joints and vertical construction joints are keyed. Past concrete testing shows high concrete strength. No elevation changes in surveys. No visual evidence of increased stress. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | USUAL | Penstock | Double curvature thin arch dam with a central overflow section with flashboards. One abutment has a gravity wing dam with rock anchors. | The butterfly valve or surge tank components fail causing a concentrated release of water from the flow line without completely interrupting flow to the penstock. Undermining of the penstock supports causes a progressive failure of the penstock. | Upgrade the communications and remote control of the butterfly valve. Flow meters could add redundancy to pressure switch system. Locate an emergency generator at the head gates for use during power loss. | A butterfly valve has failed in the past. If automatic or remote head gate closure were to fail it could take up to 1/2 day to get the head gate closed. | Penstock pressure gage at the powerhouse automatically shuts head gate to minimize releases. Operator can also close the gate from the powerhouse. |
| CONCRETE ARCH | USUAL | Sliding | Gravity arch dam with a constant radius and remote spillway. | Sliding stability failure of the arch dam under all loading conditions. Factors making sliding failure more likely are thermal stresses, ice buildup and damage from past ice loading. | Seepage monitoring, settlement and alignment surveys, and visual abutment observations. Remove vegetation from abutments to aid in visual assessments. Formalize post earthquake inspections. | Induced thermal stresses. Ice builds up on the dam and has caused past damage to the parapet wall. | Crest crack monitors do not indicate movement. Past ice damage repairs increased resistance to damage. Calculated stresses may be conservatively high. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | USUAL | Abutment | Gravity arch dam with a constant radius and remote spillway. | Failure of the arch dam abutments due to bedrock instability under the arch thrust loading, results in a breach and uncontrolled loss of the reservoir. | Seepage monitoring, settlement and alignment surveys, and visual abutment observations. Remove vegetation from abutments to aid in visual assessments. Formalize post earthquake inspections. | Abutment above the arch dam is very weathered. No geotech investigations of the abutment rock. | Dam is well orientated to the abutment and the rock appears strong. Abutment has rock discontinuities that are favorably orientated, with no potential wedges or blocks that could affect stability. Photo documentation shows that foundation preparation is well done. |
| CONCRETE ARCH | UNUSUAL | Sliding | Concrete arch dam with a thrust block section, spillway section, a gravity monolith wing section, and a concrete core wall embankment. | Flood flows up to PMF or surcharge from a lahar displacing the reservoir overtops the thrust block. Sliding failure of the thrust block leads to failure of the arch dam. | Analyze the thrust block for stability during overtopping and include in remediation with post tension tendons if appropriate. | The Thrust Block has not been analyzed for current levels of surcharge loading. It appears likely that, without strengthening, the Thrust Block stability will not meet FERC stability criteria. | The foundation of the Thrust Block is strong, sound rock and weak joints or bedding planes are not present. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | UNUSUAL | Overtopping | Central concrete arch dam, left thrust block with an ogee spillway, right buttressed concrete gravity section. | Overtopping during high flow event leads to the erosion of abutment rock, leading to instability of the thrust block, and failure of the arch dam. | Review operating procedures to ensure that they adequately address debris blocking of spillway. Survey the reservoir perimeter for sources of debris. Visually monitor the drains to confirm that they are functional, remove vegetation for clear view of the drains. Verify as-built configuration of thrust block and use in stability evaluation. | Erosion was evident at thrust block after past overtopping event. Saturation of backfill at diversion wall at right abutment could increase erosion potential. | Foundation rock has shown to be erosion resistant during past overtopping event. |
| CONCRETE ARCH | UNUSUAL | Overtopping | Concrete thick arch dam with spillway at the central portion of the arch containing slide gates. | Abutment is overtopped by as much as 10 feet eroding abutment rock. Progressive loss of abutment rock leads to undercutting of arch dam toe, loss of foundation support, partial failure of arch dam. | Structural modifications to prevent flow from reaching the non-overflow sections. Evaluate removal of spillway gates to eliminate overtopping potential. Evaluate abutment geology and possible erosion protection measures. | Abutment rock is adversely jointed. Shale beds create weak zones for erosion initiation. Arch is not keyed into the abutment and thrust makes a low angle with abutments. Rock bench is unlikely to resist prolonged discharge. Access is difficult for inspection. Piezometers indicate high pressures in the abutment. PMF could overtop for 2-3 days. | Arch action places foundation in compression. Abutment rock is strong with favorable bedding orientation. Most vulnerable area is protected with a layer of concrete. No record of crest displacement and lack of diagonal cracking indicate ability of abutments to carry load. Abutment shape would direct overtopping flow away from contact area. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | UNUSUAL | Overtopping | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | During a large flood debris from the reservoir collects on the log boom, the log boom breaks free and plugs the spillway gates. Overtopping of the arch dam causes erosion of the abutments and undermining of the dam and thrust block, resulting in loss of support and arch collapse. | Continue inspection and monitoring of log booms. Consider additional engineering of log booms. | Up to 19 feet of overtopping assuming no discharge from spillway gates at peak of PMF. Debris buildup has occurred during historical floods and a log boom broke during a flood. Debris is likely to be drawn into spillway gates. Abutment rock has variable strengths. | Concrete protection at base of arch. Historical floods may have cleared out available debris. Gates are 50 feet wide and would be hard to plug. Two log booms provide redundancy. Log boom maintenance is performed. Majority of abutment rock is sound and considered to be erosion resistant. No intersecting joints in abutment rock creating planes of weakness. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | UNUSUAL | Structural Stability | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | During a large flood debris from the reservoir collects on the log boom, the log boom breaks free and plugs the spillway gates. Reservoir level raises to level higher than previously analyzed for PMF loading. Dam overstresses resulting in arch collapse which occurs before overtopping erosion begins. | None Identified | An estimated 19 feet of overtopping could occur assuming no discharge from the spillway gates and this level of overtopping has not been analyzed. Thrust block factor of safety is difficult to estimate for levels above the PMF. | Linear extrapolation of overtopping stresses indicate acceptable levels. Concrete is in excellent condition. Arch has plenty of reserve capacity to redistribute tensile stresses without compressive overstress. Thrust block and spillway are keyed into the abutment rock. Complete spillway blocking is unlikely. |
| CONCRETE ARCH | UNUSUAL | Sliding | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | Under increased load from a flood or earthquake a sliding failure of the spillway structure could open up a breach. | Stability analyses are needed and should include the effects of passive rock key and dowels. PMF routing and peak reservoir levels should be checked before performing analyses. | No stability analysis performed. No foundation drains to relieve uplift pressures at depth. Cannot verify that the half round drains were installed and are functional if installed. Current peak PMF level is higher design. | Concrete is in good shape, well bonded in lifts, dowels into rock, and is keyed a minimum of 5 feet into rock. Half round drains are shown in drawing and may be providing drainage. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | UNUSUAL | Thrust Block | Double curvature thin arch dam with a central overflow section with flashboards. One abutment has a gravity wing dam with rock anchors. | Flood or earthquake loading leads to a sliding failure of the gravity section. Failure of this section leads to loss of support for the arch dam and its failure results. | Continue alignment survey program and crack monitoring program. Crack monitoring can be used to monitor the post tension loads in the anchors. Analyze the sections for stability due to failure effects on the arch. | Has not been analyzed for current seismicity. Cracking and leakage was observed in the gravity section prior to anchor installation. | Anchors were installed and stopped crack movement trends. Drilling records show favorable foundation conditions. Previous seismic analyses indicate large FS. |
| CONCRETE ARCH | SEISMIC | Foundation Failure | Concrete arch dam with central gated spillway. | Earthquake event leads to stresses that exceed the shear strength at the foundation contact. Load redistribution could lead to diagonal cracking through the base. | Strong Motion Accelographs (SMA) installed at the dam to trigger alarm and need for post seismic event dam inspection. Develop a reservoir drawdown plan to be initiated when potential post earthquake failure is developing. | | This shear failure condition is being assessed and it is expected that no significant shear strength deficiencies will be found and that the local stresses are acceptable. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | SEISMIC | Structural Stability | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | Earthquake loading causes horizontal cracks to develop in the center portion of the dam, and diagonal cracks to develop near and parallel to the abutments, connecting to form blocks that rotate downstream causing the arch to completely collapse. | None Identified | Cantilever tensions on downstream face close to apparent dynamic tensile strength. Horizontal cracks near center of dam on each face are probable. | Probably have a net compressive force across the contraction joints. Therefore, horizontal arch tension can be relieved by joint openings without disrupting arch action. Dam design neglects cantilever structural capacity. Downstream face arch and cantilever tensions near abutment suggest principal stresses are below probable tensile strength. Upstream face tensile stresses are lower than downstream face stresses. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | SEISMIC | Sliding | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | Earthquake induces dynamic loads due to the arch acting on the thrust block, and the inertia of the thrust block itself overcome the available strength at the foundation interface. This leads to sliding of the thrust block, loss of support for and rupture of the arch and release of the reservoir. | Perform time history seismic load case analyses. Include rock wedge and anchors in the new analyses. Perform post-earthquake case. | New seismic loads could be worse since spectral accelerations are greater at fundamental period for the structure. Subduction zone earthquake has a longer duration. One exploratory boring indicates the concrete rock contact is only partially bonded. Significant movement of the thrust block could eliminate compressive forces across the contraction joints, eliminating the ability of the arch to redistribute loads. | Current analysis assumes the entire base is cracked, partly on the basis of what could be fictitious tensile stresses at contact. Analysis is conservative; response spectrum method estimates peak response, perhaps on the high side, hinged base on arch maximizes thrust block load. post earthquake FS may be adequate. Thrust block is anchored into bedrock. Passive rock wedge due to foundation excavation at downstream toe up to 15 feet at left side of spillway. Rough surface under thrust block increases friction. Piezometer data indicates water level below the rock/concrete contact. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | SEISMIC | Spillway Gate | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | One or more radial arms buckle under seismic loading. This leads to failure of the gate and uncontrolled discharge through one or more spillway bays. | Consider refining seismic gate analysis. | Calculation with Westergaard mass and response spectrum shows interaction ratio for top arm and MCE loads. The indicated buckling mode of failure results in complete loss of member strength (no plastic capacity). Seismic criteria have not been fully determined, and spectral accelerations at natural period of gates could go up. | Transient elastic buckling may not result in complete failure if load redistributes momentarily to other members. Radial arms have been strengthened by addition of structural bracing. Unlikely that all three gates would fail. Transient load may be short enough such that buckling will not occur. Revised analyses may benefit from lower spectral accelerations, depending upon the modal response of the gates. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE ARCH | SEISMIC | Structural | Thin variable-radius concrete arch structure with flared abutments. A gated spillway is adjacent the thrust block of the right abutment, powerhouse is located at the base of the arch dam. | The cross canyon earthquake causes the pier reinforcement to yield, the piers fail by sliding or overturning, with loss of the two adjacent gates leading to an uncontrolled discharge. | Perform a pier analysis considering cross canyon earthquake motions. | No analysis performed for this failure mode. The hoist deck bolts are neither numerous enough, nor large enough to allow the hoist deck to provide significant lateral load resistance. Due to the slender aspect ratio of the piers in the lateral direction (4:1 height:thickness), amplification of peak ground acceleration is likely. | Ten foot thick piers at gates. Hoist deck bolted to piers. Gates (face plates) provide lateral support. Due to steel reinforcing in the piers, and the steel in the gate, ductile behavior is possible in the lateral direction. Therefore, the pier may deform substantially, without catastrophic failure. |
| CONCRETE ARCH | SEISMIC | Penstock | Double curvature thin arch dam with a central overflow section with flashboards. One abutment has a gravity wing dam with rock anchors. | Earthquake loosens the jointed bedrock and induces a rock fall that punctures the penstock. The puncture is large enough to cause a complete failure of the penstock resulting in an uncontrolled release that could flow into the powerhouse and the operator camp area. | Continue penstock inspection program to ensure structural integrity and resistance to seismic loads. Investigate rock configuration above hoist house for rock fall potential. | Rockslides have occurred in the past. Some penstock support may not be founded on bedrock. If automatic or remote head gate closure were to fail it could take up to 1/2 day to get the head gate closed. | No breaks of penstock from rockslides have occurred. Penstock inspection program exists to help ensure adequacy of supports/integrity of the pipe. Penstock system is flexible and has expansion joints to withstand some seismic load. Head gate pressure switch or operator could remotely shut the head gate to minimize release. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE GRAVITY | USUAL | Landslide | Concrete gravity dam with an integral powerhouse section and gated spillway section. | Massive rock at the right abutment is marginally stable, under static conditions the rock block could fail and strike the dam and create a breach and uncontrolled release of the reservoir. | Inspect periodically for renewed evidence of movement at the rock block, especially after any period of intense rainfall or felt earthquake. | Adverse joint orientation, leave the block unsupported at the toe of a potential failure plane. Fresh evidence of movement along the slope, and failure of at least part of the block appears inevitable. A clay filled joint in similar orientation was found in an exploratory adit suggesting that relief extends deep beyond the slope. | The position of the block appears that it may not strike the dam and land in the stilling basin, away from the toe of the dam. Such a landslide would not cause the dam to fail but could cause some structural damage. |
| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam with an integral powerhouse section and gated spillway section. | Planes of weakness in the foundation rock lead to dam movement and buildup of high stresses at the toe and in the foundation contact. Progressive movement and foundation deterioration lead to a sliding failure of the dam. | Periodic measurements of alignment, settlement, piezometric levels, and drain discharge. Regular visual inspections between measurements. | None identified. | Metabasalt foundation rock has high strength. Foundation investigation did not discover any weak zones in the foundation. Foundation was well prepared during construction, it has adequate roughness and keyed. Drains are cleaned periodically and are functioning. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE GRAVITY | USUAL | Sliding | Rockfill embankment with a central earth core protected by three transition zones on each side. | Calcite or iron bacteria sludge could block drain holes leading to an increase in the uplift pressures of the gated spillway section. If sufficient uplift pressures were developed, a sliding failure could occur. | Relief hole pressure monitoring on a quarterly basis and drain cleaning every five years. | Analyses indicate that the structure is not stable without uplift reduction from the drains. Cohesion assumed in the analyses is high. Not all drains can be accessed for cleaning and monitoring. | Performance of drains to date has been good. Drains are monitored regularly. A longitudinal drain pipe connect the drain holes creating some redundancy if drains should plug. Monitoring data does not show long term increase in pressures. Only 10 percent drain efficiency is necessary for adequate factor of safety. |
| CONCRETE GRAVITY | USUAL | Penstock | Concrete gravity arch dam, with downstream stepped face. Gated ogee type spillway is located on the crest of the dam with moveable gate hoists. | Failure of one of the penstocks causes erosion of the access road above the pipe and prevents access to close the head gates. The reservoir would be drained to the level of the penstock intake. | Maintain the penstocks and implement a steel thickness measuring program. | Headgates are operated manually and access time is about 20 minutes. Access to the head gates would be lost. Minor leakage has been noted at the penstock expansion joint. | One the operator arrives the head gates can be closed quickly. The penstocks are instrumented. Maximum flow would drain the reservoir to the penstock level, but would not cause a significant downstream hazard. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE GRAVITY | USUAL | Diversion Tunnel | Concrete gravity arch dam, with downstream stepped face. Gated ogee type spillway is located on the crest of the dam with moveable gate hoists. | Failure of the diversion tunnel plug during normal or flood operation would release 20,000 cfs and drain the reservoir. | Monitor the downstream tunnel portal for signs of leakage. Locate tunnel plug drawings and evaluate design. | Details of the concrete plug were not known at the time of the PFMA. | Tunnel was drilled and blasted leaving a rough surface for the plug to bond to. Plug was grouted after placement. Shear strength of the plug concrete and rock walls are expected to be adequate. |
| CONCRETE GRAVITY | USUAL | Sliding | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Sliding instability of spillway monoliths could occur along previously unevaluated sliding plane at spillway section. Movement of monoliths could cause loss of spillway gate operability. | Analyze the stability along the potential failure plane. Confirm shear strength parameters. Continue monitoring drains and piezometers and alignment of spillway monoliths. Conduct post-earthquake inspection. | Analysis of 2 sliding planes were not reported. | Generally good foundation rock quality. Foundation has grout curtain and drains. Measured drain efficiency is higher that assumed in analyses. Uplift pressure is monitored. Massive structure. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| CONCRETE GRAVITY | USUAL | Erosion | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Erosion at spillway channel during discharges undermines apron through milling action, undermining of apron and energy dissipaters lead to settlement and cracking, progressive erosion undermines the spillway monoliths. Displacement of spillway monoliths damages one or more spillway gates resulting in inoperability or uncontrolled release. | Limit single spillway discharges and distribute between spillways. Continue periodic inspection. | Significant erosion has occurred. | Visual inspections are made by a diver. No impact observed during recent full discharge. |

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| CONCRETE GRAVITY | USUAL | Sliding | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Corrosion of upstream foundation anchor tendons leads to loss of pre-stress force. Sliding instability results under normal loading conditions and above. Collapse of one monolith and uncontrolled release leads to progressive failure of the gravity section. | Assess condition of anchors as possible. Check lateral crest displacements and compare to expected differential movement based on stiffness of gravity section and adjacent monoliths. Check monitoring sensitivity for adequacy to detect movement. Evaluate stability without anchors, and evaluate adding additional anchors or mass. | No specific information available on the installation of the anchors. No mention of corrosion protection in the documents. No access to inspect tendons. Anchors were intended for short term use and now have been in extended service. Second stage grout had high permeability. Factor of safety is greatly reduced without tendons. No shear keys between monoliths. Domino failure likely should an initial monolith fail. | Instrumentation is in place to detect movement. No observed displacement since first filling. |
| CONCRETE GRAVITY | USUAL | Stop Logs | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Long term corrosion of bulkheads, stop logs, and/or gate guides concrete leads to overstress and structural collapse of the bulkheads. An uncontrolled release, and downstream erosion and damage results. | Periodic inspection of bulkheads and deterioration of gate guides. Maintain and replace as necessary. | Replacement stop logs failed upon installation and were replaced. Bulkheads are inaccessible for detailed inspection. | Unlikely that multiple gates would fail at the same time. Bulkhead wheel gates can be put in if a bulkhead/stop logs fail and can be lowered under high velocity flows. |

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| CONCRETE GRAVITY | USUAL | Spillway Gate | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Corrosion of post tensioned trunnion anchor assemblies leads to loss of load capacity and movement of trunnions. Failure of a gate by twisting in partial or total collapse. Uncontrolled release could occur with the potential to cause erosion problems below the apron. | Periodic inspection of piers and anchor heads for cracking and corrosion. | Stress concentration in the area of the trunnions. Anchor assemblies are inaccessible for inspection. | No signs of corrosion products on the surface or cracks in the anchor heads or piers except for one gate. |
| CONCRETE GRAVITY | USUAL | Sliding | Timber crib dam with upstream concrete facing, central mass concrete section and downstream concrete apron. Central section is overflow with flashboard and gated sections. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Sliding failure along concrete rock interface at the invert of the sluiceway. | Perform stability analysis to verify stability. | No instrumentation located on this dam section. Potential for shale/weak rock at depth. During large floods, potential for erosion at right abutment. | Founded on rock. Erosion of rock has not been experienced in historical floods. |

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| CONCRETE GRAVITY | USUAL | Ice loading | Overflow ogee-shaped concrete gravity dam topped with flashboards supported by a steel frame. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Ice loading on the flashboard section exceeds the structural capacity of the steel support structure. Failure of the steel support structure releases a "sunny day" flood flow. | Develop a Standard Operating Procedure for ice conditions. | Ice damage has occurred in the past. Loads directly transferred to the structure. | Ice conditions have been handled in the past. Some strengthening of the structure has been done. |
| CONCRETE GRAVITY | USUAL | Sliding | Overflow ogee-shaped concrete gravity dam topped with flashboards supported by a steel frame. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Upper monolith of right fore bay section separates along lift joint above buttress level resulting in a overturning/sliding failure and an uncontrolled release of the reservoir. | Evaluate the existing survey monitoring program for accuracy. Analyze the upper section of the monolith. | Narrow wall section. Leaking cold joint. Not structural analysis of stability at lift joints in the wall. Survey indicates apparent movement. High piezometer reading. | Survey set up is not good for accurate measurements. Magnitude of wall movement may be very small and is not visually detectable. Flows through lift joint do not change. No history of ice loading problems. |

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| CONCRETE GRAVITY | USUAL | Spillway Gate | Concrete gravity structure with a central integral spillway equipped with drum gates, and with end piers separating the overflow section from non-overflow gravity sections. | Misoperation or mechanical failure lead to inadvertent dropping of a drum gate resulting in excessive discharge downstream in recreational areas. | Continue program of inspecting operating controls, piping, and valves. | An inadvertent gate drop has occurred in the past. Drum gates at other projects have opened due to mechanical failure. | A malfunction of the PLC causes the system to go into status quo mode and keep the gates at the prior position. Unintended operation of the gate valves and a change in gate position triggers alarm at the hydro control center. Manual controls at the dam are locked and cannot override electronic controls. The inlet valve will automatically open if gate drops below the set point. Would need to lose both station service and EG with outlet open in order to inadvertently open the gate beyond the intended set point. |

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| CONCRETE GRAVITY | USUAL | Flashboards | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Load rejection, seismic loading, or rock fall leads to premature tripping of the flashboards. Depending on how many flashboards fail, up to 29,000 cfs may be released endangering downstream recreators. | Maintain warning system, siren, and signage. Develop detailed instructions for operation, inspection, and replacement of flashboards. | Flashboards have tripped in the past. Relatively fragile structure. Flashboards require sophisticated reconstruction each time they are tripped. When flashboards fail, the failure could be quick. | Flashboards were recently analyzed. Recent load rejection caused 6 inches of overtopping and flashboards did not fail. The flashboards were recently reconstructed. There is a forebay high water alarm. |
| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Sliding failure of the spillway section under all loading conditions, resulting in breach and uncontrolled release into the reservoir. | Continue daily monitoring of the project. Formalize sediment height monitoring program and post earthquake inspection procedures. | Probable weak zone near base. There is a fractured zone of rock near the toe and sheared rock under the foundation. Sediment build up in front of the dam. | Analysis shows reasonable FS without cohesion and assumed full uplift. Deep foundation anchors were installed to sound bedrock. Keys between adjacent spillway blocks. |
| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Weak concrete near base, sheared rock and a laminated rock zone in the foundation lead to a sliding failure of the left abutment gravity section under all loading conditions. | Continue visual observations with emphasis on seepage. Evaluate need to alignment and settlement surveys. | Probable weak zone near base. There is a fractured zone of rock near the toe and sheared rock under the foundation. There is a weak zone in the concrete about 10 feet down (lamination). No original drawing from actual construction. | Analysis shows reasonable FS without cohesion and assumed full uplift. Deep foundation anchors were installed to sound bedrock. Minimal seepage from abutment contact. Monitoring of vertical and horizontal deflection. Epoxy grouting and post tensioning addressed the weak concrete zone |

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| CONCRETE GRAVITY | USUAL | Piping | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Deterioration of left abutment's sheet pile cutoff wall and piping of the surrounding material leads to failure of the left abutment and uncontrolled release of a portion of the reservoir. | Monitor seepage, and make daily inspections. | Sheet piling can corrode. Not much data regarding the sheet pile. Pipable material in the left abutment is present as shown by exploration boring. | Any seepage increase would be observed quickly. Sheet pile wall is not exposed to the elements. Not much head or pressure to drive the seepage. Failure would only release the upper portion of the reservoir , and is unlikely to threaten concrete gravity portions of the dam. |
| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam consisting of a gated ogee spillway, a non-overflow intake section and two narrow non-overflow gravity block sections. | Erosion of the toe during spill events shortens the concrete interface. Sliding failure of the spillway results. | Five year toe erosion inspections and after high discharge events. Weekly visual monitoring of the spillway during routine operator's inspections. | Significant toe erosion has historically occurred. Not visible during normal inspections. | Threshold erosion levels have been quantified to initiate remedial repairs. Previous concrete repairs have made improvements to erodibility. Base map is established to monitor erosion. Foundation asperities resist sliding. Spills are rotated between gates to balance erosive forces. |

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| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam consisting of a gated ogee spillway, a non-overflow intake section and two narrow non-overflow gravity block sections. | Sliding stability of the spillway section under all loading conditions resulting in a breach and uncontrolled release of the reservoir. | Monitor toe erosion, alignment and settlement, and formalize a program of sediment monitoring. | Silt loading on dam could change. | Foundation interface has significant asperities. Efficient shape of gravity dam mobilizes vertical upstream water resistance. Toe of monolith structure is in diamond shaped rock slot. Base of the structure was constructed monolithically. Photo documentation supports friction angle of 55-65. Good construction techniques and base preparation are documented. Foundation is properly drained. |

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| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity section with integral powerhouse and remote spillway.. | Poor bonding to foundation rock and between cold joints, and cracking along length of dam at the penstock level exists. These conditions lead to a sliding failure of the powerhouse section leading to breach and uncontrolled release of the reservoir. | Continue monitoring program that includes: alignment and settlement monitoring, photographic monitoring of leaks, and visual monitoring. Evaluate the need to recalculate the stability based on a higher PMF pool. Formalize the post earthquake inspection program. | This dam section spans over non-cohesive alluvium and is supported on bedrock at the abutment ends. Potentially higher PMF pool than assumed in the analysis. Cracking evident along the length of the dam at the penstock level, which could be a potential failure plane. Core testing indicates that foundation contacts are not intact. Unbonded concrete cold joints were the norm. | Section is wedged between rock abutments. Analysis is conservative. Some evidence of foundation keying. Rock jointing is favorable with some asperities. |

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| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity section with integral spillway section. | Areas of the foundation have non-cohesive foundation deposits and poor bonding to foundation rock and between cold joints. These conditions lead to a sliding failure of the gate section, breach and uncontrolled release of the reservoir. | Continue monitoring program that includes: alignment and settlement monitoring, photographic monitoring of leaks, and visual monitoring, apron undercutting monitoring. Evaluate the need for no-cohesion analysis and recalculate the stability based on a higher PMF pool. Formalize the post earthquake inspection program. | Potentially higher PMF pool than assumed in the analysis. Core testing indicates that foundation contacts are not intact. Unbonded concrete cold joints were the norm. | Conservative friction factor assumed in the analysis. Drawings indicate foundation keying. Cyclopean concrete used at the cold joints. Foundation photographs indicate significant asperities. Construction photos indicate good foundation prep work. |
| CONCRETE GRAVITY | USUAL | Piping | Concrete gravity section with integral spillway section. | Alluvial materials under the left pier of the gate section are piped out due to high levels of seepage in this area. Loss of these materials is not expected to fail the gravity section as it bridges over these materials but could result in an large uncontrolled release through a resulting void. | Continue visual inspection and photographic monitoring of seepage. Formalize the post earthquake inspection program. | 3-0 to 60 cfs of seepage has historically been measured at this dam section. | Pier bridges the alluvial section. Concrete has been placed to contain the alluvial material. Repair efforts have decreased the seepage by 50%. The forebay has a low level alarm. |

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| CONCRETE GRAVITY | USUAL | Penstock | Concrete gravity dam with integral spillway with lift gates and stop log bays. | Failure of the retaining wall at the flow line leads to a slope failure, or a slope failure at another location along the length of the flow line, undermines the flow line support, ruptures the steel pipe, and leads to an uncontrolled release of water. | Annual survey of the retaining wall and quarterly inspection of the flow line. Inspection of the flow line after all felt earthquakes. | history of slides on the steep slope adjacent to the flow line. Bedrock subject to surficial weathering and surficial sloughing/rock toppling. | No movement at retaining wall to date. Failure would be detected by a unit trip. Generally favorable bedrock bedding with regard to rock face stability. |
| CONCRETE GRAVITY | USUAL | Structural | Concrete gravity dam with integral spillway with lift gates and stop log bays. | Deterioration of the surge chamber concrete leads to a failure of a side wall results in an uncontrolled release. | Quarterly visual inspections and annual photographic documentation. Inspection after all felt earthquakes. | Structure is old 50+ years, and has numerous cracks and leaks. Freeze thaw damage is evident on outside surface. | Visually inspected quarterly. No concrete cracking observed inside the concrete chamber. |
| CONCRETE GRAVITY | USUAL | Structural | Concrete gravity dam with integral intake and powerhouse and zoned earthfill wing dams. | Unnoticed or un-repaired corrosion of the reinforcement of the upstream water retaining powerhouse wall leads to excessive stress concentration. The wall fails as a result and leads to uncontrolled release of the reservoir to the invert of the intake structure. | Structural monitoring program. | None | Structural monitoring. |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete arch dam with a thrust block section, spillway section, a gravity monolith wing section, and a concrete core wall embankment. | Flood flows up to PMF or surcharge from a lahar displacing the reservoir overtops the gravity wing dam monoliths. Shear friction criteria are exceeded and overturning or sliding failure results in an uncontrolled release of the upper reservoir. | Begin remedial design for post tension tendons that will allow overtopping. Studies have already been completed the indicated a low probability of abutment scour. Install piezometers to confirm uplift assumptions. | Large floods overtop the dam parapet wall. The stability found for the gravity wing dam monoliths does not satisfy FERC guidelines with a surcharge over El. 1208. | The foundation of the gravity wing dam is strong, sound rock and weak joints or bedding planes are not present. Geologic evaluation and kinematic analyses of the abutment rock indicates no capable planer or wedge failures are possible.The excavated surface at the contact was cleaned to sound fresh rock and has a surface, which generally is sloped upward in the downstream direction. The final excavated surface of the gravity dam foundation can be seen in photographs to be very irregular with large asperities. A number of exploratory holes have been used along the reach of the wing dam to determine an estimate of the uplift pressure existing across the section. In general, the measurements have shown the actual uplift pressure is |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete arch dam with a thrust block section, spillway section, a gravity monolith wing section, and a concrete core wall embankment. | Flood flows up to PMF or surcharge from a lahar displacing the reservoir overtops the gravity wing dam monoliths. Tendons fail and therefore shear friction criteria are exceeded and overturning or sliding failure results in an uncontrolled release of the upper reservoir. | Monitoring program should include lift off testing of tendons. Test 1/4 of the tendons every 5 years so each tendon is tested on a 20 year cycle. | Loss of pre-stress force is an occurrence, which is not uncommon for post-tensioned anchors. | Lost of pre-stress force can be restored by re-stressing if the anchorage system designs permits this to be done. |

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| CONCRETE GRAVITY | UNUSUAL | Debris | Concrete arch dam with a thrust block section, spillway section, a gravity monolith wing section, and a concrete core wall embankment. | During large flood event debris is collected on the upper reservoir log boom. The log boom detaches and a raft of debris blocks the spillway. Overtopping results and failure of the gravity wing dam monoliths result. | Keep the shoreline free of debris. Maintain the log booms with emphasis on the anchorage and linkage and include in routine inspections and note the debris buildup. | Heavy debris loading has been noted in the past.Log booms are not 100% effective in avoiding debris problems at spillways.Operational staff may have the tendency to view log booms only as an operational adjunct or personnel safety precaution and not as an essential dam safety measure. | Smaller debris can pass through the gate openings without difficulty.The log boom installation at Alder has prevented any debris problems at the spillway in the past.The log boom does use steel plates and chain at the links instead of simply running the chain through bored holes in the end of the logs and, therefore, these connection points are not as subjected to wear and decay.The amount of capacity reduction from partial blockage of a bay of the spillway is unlikely to create significant surcharge above the level due to the event itself. |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Arched concrete gravity dam with integral spillway, gravity wing dam section and concrete core wall section. | Flood flows up to PMF or surcharge from a lahar displacing the upper reservoir and flooding the lower dam, overtops the gravity wing dam monoliths. Shear friction criteria are exceeded and overturning or sliding failure results in an uncontrolled release of the upper reservoir. | Include studies with those for the upper dam. Include flows for assumed post tensioned configuration at the upper dam and calculate increased flood flows due to combinations of postulated failures of various wing dam sections. | The gravity dam critical monolith is unstable due to uplift pressure separation at the dam base at normal full pool. The gravity dam critical monolith does not meet the Unusual Condition stability criteria of 2.0 for a reservoir surcharge above normal pool with assumed foundation conditions. | Foundation strength parameters greater than those used for the Unusual Load Condition may yield acceptable safety factors above normal pool on the assumption that the core wall fails prior to full PMF pool elevation. |

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| CONCRETE GRAVITY | UNUSUAL | Spillway Gate | Arched concrete gravity dam with integral spillway, gravity wing dam section and concrete core wall section. | Operating condition combination failures such as; power outage, station service failure, standby generator failure, hoist motor failure. These lead to loss of spillway operability and eventual overtopping of the dam. Wing dam sections fail under overtopping and lead to uncontrolled release of reservoir. | Develop spillway operating procedures for major flood events and for addressing power failures. Continue annual testing of spillway gates. | Any significant flow over the parapet wall would result in not meeting the Unusual loading stability criteria. | Redundancies in power supply sources to the spillway gate hoists such as station service, standby generator at intake structure, and gas operated generators for 2 of the 4 gates. Freeboard of 10.8 feet between Normal operating level and top of parapet wall. Gates and hoists are annually tested. During major flood event or changes in spillway discharge, the spillway is staffed. The gates can be remotely controlled. There is secondary access to the dam using the old access road. |
| CONCRETE GRAVITY | UNUSUAL | Overtopping | Central concrete arch dam, left thrust block with an ogee spillway, right buttressed concrete gravity section. | During high flow event, debris blocks the spillway leading to the erosion of abutment foundation rock and eventual failure of the gravity spillway section. | Review operating procedures to ensure that they adequately address debris blocking of spillway. Visually monitor the drains to confirm that they are functional, remove vegetation for clear view of the drains. | Debris reduces spillway capacity. The bridge or spillway gates could be lost or damaged by debris at flows much less than the PMF. | Dam has performed well during past flood events. Concrete apron and foundation rock are erosion resistant. Spillway is well keyed into the foundation. |

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| CONCRETE GRAVITY | UNUSUAL | Spillway Gate | Concrete gravity arch dam, with downstream stepped face. Gated ogee type spillway is located on the crest of the dam with moveable gate hoists. | During flows approaching the PMF, trash or other operational problems inhibit the raising of the spillgates. Overtopping of the gate structures leads to failure of the upper gate section of the dam. Failure of the gate structures would release the upper portions of the reservoir. | Review debris management procedures. Continue regular inspections of the gates and hoists. | There is only one hoist for 11 gates, and it must be relocated manually between gates. Structural failure of the gates is possible if the gates are overtopped by several feet. Debris inhibits the ability to operate the spill gates, larger logs will not pass through the gates. | The abutments are erosion resistant rock. Overtopping would not overstress the dam. Hoist are maintained and test operated regularly. Overtopping the gravity arch dam would not cause a release of the reservoir. |
| CONCRETE GRAVITY | UNUSUAL | Thrust Block | Concrete gravity arch dam, with downstream stepped face. Gated ogee type spillway is located on the crest of the dam with moveable gate hoists. | The intake structure which serves as a thrust block for the gravity arch dam has not been included in previous analyses. Foundation Failure of the intake structure under normal, flood, or seismic loading, would lead to instability of the gravity arch dam and failure. | Analyze the intake structure for stability under PMF and seismic loading. | Tuff layer in the abutment is not as strong as other foundation materials. Intake structure has not been included in previous analyses. | The arch dam may not rely on the stability of the intake/thrust block and be stable as a gravity structure. Stresses at the abutment are expected to be low. No adverse geologic orientations are apparent in the abutment. |

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| CONCRETE GRAVITY | UNUSUAL | Overtopping | Concrete gravity dam with an integral powerhouse section and gated spillway section. | The left abutment cut off wall is overtopped by flood flows under PMF loading resulting in the erosion of the abutment (sand and gravel terrace deposits that overlie bedrock) creating a breach in the abutment. | Develop and SOP for emergency closure (coffer dam with fill) at cut off wall. | Lateral extent of granular deposits adjacent to this section are unknown and there is no solid rock face to limit horizontal breach dimension. | Presence of bedrock limits vertical extent of erosion. Cut off wall is founded on bedrock. Overtopping occurs above historical flood levels. Slow developing failure condition. |
| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete gravity dam with an integral powerhouse section and gated spillway section. | Gravity section is overtopped during PMF flooding. High water levels cause an increase in uplift pressures at the base, creating a cracked base condition, and a sliding failure results | Continue existing drain and piezometer monitoring program. Drains were drilled out recently. | Drain efficiency study based on drawdown, not raising of reservoir level. Section would be overtopped during PMF. No access to gallery drains and piezometers during flood conditions. | Drain and piezometer monitoring programs exist. Adequate factor of safety with approx. 50% drain efficiency. Monitoring of piezometers indicate drain efficiency is maintained at between drawdown and normal water levels. |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete gravity structure with a post-tensioned right abutment section, a central curved spillway section equipped with wooden flashboards, a waste gate section, and a post-tensioned intake section. | Under PMF or seismic loading conditions a sliding or sliding failure of the gravity sections occurs along a horizontally bedded shale/sandstone layer. Deteriorating anchor tendons contribute to the instability. | Continue current monitoring program. | Drill logs indicate horizontally bedded shale and siltstone foundation pose that could be suseptable to sliding. Tendons are older technology and single corrosion protected. Original concrete quality is questionable. | Stability analysis indicates a high factor of safety. Structure is post tensioned. Water chemistry indicates an environment not severe for corrosion of tendons. Well documented construction techniques with high surface roughness. Tendon relaxation has been evaluated in stability analyses. Monitoring program exists for movement at some dam sections. |
| CONCRETE GRAVITY | UNUSUAL | Sliding | Timber crib dam with upstream concrete facing, central mass concrete section and downstream concrete apron. Central section is overflow with flashboard and gated sections. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Overtopping of the non-overflow section results in the failure of the surge chamber and unit penstocks. | None Identified | Aging of penstock steel. | Annual penstock inspection program. |

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| CONCRETE GRAVITY | UNUSUAL | Overtopping | Timber crib dam with upstream concrete facing, central mass concrete section and downstream concrete apron. Central section is overflow with flashboard and gated sections. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Under PMF loading conditions overtopping of the gravity intake connecting wall erodes the backfill and overturning of the wall results. Failure of the flow line for two Units could also result. | Evaluate the foundation rock line for progressive erosion potential. | No drains located in this section of the dam. Erosion of rock is possible under large flood flows. | Construction photos indicate wall is keyed into the right abutment rock. Area has experienced flows with minimal erosion taking place. |
| CONCRETE GRAVITY | UNUSUAL | Overtopping | Overflow ogee-shaped concrete gravity dam topped with flashboards supported by a steel frame. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Overtopping of the abutment concrete walls during floods approaching the PMF erodes the soil foundation resulting in a breach of a portion of the wall and uncontrolled release of the reservoir. | Future paving of trail section will limit erosion potential at left abutment. | Wall will likely overtop at flows less than the PMF. Wall likely founded on soil and downstream fill is erodible. | Erosion depth limited by underlying rock. Downstream paving will provide some erosion resistance. Limited crest length. Low gradient from upstream to downstream. |

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| CONCRETE GRAVITY | UNUSUAL | Debris | Earthfill embankment with an RCC gravity dam section and intake structure. | Overtopping erosion of the fore bay embankment sections during a flood event due to loss of hydraulic control through the following events: flow through the units stops as a load rejection, automatic opening of the spillway gates fail due to loss of both service and emergency power, automatic closure of the diversion gate fails and cannot be manually closed in a timely manner. | Survey the crest of the embankments to identify low spots, determine the minimum freeboard, install a lower limit switch on the bottom of the tunnel gate to ensure closure, and estimate the potential for debris blocking the gates. | Rock falls or landslides during high precipitation could block the spillway or access to the intake, gate controls, and emergency generator. | Redundant systems are in place and multiple independent losses or failure would have to occur. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
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| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete gravity structure with a central integral spillway equipped with drum gates, and with end piers separating the overflow section from non-overflow gravity sections. | Flood flows exceeding the IDF flows raise the hydraulic loading to a level where stability criteria are not satisfied. Sliding and/or overturning failure of abutment non-overflow sections results and would lead to failure of dam and uncontrolled release. | None Identified | No foundation drains to reduce uplift pressure on the dam. Stability analysis indicates potential instability at levels above 60 percent of the PMF. | Construction photos indicate the dam is founded on competent rock with a rough surface. Foundation preparation and cleanup was favorable for a good bond. Shear keys will transfer load from the abutment sections to the adjacent spillway section, which is stable for floods up to the PMF. The stability analysis does not take into account the 3D side friction effects. |
| CONCRETE GRAVITY | UNUSUAL | Landslide | Earthfill embankment with an RCC gravity dam section and intake structure. | Landslide on river side of the canal breaches the canal. Slope failure could occur due to a rise in phreatic surface within the canal embankment and river slopes below the embankments during high precipitation events. | Inspect the area between the canal and river. Take baseline photographs to compare after a large flood. Monitor areas for detection of marginally stable conditions. | History of slides along the banks of the river. This area has not received much attention in past evaluations of the development. Critical area with a thin are between canal and river exists with a steep slope. River undercutting the toe of the slope could increase stability concerns. | Breach of the canal would cause closure of the tunnel gate limiting flow release potential. Some areas have been stabilized and have adequate stability analysis results. No evidence of active sliding. |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Earthfill embankment with an RCC gravity dam section and intake structure. | Sliding failure of fore bay intake or emergency spillway structure under increased hydrodynamic loads due to weak rock at the dam-foundation contact. | Collect information on the foundation properties. | No exploration of the intake foundation. The sliding factor of safety for seismic loading was not calculated during the stress analysis. The gravity sections are thin in comparison to other gravity dams. | Post earthquake stability analyses FS are adequate. 3D effects were not considered in the stress analysis. |
| CONCRETE GRAVITY | UNUSUAL | Erosion | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Erosion at the toe of the spillway channel progressing due to a fracture zone in the bedrock foundation. This condition and silt buildup on the upstream side lead to sliding failure of the spillway resulting in breach and uncontrolled release into the reservoir. | Continue the five year inspection at the toe of the spillway and daily monitoring of the project. Formalize sediment height monitoring program. | Erosion has historically occurred. There is a fractured zone of rock that is more prone to erosion. | Regular inspections are made. Toe has been armored with concrete. Dam is post tension anchored. Documentation shows good foundation preparation. There is a deep plunge pool. Asperities provide high sliding resistance. Keys are formed between adjacent blocks of the dam. |

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| CONCRETE GRAVITY | UNUSUAL | Overtopping | Concrete gravity dam with an overflow ogee spillway section equipped with flashboards, an intake and powerhouse section, and an abutment section wing dam. | Overtopping of the left abutment during flood loading erodes the abutment soil cover. Potential area of erosion is limited by depth of erodible material and may limit the breach size, incremental inundation depths are un-quantified. | Investigate the incremental impacts of the assumed breach configuration. | PMF causes 10 days of overtopping with a maximum of 14 feet in depth. Erosion could wash out native/backfill material potentially up to 15 feet in depth. | Downstream of abutment bedrock is observable that would limit the erosion to a section 30 to 40 feet wide. |
| CONCRETE GRAVITY | UNUSUAL | Erosion | Concrete gravity dam consisting of a gated ogee spillway, a non-overflow intake section and two narrow non-overflow gravity block sections. | Passing of flood flows through the spillway erodes the toe of the spillway. Over time the shortening of the foundation interface leads to instability and a sliding failure of the spillway section and uncontrolled release of the reservoir. | Five year erosion monitoring inspections and weekly visual monitoring during routine operator inspections. | Significant toe erosion has historically occurred. Not visible during normal inspections. | Threshold erosion levels have been quantified to initiate remedial repairs. Previous concrete repairs have made improvements to erodibility. Base map is established to monitor erosion. Foundation asperities resist sliding. |

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| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete gravity dam consisting of a gated ogee spillway, a non-overflow intake section and two narrow non-overflow gravity block sections. | Under PMF loading conditions the intake section overtops for 200 hours. A sliding stability failure of the intake section is initiated by this condition leading to breach and uncontrolled release of the reservoir. | Monitoring toe erosion, alignment and settlement, and formalize a program of sediment monitoring. | Silt loading on dam could change. No access to dam at high flows. | Foundation interface has significant asperities. Efficient shape of gravity dam mobilizes vertical upstream water resistance. Toe of monolith structure is in diamond shaped rock slot. Base of the structure was constructed monolithically. Photo documentation supports friction angle of 55-65. Good construction techniques and base preparation are documented. Foundation is properly drained. |
| CONCRETE GRAVITY | UNUSUAL | Sliding | Concrete gravity dam consisting of a gated ogee spillway, a non-overflow intake section and two narrow non-overflow gravity block sections. | Unfavorable foundation orientation of two intake section gravity blocks leads to instability during PMF loading conditions. Long duration of overtopping leads to failure of one or both blocks, a breach and uncontrolled release of the reservoir. | Monitor sediment loading. Daily visual monitoring. Monitor alignment and settlement quarterly. | Analysis does not account for adverse foundation condition. | Sections appear to be keyed together. Any movement should be apparent during daily inspections. Gravity blocks are monolithically constructed and post-tensioned. |

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| CONCRETE GRAVITY | UNUSUAL | Overtopping | Concrete gravity dam with integral spillway with lift gates and stop log bays. | A spillway rating curve taking orifice flow into account, reduced the expected discharge. As a result the dam overtopping will occur for a longer period of time and at a higher level than expected. Overtopping flow could erode the left abutment rock leading to failure of the left portion of the gravity dam. | Inspection of the abutment rock quarterly. Inspect the toe of the dam annually or after high flow events. Operate all gates during high flows to avoid overtopping scenarios. | History of seepage at the left abutment. Spillway gates are manually operated. No upstream gauge for early warning of high flows. History of bedrock erosion at the toe. | Stability analyses indicate stability under flows up to the PMF with conservative phi and c. Bedrock is expected to erode slowly. In place high water alarm and spillway gate operating procedure. Buttress walls on downstream face should limit erosion. Left abutment has been grouted. |
| CONCRETE GRAVITY | UNUSUAL | Debris | Concrete gravity dam with integral gated spillway. | Debris buildup causes loss of spillway capacity causing overtopping. This results in progressive erosion at the toe of gravity block section leading to failure and the uncontrolled release of reservoir. | Reduce stranded logs along reservoir banks. Remove boat barrier before debris mats build up. | Boat barrier and debris barrier can collect large amounts of debris at high flows and endanger the spillway capacity. Parapet wall does not extend to the abutments, creating a short circuit path for overtopping flow. Current logging practices in the basin will increase debris loads. | Significant freeboard exist (up to 23 feet) with some debris accumulation. Experience from large floods, of lesser magnitude than the PMF, will improve debris handling procedures.. |

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| CONCRETE GRAVITY | UNUSUAL | Debris | Concrete gravity dam with integral gated spillway. | Debris buildup and vortex suppressor cause loss of spillway capacity resulting in loads 6 ft higher than as-designed. | Install sandbags and jersey barriers at abutments and openings in parapet walls prior to peak. Remove vortex suppressor, and extend debris barrier underwater skirt. | Debris collects at the vortex suppressor, which is adjacent to one spillway. Current logging practices in the basin will increase debris loads. | Significant freeboard exist (up to 23 feet). Experience from large floods, of lesser magnitude than the PMF, will improve debris handling procedures.. |
| CONCRETE GRAVITY | SEISMIC | Structural | Central concrete arch dam, left thrust block with an ogee spillway, right buttressed concrete gravity concrete gravity section. | Loss of stability under seismic loading leads to failure of the spillway section. | Complete a seismic review of the site ground accelerations and update the stability analysis. | Probabilistic regional estimates are higher than those assumed in the analyses. | Shear strength of the bedrock is high with a rough irregular surface. Closest known fault is 70 km from the site. |
| CONCRETE GRAVITY | SEISMIC | Overtopping | Concrete gravity dam with an integral powerhouse section and gated spillway section. | Earthquake causes structural failure of the spillway gates and/or piers rendering them inoperable. If high flow events coincide that exceed the capacity of the other outlet works that dam would be overtopped which could lead to failure of the dam. | Visual inspection after any felt earthquake. | None identified. | Ground accelerations are low and the piers and gates are expected to withstand the MCE. |

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| CONCRETE GRAVITY | SEISMIC | Sliding | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Damage during earthquake leads to loss of water stops or cracking of the monolith joints, excessive leakage into the upstream drainage gallery, inflow exceed pump capacity, tail water drain does not open and pressure in gallery could increase to head water pressure, pressure is applied through foundation drains to foundation contact increasing uplift pressure. Increase in uplift forces leading to sliding failure of powerhouse section. | Establish threshold values for uplift pressures based on stability analyses. Check capacity of sump pumps and tail water drain to handle inflows. Check design logic of foundation drains and valves to confirm that high water pressure in galleries would not be able to backpressure drains. Check drain performance/integrity after earthquakes. | Opening of tail water drains requires operator access to the sump. If inflows are not drained off fast enough, the pressure may increase above tail water level. Drains only cleaned once a year. Tail water drain valves have not been operated for some time and operability is unknown. | Galleries have automatic sump pumps. Leakage into gallery is monitored by weirs and gallery is inspected regularly. Flooding galleries alone is in itself not a concern. Tail water drains with manual valves are available to limit pressure buildup. |
| CONCRETE GRAVITY | SEISMIC | Spillway Gate | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Damage or infill during earthquake leads to loss of function of the foundation drains. Increased uplift pressures in a post-earthquake condition result in lower stability. Sliding failure of the powerhouse section results. | Establish threshold values for uplift pressure consistent with stability analyses. Review uplift pressures and need for drains in stability. | None identified. | powerhouse foundation has a positive slope. Grout curtains and drains exist. Piezometers indicate low foundation pressures. |

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| CONCRETE GRAVITY | SEISMIC | Spillway Gate | Concrete gravity structure with a central integral spillway equipped with drum gates, and with end piers separating the overflow section from non-overflow gravity sections. | Failure of drum gate hinge pins due to seismic loading. Hinge failure could lead to gate rotation about the vertical access leading to the loss on one or both gates and uncontrolled release of reservoir. | Inspect the inside of the drum gates and hinge pins. Analyze the hinge pins and drum gates under seismic loading. | Short hinge pin section. The hinge pins are inside the drums and are very hard to access, pins have not been inspected and condition is unknown. Hinge pin corrosion is a documented problem with drum gates. | Unlikely that the gate could actually fail to the extent where it separates from the dam. The gate is restrained by the tub lip and would probably wedge in place. Gate may not rotate about the vertical access and then both pins would not fail. The hinge pins have lubrite bearings, which should be in good condition. |

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| CONCRETE GRAVITY | SEISMIC | Sliding | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Deterioration of downstream buttresses reduces the base length of the powerhouse structure. Earthquake loading under the MCE results in an overturning failure of the powerhouse section. | Inspect the powerhouse and the buttresses after a felt earthquake. Perform a parametric study of the powerhouse stability with respect to the buttresses. | Buttresses are deteriorating which could reduce the effective base length by approx. 1/3. | Analysis indicate that factors of safety are met. Side friction from the adjacent fills was neglected in the analysis. |
| CONCRETE GRAVITY | SEISMIC | Structural | Concrete gravity dam with integral spillway with lift gates and stop log bays. | At normal full pool, seismic shaking causes cracking at the foundation interface resulting in loss of cohesion and leads to a sliding failure of the central pier section. | Analyze the stability under post-earthquake conditions. Visually inspect the dam after felt earthquakes. | ASR has been detected in dams original concrete sections. Silt buildup could adversely affect stability. Limited earthquake records for the area Limited local fault investigations. | Bedrock is sound, favorably bedded, and has significant asperities. Dam appears to be keyed into the foundation rock. Pseudo-static analysis indicates adequate factors of safety with conservative assumptions. Structures are short, stiff, and founded on bedrock to reduce amplification effects. |

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| EARTHFILL | USUAL | Structural | Rockfill embankment with a central earth core protected by three transition zones on each side. | Corrosion of reinforcing steel due to moisture penetration through cracks in the concrete weakens the strength of the wall. Driving force of the rockfill fails the retaining wall leading to loss of support. Sloughing of the rockfill could to a breach the embankment and/or block access to the powerhouse. | Seal the cracks to prevent moisture penetration and periodically monitor for signs of deterioration or new cracking. If indications of this are observed concrete coring/testing or remediation should be employed. | Cracks were observed early in the project. Cracks allow moisture penetration and rebar deterioration. Wall reportedly deflected during placement of the rockfill behind it. | Rockfill does not hold moisture and therefore little is available for penetration into the cracks. No iron staining noted on the wall. Design accounts for some rebar deterioration. Failure of wall may not leads to significant amount of sloughing to breach the embankment. |

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| EARTHFILL | USUAL | Piping | Rockfill embankment with a central earth core protected by three transition zones on each side. | Seepage through windows in the grouted gravel foundation materials or the sheet pile cutoff wall carries fines leading to a piping failure breach of the embankment. | Monitor piezometers (pz) quarterly and visual observation of potential depressions, sinkholes, downstream seepage. Set thresholds for pzs. Develop a cross section to the show the relationship of piezometers to embankment and foundation strata. Sonar survey upstream of embankment for signs of sinkhole development and future comparison. | Depressions occurred near this location on the upstream slope during initial filling of the reservoir. Some evidence of riprap settlement noted in the last 15 years. | Apparent low gradients downstream of core/cutoff. Gravel foundation was grouted. Embankment materials is not conducive to piping or holding an open pipe. No apparent seepage exit for a large distance downstream. Embankment monitored by piezometers which show steady or declining readings. upstream clay blanket installed after occurrence of depressions appears to have mitigated re-occurrence. |

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| EARTHFILL | USUAL | Piping | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | Piping of the core material through vertical jointing in foundation rock, or through the embankment, leads to loss of embankment material and failure of embankment dam. | No additional measures identified. Seepage emergence points are not observable. Continue visual surveillance. Investigate a method to evaluate and monitor seepage. | Jointing in the foundation rock is vertical and the grout holes were drilled vertical making it possible that not all joints were adequately grouted. Shortest seepage path is across the top of the concrete cap. The gradation curves for the filter material were not available, and compliance with filter criteria could not be checked. | Tertiary grout holes were employed in areas with high grout takes. Average grout takes were not high. A concrete cap was placed below the core material ensuring a good connection with the foundation, and dental concrete was employed outside the core contact area. Seepage path connectivity with the foundation and the core material does not seem likely. |

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| EARTHFILL | USUAL | Piping | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | Piping through along the penstock that penetrates the embankment, or through the embankment itself, leads to loss of embankment material and failure of embankment dam. | Continue visual surveillance with emphasis at penstock location. Investigate a method to evaluate and monitor seepage. | The penstock encasement penetrates the core of the embankment. | The penstock is encased in concrete, and two seepage collars and grooves were installed to extend the seepage path through the core. There are two filter zones downstream of the core to prevent movement of the core material. Construction photos document the seepage collars and grooves and the compactive effort adjacent to the penstock. |
| EARTHFILL | USUAL | Penstock | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | Penstock that penetrates the embankment ruptures under normal loading due to operation error or seismic loading, release of water eroded the left groin of the embankment resulting in an uncontrolled release of the reservoir. | Continue to inspect and maintain the penstock and perform steel thickness measurements. | Penstock collapsed previously upon closing of the head gate. Failure of the penstock could erode the left groin material. | A standpipe was added to prevent a vacuum after the penstock collapse incident. A five foot layer of larger diameter rock protects the downstream slope of the dam. Total rupture of the pipe is not expected. Head gate can shut off flow of water if a rupture is detected. |

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| EARTHFILL | USUAL | Piping | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Seepage and piping lead to internal erosion of the embankment or foundation. Uncontrolled flow through piped channels fails the downstream embankment or the complete embankment leading to uncontrolled release of reservoir. | Consider adding a filter/drain system and seepage measuring system with alarms. Continue twice daily visual monitoring with emphasis on seepage volume and fines content. | Foundation and embankment materials may be capable of being transported. Core and transition were not placed on bedrock. Small amount of freeboard exists. If piping occurs ample time may not exist to place a reverse filter to prevent failure. | Low differential head reduces the hydraulic gradient. Ability to lower reservoir quickly through the spillway could reduce damage. Seepage areas are monitored twice daily. |
| EARTHFILL | USUAL | Piping | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | High reservoir seepage levels create piping in the left abutment natural alluvium deposit. Internal erosion leads to settlement and rupturing of upstream seepage blanket and increased piping/seepage. Loss of embankment and/or abutment leadings to loss of freeboard and uncontrolled release of reservoir. | Place a piezometer at the toe of the left abutment blanket embankment. Continue monitoring program with current piezometers and visual surveillance for since of piping. | Progressive increase of the phreatic surface in observation wells in the area of the impervious blanket. One well indicates a phreatic surface at ground level. Unconfirmed reference to a report of a sinkhole. No piezometers at the toe of the impervious blanket groin. Gravel blanket downstream if impervious blanket obscures observation of sand boils. | Low hydraulic gradient through pervious overburden makes piping unlikely. A system of piezometers monitors the abutment area. Main seepage flow in the abutment is not expected to threaten the embankment slope stability. |

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| EARTHFILL | USUAL | Piping | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Seepage exists downstream of left embankment through unknown routes of the bedrock foundation or the embankment. If piping were to progress back under the left embankment section, then slumping of embankment could cause loss of freeboard and overtopping. | Determine the source of the flow. Continue daily visual monitoring and seepage flow. | Seepage path is unknown. | Seepage is visually monitored. Stability of embankment is improved with backfilled blanket of sand and gravel. |
| EARTHFILL | USUAL | Piping | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Piping through possible window in slurry cutoff wall into downstream alluvial foundation leads to uncontrolled seepage. Destabilization of foundation leads to failure of embankment. | Continue to monitor groundwater with periodic inspections of manholes and downstream observation wells. | Alluvial materials are heterogeneous and could have open-graded gravel or rock zones which could be capable of material transport. Slurry trench does not have transition zones on either side. Manhole observation point occasionally has a little water in it. Can't be sure of placement of materials in the slurry trench. | No signs of vegetation indicating seepage. Observation wells and manhole points instrument this area. Open work gravel-zones were reported to be discontinuous. Slurry trench is backfilled with well graded materials to be filter compatible. Good documentation of alluvial grouting. |

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| EARTHFILL | USUAL | Piping | Central concrete section with units and spillways flanked by zoned embankment sections that tie into the abutments. | Long term settlement of the embankment section leads to separation of the embankment materials against concrete gravity section. This initiates piping and causes settlement of embankment materials. | Install deeply bedded settlement monument at this location. | No concrete key (fin) at the wall into the embankment. History of settlement in the paving adjacent to the wall, as much as 6 inches. | Battered wall with offset downstream of core in zone of filter material. Grouted and placed on bedrock. Compaction against wall was performed with special care. |
| EARTHFILL | USUAL | Piping | Central concrete section with units and spillways flanked by zoned embankment sections that tie into the abutments. | Seepage at abutment contact zone leads to piping failure. | Inspect abutment area and embankment regularly. | None identified. | Adequate foundation clean up. Care exercised in compacting soils. Abutment was grouted. |
| EARTHFILL | USUAL | Slope Stability | Central concrete section with units and spillways flanked by zoned embankment sections that tie into the abutments. | Settlement of surcharge material over the core trench results in cracking of the core. Piping is initiated and progression of erosion leads to failure of the embankment section. | Install crest monuments. | Settlement has been observed. Slurry was squeezed out during construction which could have created a void. Cannot observe the toe for seepage. | Constructed under adequate conditions, with quality control. Cutoff constructed in bedrock. Upstream and downstream filters. Visual inspection is conducted weekly by operator and monthly by engineer. |

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| EARTHFILL | USUAL | Slope Stability | Central concrete section with units and spillways flanked by zoned embankment sections that tie into the abutments. | upstream embankment slope stability failure following reservoir drawdown leads to loss of freeboard, overtopping, and failure of the embankment. | Monitor embankment during reservoir drawdown. | Settlement has been observed. Slurry was squeezed out during construction which could have created a void. | Constructed under adequate conditions, with quality control. Cutoff constructed in bedrock. Upstream and downstream filters. Visual inspection is conducted weekly by operator and monthly by engineer. |
| EARTHFILL | USUAL | Erosion | Central concrete section with units and spillways flanked by zoned embankment sections that tie into the abutments. | A water supply conduit that penetrates the embankment section ruptures leading to erosion of embankment materials and progressive failure of the embankment. | Perform visual inspections of the conduit's alignment and interior periodically and after seismic events. Place a settlement monument on the embankment crest at this location. | Conduit is pressurized and carries a large quantity of flow. A rigid structure surrounded by a flexible one. | Conduit can be shutoff on upstream side. Has two collars along its length to act as water stops. |
| EARTHFILL | USUAL | Piping | Homogenous earthfill embankment. | Sinkholes develop undetected and lead to piping and/or collapse of the crest of the embankment. Breach results and uncontrolled release of the reservoir occurs. | Partition the reservoir to limit the volume of any breach of the lower reservoir. Continue daily visual monitoring. | History of active sinkhole development and the presence of sinkholes near the heel of the embankment. | Embankment materials are not susceptible to piping. Sinkholes may not enlarge sufficiently to initiate piping. Driving force is low at the critical embankment section. Embankment is inspected daily. Freeboard is generous. |

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| EARTHFILL | USUAL | Piping | Earthfill embankment with an RCC gravity dam section and intake structure. | Possible poor compaction at the embankment contact with RCC dam section creates a seepage path and initiation of piping. Should erosion extend to the reservoir and an open pipe develop collapse of the embankment and breach would occur.. | Continue program of toe drain monitoring, and visual inspections for signs of new seepage, and/or soil being carried by seepage water. Determine if embankment blanket drain does not tie into the RCC toe drain. | Embankment is a homogenous fill and includes non-plastic silt which is more vulnerable to erosion. Seepage was observed on the downstream face of the embankment soon after refilling the forebay. Special small compaction equipment can result in non-uniform density in the fill and create a preferred seepage path. | The seepage path is long and the gradient is low at the RCC/embankment interface. Grout treatment was applied at the interface between RCC and embankment fill. RCC toe drain and the embankment blanket drain are filtered to prevent piping of fine grained materials. No evidence of seepage occurring at the interface and low overall seepage in the embankment. Construction specifications and quality control records show the embankment was well compacted. |
| EARTHFILL | USUAL | Piping | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Piping initiated along aging cmp through the embankment leading to failure. | Monitoring program for upstream sinkholes, downstream seepage, turbid seepage. Inspect drain line with remote video camera. | The cmp is aging and its condition is unknown. | Currently functioning adequately. |

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| EARTHFILL | USUAL | Piping | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Piping through the embankment shell or through the foundation alluvial materials lead to collapse and failure of the embankment. | Monitoring program for upstream sinkholes, downstream seepage, turbid seepage.  Emphasis at cmp. | No positive leakage/seepage control measures provided at the foundation basalt/alluvium contact with the embankment. Sinkholes reported at the upstream embankment toe area and in the invert and sides of the canal. | Embankment is zoned with compatible material. No surface evidence of piped material deposits. |
| EARTHFILL | USUAL | Foundation Failure | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Settlement of foundation basalt bedrock due to internal cavities and voids leads to a severe breach of the canal and forebay concrete lining. | Segmented leak detection system below the canal's concrete lining to provide early warning of problem areas. Periodic visual observation of conditions in drained canal. | Potential for the development of large sinkholes.  Difficult to identify basalt features from surface observation and large voids may exist near the surface. | Concrete lining is reinforced and designed to span large cavities up to ten feet in diameter. Leak detection system will provide an early warning of possible problem areas.  Compaction grouting of the bedrock will provide structural support. |
| EARTHFILL | USUAL | Piping | Concrete gravity dam with integral intake and powerhouse and zoned earthfill wing dams. | Unnoticed long term seepage through the embankment sections initiate piping through the shells, causing loss of ground, and uncontrolled loss of reservoir to the top of rock. | Increase visual monitoring at high pools. | Downstream shell may not have filter compatibility with the core. | Water level unlikely to rise to an elevation for sufficient time to establish steady state seepage.  Regular Inspections.  Advance notice of flood events that increase pool elevation. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
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| EARTHFILL | UNUSUAL | Overtopping | Rock filled timber crib dam, faced with upstream planking. A central flashboard spillway with a reinforced concrete chute. | Local thunderstorm or sudden discharge from upstream dam leads to sudden increase flows. Untripped manual flashboards leas to overtopping of the embankment dam section. Overtopping erodes the embankment section and leads to uncontrolled release of the reservoir. | A plan for tripping the flashboards early in the flood event to minimize headwater levels. Need to confirm that flashboards can be tripped with water flowing over them. | Flashboard operation is manual and ability to trip during high flows is uncertain. Embankment materials are considered likely to erode under overtopping. | Operators are local and can respond quickly, overtopping of flashboards occur prior to level that overtops the embankment section. |
| EARTHFILL | UNUSUAL | Erosion | Arched concrete gravity dam with integral spillway, gravity wing dam section and concrete core wall section. | Flood flows up to PMF or surcharge from a lahar displacing the upper reservoir and flooding the lower dam, overtops the right abutment concrete core wall embankment section. Erosion of the downstream shell leads to instability of the concrete wall and ultimate failure of the embankment section. | Include studies with those for the upper dam. Include flows for assumed post tensioned configuration at the upper dam and calculate increased flood flows due to combinations of postulated failure of embankment core wall section. | Several different causes of high reservoir surcharge might initiate erosion overtopping and failure of core wall section. If adjoining monolith 16 becomes unstable, the core wall will probably also fail. | Core wall embankment is well compacted. Downstream embankment has an impervious embankment section (till) against the core wall with the remainder of the shell semi-pervious fill. Core wall with a thickness of 5 feet is socketed into and founded on sound bedrock for its entire length. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
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| EARTHFILL | UNUSUAL | Spillway Gate | Rockfill embankment with a central earth core protected by three transition zones on each side. | Spillway gates become inoperable during flood leading to overtopping of embankment and failure. | Test and inspect gates as defined by FERC guidelines. | Gate operation is necessary to pass floods approaching the PMF without overtopping. | Flood does not develop rapidly and there is time to respond to a gate failure with some available freeboard. Two backup power sources are available. Project is manned 24 hours per day. Gates are maintained and tested regularly. Separate hoist for each gate. |
| EARTHFILL | UNUSUAL | Slope Stability | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | Two crest raises over the life of the project has created steepened slopes at the upper portion of the embankment. Full loading under the PMF causes a slope stability failure of the downstream face and release the reservoir. | Continue visual monitoring for slumps, sloughs, and erosion. Review the core shear strength parameters to determine if a bilinear shear strength envelope is appropriate. | Downstream slope stability factor is marginal under PMF loading. Splash over the spillway chute has caused some erosion of the embankment in the past that required modifications to be installed. | Upstream slope stability factors are adequate under PMF loading and rapid drawdown conditions. The marginal downstream safety factor is for shallow surface failure that is not expected to release the reservoir and was performed with a conservative shear strength for the core material. Sheet pile is embedded into the core making an effective cutoff. |

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| EARTHFILL | UNUSUAL | Spillway | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | During high flows through the spillway creates a rock fall and/or failure of concrete training walls and lining blocking the spillway chute. Overtopping of the embankment dam results and leads to breach and dam failure. | Continue visual monitoring and assessment of spillway chute rock walls and concrete sections. | Spillway was seriously eroded and damaged by past flood. | Spillway is cut into rock and was grouted during construction. Cut slopes in the spillway are 1:1 with discontinuities in the rock mass mostly vertical making for a stable slope. Additional protection has been applied to the spillway chute walls with concrete and shotcrete. Spillway was modified after the previous flood event, constructing a flip bucket/stilling basin and lining the chute with concrete. |
| EARTHFILL | UNUSUAL | Spillway Gate | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Failure of spillway gates to function during to flood flows due to loss of control systems, or mechanical failure. Inability to open a sufficient number of gates could overtop the embankment dam section leading to failure. | Time gate maintenance for non-flood season. Provide regular maintenance of gate drives, control systems and gate guides. Continue periodic inspections and testing. | It takes more time to repair mechanical failures than control systems. | PMF can be passed without all of the spillway gates. Sufficient warning of high flows due to upstream facilities. Operators are available at all times and conduct daily inspections. |

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| EARTHFILL | UNUSUAL | Overtopping | Earth and rockfill embankment with an inclined impervious core, protected by upstream and downstream filters. | Fish handling barge breaks free of it's moorings during a flood event, drift in to the spillway, blocking discharge and causing the reservoir to rise overtopping the embankment dike section, leading to erosion and eventual breach. | Design the barge to break away and beach itself in a preferred location. Construct a standoff system to prevent the barge from blocking the spillway. | Embankment dike is vulnerable to erosion from overtopping. History of movement of the fish handling barge during spillway discharge. Capacity of the current anchoring system is unknown. | Fish handling barge could break up and be passed through the spillway. Discharges through the spillway are relatively brief. A new fish handling facility and anchorages is currently being designed. |
| EARTHFILL | UNUSUAL | Spillway Gate | Earth and rockfill embankment with an inclined impervious core, protected by upstream and downstream filters. | Spillway gates at the main dam become inoperable during flood event. Reservoir rises and overtops leading to overtopping of the embankment dike section, erosion and eventual breach. | Check the condition of the spillway gate hoists, and redundancy of power supply to gates. | Lack of redundancy of routes to power supply to the gates. Condition of the wire ropes connecting the gates is unknown. | Satisfactory performance of gates during recent floods, and a regular testing exercise. Gates can be operated manually and are manned during flood flows. |
| EARTHFILL | SEISMIC | Slope Stability | Rock filled timber crib dam, faced with upstream planking. A central flashboard spillway with a reinforced concrete chute. | Seismic event leads to deformation of the embankments section. Should the deformation breach the embankment the reservoir would be released. | Inspect the embankment and timber crib section after earthquakes. | The USGS probabilistic acceleration is greater than that from the MCE of the project. | Displacements in the embankment section are expected to be acceptable without a loss of the reservoir. |

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| EARTHFILL | SEISMIC | Low Level Outlet | Zoned earthfill dam with central asymmetrical core and upstream/downstream filter zones, supported by upstream and downstream shells of pervious rockfill. | Earthquake shaking causes low level gate tower to fail and ability to lower the reservoir is lost. The spillway is ungated overflow type. | Review the stability of the tower under earthquake loading to ensure that the low level outlet remains operable. | The tower cross section at the top is greater than where it exits the embankment and equipment at the top adds mass. Tower response to earthquake has not been recently analyzed. | Failure of the tower would not result in loss of the reservoir. Only inability to operate the gate. PGA values are considered appropriate. |
| EARTHFILL | SEISMIC | Slope Stability | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Earthquake causes settlement of embankment crest, cracking of the embankment result creating erosion paths, progressive erosion leads to slumping of the embankment, loss of freeboard, and failure of embankment section. | Establish a post earthquake recovery plan, with sources of fill for crack filling. Post earthquake inspections including instrumentation, and visual inspection for cracks and settlement at the crest. | Displacement would be accompanied by surface cracking. No onsite stockpiles of material to fill cracks in post-earthquake. | Estimated deformations are small and less than the available freeboard. Calculated deformations are considered conservative estimates based on current seismicity. |

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| EARTHFILL | SEISMIC | Slope Stability | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Seismic event leads to settlement of embankment and/or separation of embankment from adjacent concrete gravity section leaving a gap, a local erosion path is opened, leading to slumping, loss of freeboard, subsequent erosion and progressive dam failure. | Post earthquake inspection of embankment section, establish provisions for recovery plan and quick repairs with sources of fill material. | Difficult to get good compaction adjacent to concrete structures. | Hand compacted at interface. Cut-off wall at the interface with the embankment. Expected slip circles do not intersect the core. Core is backed with well graded transition zones that meet filter criteria. Downstream shells are pervious sandy gravels. |
| EARTHFILL | SEISMIC | Spillway Gate | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Earthquake initiated liquefaction of foundation materials beneath and downstream of the embankment created loss of strength in the foundation materials leading to slumping. Loss of freeboards leads to overtopping and progressive erosion failure. | Evaluate up to date ground motions and review previous earthquake analysis. | Embankment shells are founded on pervious alluvium and material may be liquefiable. | Previous studies indicate high factors of safety. SPT values from previous exploration are N>25. |

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| EARTHFILL | SEISMIC | Spillway Gate | Multi sectioned dam with left and right zoned embankments (central core with upstream and downstream shells), and left and right gravity sections, and two central gravity sections consisting of a gated spillway section and powerhouse section. | Earthquake ground motions fail the anchor bolts of the emergency generators resulting in in loss of standby power units. Power to the spillway gates and sump pumps in drainage gallery is lost. Loss of spillway capacity could lead to overtopping and failure of the embankment sections. | Upgrade the emergency generators for seismic resistance and check anchor bolts at least annually. | Diesel generators may not be earthquake resistant designed. Unknown if anchor bolts can withstand expected shear loads. | Alternate power supply is available, and mobile generators. |
| EARTHFILL | SEISMIC | Slope Stability | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Under a significant or MCE event the side canal embankment would be subject to strong shaking. The crest or slopes of the canal could settle or slump sufficiently to allow flow of water over the embankment. Overtopping of the embankment could result in erosion and failure of the embankment and loss of water in the canal. | Earthquake stability and liquefaction analyses of canal embankments. | Area of canal identified as susceptible to liquefaction. | Significant portion of the canal is buttressed. Minimal consequences for the majority of the canal sections. |

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| EARTHFILL | SEISMIC | Piping | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Seismic event creates separation between the concrete intake structure and the embankment materials open up an uncontrolled seepage path and result in piping and failure of the embankment. | Earthquake analysis of response of intake structure and intake embankment to evaluate to the possibility of separation. | Earthquake response in the concrete intake will be different than the intake embankment and between the intake and the concrete canal lining resulting in separation at these interfaces. | Crack stopper materials were placed in the embankment at these interfaces to protect against piping development. |
| EARTHFILL | SEISMIC | Liquefaction | Power canal with a zoned embankment, partially concrete lined, with a forebay, and a concrete intake structure. | Liquefaction of canal embankment during seismic event leading to slide failure or excessive deformation and breach of the embankment. | Earthquake stability and liquefaction analyses of canal embankments. | Seismicity is high (.39 PGA). No significant data on liquefaction potential in some sections of the canal. Cracking of the canal liner could occur. | Canal normally has 7 feet of freeboard. PGA may be less than embankment yield acceleration. Concrete liner with drainage system does not allow seepage forces to develop in the embankment. |
| EARTHFILL | SEISMIC | Liquefaction | Earthfill embankment with an RCC gravity dam section and intake structure. | Liquefaction of low density foundation or canal embankment materials during seismic event leading to a flow slide failure and breach of embankment. | Survey the embankment to determine location where deformations could be the greatest (i.e. areas with less downstream buttressing material.) | SPT data in the old embankment dam materials indicated that liquefaction was likely for a large magnitude seismic event. Longer duration subduction zone event corresponds to more potential for liquefaction and deformation. | Low embankment height. Small deformations are likely and freeboard is a large percentage of the dam height. |

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| ROCKFILL | USUAL | Piping | Rockfill dam with an upstream concrete and aluminum facing, and a side channel uncontrolled spillway. | Seepage from within the foundation embankment or along the penstock and low level conduit through the dam could lead to piping of material within the dam with the ultimate result of settlement of the dam crest below the level of the spillway. This in turn could result in failure of the dam and an uncontrolled release of water from the reservoir. | Monthly visual inspections to provide an advance notice; if there is a change in the pattern then document. Current meter has been installed with the inflow conduit for the seepage pump back system. Changes in the existing seepage patterns can be identified. | High seepage quantities exceed expectations. Historical total seepage is not well quantified. | Seepage is not unexpected. Settlement measurements show no loss of material. Size of rock fill is not transportable. Water runs clear and clean. Seepage is measured at pump back system. |
| ROCKFILL | USUAL | Penstock | Rockfill dam with an upstream concrete and aluminum facing, and a side channel uncontrolled spillway. | Failure of penstock due to unstable soil sub grade (land slide prone saturated colluvium) and/or aging support structures. An over-velocity valve at the upper end of the penstock could malfunction and not shut off the flow of water, releasing the entire reservoir. | penstock and over velocity valve should be regularly inspected and maintained to allow for penstock flow to be shut off. | Valve may malfunction. Penstock supports have shifted in the past and are aging. Penstock and supports are above ground and exposed to damage. | Shut off valve is in place and can be tested annually. Penstock is inspected annually and documented. |

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| ROCKFILL | USUAL | Slope Stability | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Slope stability failure of the left abutment section caused by global slope failure or failure of the upper portion of the downstream face which is constructed of large rockfill and performs as a retaining wall. Release of water is not expect unless upstream concrete facing is damaged, but reservoir limitation would be necessary during repairs. | Continue monitoring the settlement pins on the concrete face and visual observations at the downstream toe. Monitor seeps for sediment transport. | Longitudinal and transverse cracks are developing and getting larger in the pavement on the crest. Specific construction details of the rock retaining wall are not known. | Total maximum settlement to date is within tolerable limits. Concrete facing has no significant sags. Cracking in the concrete crest is monitored and has shown no adverse trends. |
| ROCKFILL | USUAL | Slope Stability | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Seepage in the right abutment area is not completely intercepted by the drainage system which may also be partially plugged. Slope instability through loss of drainage could lead to embankment failure and partial or total loss of reservoir. | Investigate the geologic conditions of the abutment and it's stability. Clean the drain system, monitor seepage and movement of fines. | Possible modes of movement of the slope are valid. Movement of the natural slope would undermine embankment and rock fill, leading to cracking of the concrete face. Seepage is noted at the abutment. Actual parameters of the slope material are unknown. | Natural slope is relatively flat. Soils contain cobbles and boulders with a sand and fines matrix. A shear strength with a friction angle in excess of 35 degrees is expected. No indications of instability in the natural slope. |

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| ROCKFILL | USUAL | Low Level Outlet | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Ice buildup on the low level outlet Howell Bunger valve causing the vanes to fail. This results in the loss of the low level outlet valve for regulating the reservoir. | Continue to monitor for ice buildup and remove. | ice buildup has occurred in the past. | There is a backup butterfly valve and the intake has a slide gate. Removal of ice from the valve is possible with the aide of equipment. Ice buildup is not a frequent event. |
| ROCKFILL | USUAL | Erosion | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Excessive seepage beneath or through the left abutment caused by deterioration of tuff layer or through cracks in the basalt bedrock leads to erosion of the tuff layer creating a void. An uncontrolled release of reservoir would occur. | Clear brush from the seepage areas and identify locations for monitoring program. Prepare an assessment of the seeps and their geologic description. | Tuff layer is present at the invert of the spillway channel. Seepage volumes recorded are significant. | No increasing trend in seepage. No sediment transport has been observed. Area had been treated with grout. Construction document indicate that the cutoff wall was extended at the tuff layer. |

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| ROCKFILL | USUAL | Slope Stability | Earth and rockfill dam with downstream rockfill with a wide berm, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Uncontrolled seepage of sufficient magnitude leads to piping of embankment materials, loss of material and settlement leads to an uncontrolled release and possible embankment slope failure. | Settlement surveys and visual monitoring to detect settlement and embankment deformation. | The sloping core and free-draining downstream shell make uncontrolled seepage difficult to detect. | An adequate core protected by relatively thick and well constructed filters. Abutment slopes were shaped to avoid abrupt changes that might promote cracking and seepage paths. Shells are strong and compact and expected to avoid settlement. Settlement and alignment measurements and visual observations indicate normal behavior. Seepage has not been observed. |

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| ROCKFILL | USUAL | Spillway Gate | Earth and rockfill dam with downstream rockfill, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Uncontrolled seepage of sufficient magnitude leads to piping of embankment materials, loss of material and settlement leads to an uncontrolled release and possible embankment slope failure. | Settlement surveys and visual monitoring to detect settlement and embankment deformation. | The sloping core and free-draining downstream shell make uncontrolled seepage difficult to detect. | An adequate core protected by relatively thick and well constructed filters. Abutment slopes were shaped to avoid abrupt changes that might promote cracking and seepage paths. Shells are strong and compact and expected to avoid settlement. Settlement and alignment measurements and visual observations indicate normal behavior. Seepage has not been observed. |

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| ROCKFILL | USUAL | Piping | Rockfill embankment with a central earth core protected by three transition zones on each side. | Seepage through the sediment at the foundation abutments travels along the tunnel side walls or into the tunnel. Seepage erosion and expansion of the pipe lead to progressive erosion back to the reservoir. Loss of reservoir in to the tunnel or caving of the embankment materials could result in a breach of the embankment. | Monitor turbidity and sediment accumulation in existing weirs at abutment drainage tunnels with on a regular schedule. Complete inspection of tunnel conditions every 5 years. | Sediment discharge from the drains has been observed. Seepage flows are high indicating a greater potential for initiation of particle movement these flows also make sediment transport observations difficult. One weir indicates variations in flow. Open exit for material through the lower adits. | Flows have been stable over time. Collection barrels allow for observation of sediment. Hydraulic gradient is low. No recent evidence of sediment transport. |
| ROCKFILL | USUAL | Piping | Rockfill embankment with a central earth core protected by three transition zones on each side. | Drains comprised of quarry spalls that were created to facilitate construction could create a transverse flow path which would allow piping of the core material through an unfiltered flow path. Removal of material would allow caving of the dam materials and an eventual breach. | Flow measurements at weirs and take samples for turbidity measurements. | Drains of quarry rock spalls are a construction related flow in the dam design. These drains run transverse to the dam axis, which could create a piping or seepage erosion conduit at the interface with the core zone 1 material. | Quarry spall drains were grouted closed during construction. Flow measurements and piezometers have been stable. Core is protected by broad filter, which meets modern filter criteria. |

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| ROCKFILL | USUAL | Erosion | Rockfill embankment with a central earth core protected by three transition zones on each side. | Stepping of abutment rock is suspected to have caused past transverse cracking in the embankment materials through differential settlement. If transverse cracking were reactivated (crack would be high in the cross section), seepage erosion and an expansion of the path could develop leading to a breach of the embankment. | Monitor the dam crest for sign of cracking or differential settlement. | A crack was observed in the past to be 16 feet deep. Abutments are fairly steep, are not a continuous smooth slope, and step at intervals, which would promote differential settlement. Steep areas are lower in the abutment, as illustrated in construction photographs. Core is comprised of granular, non-plastic material. Cracking could be reactivated by seismic loading. | Core is protected by a wide filter which meets modern filter criteria. Filters also flair at the abutments adding protection for the non-plastic core. Dam has already experienced the majority of its expected settlement. |

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| ROCKFILL | USUAL | Piping | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Fine grained material is piped from the upstream impervious zone through the transition and into the rockfill section. Water pressure builds up behind and fails the RCC overlay and the rockfill section resulting in loss of the reservoir and downstream flooding. | Install addition settlement monuments, and test the existing piezometers to ensure they are functioning. Install a settlement alarm at a known (treated) sinkhole location. Modify the headwater and tail water alarm to respond to finer rates of change. Lower the normal reservoir elevation. Regularly inspect the drain holes in the toe of the RCC overlay and the upstream embankment for sinkholes. Investigate potential to mitigate leakage in the embankment. | Upstream impervious core and transition zone may not meet filter criteria and the transition zone may be narrower than originally designed. History of sinkhole development and repair in the embankment. | With the observed sinkholes, sediment plumes have only been observed in the tailrace twice. A limited number of samples from a previous investigation indicate that the transition zone meets filter criteria. Due to the size of the rockfill and high velocities needed to erode, failure is expected to take time and not be instantaneous, indications in leakage at the toe drains would be an early warning. |

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| ROCKFILL | USUAL | Piping | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Fine grained material is piped from the upstream impervious zone into the gravel foundation materials. Progressive piping leads to failure of the rockfill section resulting in loss of the reservoir and downstream flooding. | Investigations should be performed to determine the grain size characteristics of the fine grained foundation materials. Install addition settlement monuments, and test the existing piezometers to ensure they are functioning. Install a settlement alarm at a known (treated) sinkhole location. Modify the headwater and tail water alarm to respond to finer rates of change. Lower the normal reservoir elevation. Regularly inspect the drain holes in the toe of the RCC overlay and the upstream embankment for sinkholes. Investigate potential to mitigate leakage in the embankment. | History of sinkhole development and repair in the embankment. Seepage through the foundation was noted in previous explorations as evidenced by artesian pressures in borings at the downstream toe. | Average gradations of the finer grained material and the foundation material are close to meeting acceptable piping criteria. |

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| ROCKFILL | USUAL | Piping | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Fine grained impervious zone and transition zone are thinnest at the top of the dam. This condition promotes fine grained material to be piped along the interface with the concrete powerhouse structure. Progressive piping leads to failure of the rockfill section resulting in loss of the reservoir and downstream flooding. | An evaluation, including an exploration of the embankment materials, to determine if a global or localized fix is required. | No seepage cutoffs were installed along the powerhouse wall. Differential settling and sinkholes have been observed at this location. Transition zone may be placed narrower than originally planned and may not meet filter criteria with the rockfill material. | Analysis indicates that the fine grained and transition materials meet filter criteria. Observations of sink holes and seepage indicate that the problem may be in the upper portions of the dam. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
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| ROCKFILL | USUAL | Piping | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | The embankment is penetrated by concrete low level outlets which are plugged. Seepage erosion develops along the low level outlets and carries material into the tunnel. Progressive piping leads to failure of the rockfill section resulting in loss of the reservoir and downstream flooding. | An evaluation to determine if a global fix is required to mitigate concerns for piping along the low level outlets. Install addition settlement monuments, and test the existing piezometers to ensure they are functioning. Install a settlement alarm at a known (treated) sinkhole location. Modify the headwater and tail water alarm to respond to finer rates of change. Lower the normal reservoir elevation. Regularly inspect the drain holes in the toe of the RCC overlay and the upstream embankment for sinkholes. | Details of the sealing of the low level outlets are not well known. Crest settlement is occurring above the low level outlets. A direct path from the reservoir to the low level outlets, below the seepage collars, may exist. | Past inspection of the low level outlets indicated that no leakage past the plug was occurring. Three seepage collars on the conduit interrupt the flow path. |

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| ROCKFILL | UNUSUAL | Debris | Rockfill dam with an upstream concrete and aluminum facing, and a side channel uncontrolled spillway. | Logs and debris left to decompose occasionally come loose and float into the reservoir. During a high flow event the debris could migrate towards the dam and block the spillway. Significant blockage, in turn, could cause the spillway capacity to be inadequate and preclude overtopping of the dam and uncontrolled release of the reservoir. | Regularly inspect spillway for blockage and reservoir for excessive buildup of debris with additional inspections following high-flow events. | Cleared material (vegetation) still gets into the lake. Mature large trees exist in the vicinity. No existing log boom. Spillway is not relatively wide and could be easily blocked. | Minimum amount of material is available to block the spillway. High flows trigger an alarm and an operator inspects the dam. A maintenance program is ongoing to manage logs in the reservoir. |
| ROCKFILL | UNUSUAL | Debris | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Debris blockage of the spillway and flashboard sections leads to overtopping of the rock fill dam leading to failure and release of reservoir. | Review operations plan to address debris handling procedures and evaluate reservoir rim for debris potential. | because of no recent flooding the availability of logs may be great with rising water levels in a high flow event. | |
| ROCKFILL | UNUSUAL | Overtopping | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Overtopping of the rock fill embankment during the PMF leads to erosion of the abutments and eventual failure of the embankment. | Update the PMF with up to date HMR 57. | PMF analysis needs to reviewed and updated. Abutment materials are erodible. | Two feet of freeboard exist when passing the current PMF. New HMR is expected to reduce precipitation values. Rockfill contains 1-2 ton boulders, is resistant to erosion and is free draining. |

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| ROCKFILL | UNUSUAL | Sliding | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | PMF loading causes sliding instability along failure plane at concrete rock interface. | Evaluate the stability of the spillway section. | Failure surface was not evaluated in previous stability analyses. | Volcanic foundation rock provides a high shear resistance. Drains are installed and reduce uplift. Spillway has a low height to width ratio. |
| ROCKFILL | UNUSUAL | Spillway Gate | Earth and rockfill dam with downstream rockfill, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Seismic event damages spillway gates rendering gates inoperable. High flows exceeding the capacity of other available outlet works leads to overtopping of the embankment, progressive erosion, and failure. | Visual inspection after any felt earthquake. Develop a procedure for raising the gates with a mobile crane. | Lack of a procedure for operating the gates with a mobile crane. High estimated ground motions. | Unlikely that all three gates would become inoperable simultaneously or independent power sources would fail simultaneously. |
| ROCKFILL | UNUSUAL | Overtopping | Rockfill embankment with a central earth core protected by three transition zones on each side. | Failure of the powerhouse's ability to pass flow, inflow exceeds the capacity of the spillway, overtopping of the dam and erosion of the groins and crest lead to a breach of the embankment. | Test scenarios of generating independent of station service. Develop a procedure for decision on use of valves with turbine blocked and conduct training. Check the location of the towers providing service power. | Electrical system could be lost during a major storm. Station service comes from external source. Lines are subject to snow pack and heavy winds. Problems with the transfer switch that feeds into the powerhouse. | Three ways to transmit power from the powerhouse. Two sources of power feed the powerhouse and both have never been lost. Units can be black started. Flood must exceed spillway capacity, which is sufficient for all historical floods. |

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| ROCKFILL | UNUSUAL | Debris | Rockfill embankment with a central earth core protected by three transition zones on each side. | Debris loading blocks the spillway leading to loss of the spillway capacity, overtopping of the embankment, erosion of crest and groins, and eventual breach of the embankment. | Arrange for accessibility and availability of a mobile crane. Ensure that the crane could remove debris. Evaluate the debris boom. | May experience a greater amount of debris at flows approaching the PMF. No debris boom at the project. Upstream dam could fail during high flow event. | In highest flood of record, only a small amount of debris was observed and none of significant size. Should have ample warning to remove debris as buildup progresses. Currents at the head of the reservoir tend to direct debris and keep it in the reservoir. Debris buildup at the spillway has not been observed. |
| ROCKFILL | UNUSUAL | Landslide | Rockfill embankment with a central earth core protected by three transition zones on each side. | Landslide could block the spillway entrance or exit reducing its capacity and/or interrupt power transmission to/from the powerhouse reducing its ability to pass flow. Overtopping of the embankment, erosion of the dam crest and groins lead to eventual breach of the embankment. | Establish monitoring points and obtain survey data on a regular basis to detect movement. Have the rock mass evaluated by a geologist. | Basalt formation is on a steep dip at its contact. | No evidence that material has moved during a previous event. Blocking of spillway would be insufficient to completely block all discharge. Potential problem was recognized an considered during design. |

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| ROCKFILL | UNUSUAL | Overtopping | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Recent PMF analysis indicates a higher flow than the service and emergency spillways can pass. PMF flow overtops the training wall of the emergency spillway, and the right gravity wall, and creates an unanalyzed hydrologic loading. Should the dam experience this loading, failure of the training wall, the right gravity, and a slope stability failure could occur failing the dam and releasing the reservoir. | Confirm the condition of the downstream spillway apron and inspect after spill events. Review and confirm the recent PMF study. | Stability under the recent revised PMF levels have not been evaluated. Erosion of the spillway apron may occur under prolonged floods. Overtopping of the right gravity wall and the spillway training wall would cause erosion reducing the stability of these structures and the embankment. Settlement at the training wall may have reduced it's stability. | Factor of safety under old PMF value is very high, the new loading is not expected to reduce the FS to unacceptable levels. RCC is erosion resistant. Bedrock at the abutments and the foundation is very erosion resistant. |

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| ROCKFILL | SEISMIC | Sliding | Rockfill dam with an upstream concrete and aluminum facing, and a side channel uncontrolled spillway. | Seismic event causes sliding of the rock fill embankment leading to failure of the dam. | Continue surveying of monuments on regular schedule. Visual inspection and survey following seismic events. Maintain breach alarm in weir at downstream toe. | Lack of construction records and photos of the dam. Downstream sloping foundation. Moderate seismic environment. Rock fill is narrow compared to current design standards. | Excellent foundation materials are confirmed. Fifteen years of annual survey records for movement monuments. PGA estimate is conservative. Free draining embankment. Stability analysis indicates acceptable FS. Permanent deformation due to seismic event is not expected to cause overtopping. |
| ROCKFILL | SEISMIC | Slope Stability | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | Current PGA is higher than the design event. Ground motions near the PGA could cause excessive deformation of the rockfill and topple the rockfill wall that is the upper portion of the downstream face. Release of the reservoir is not expected but extensive damage to the crest and would occur. | Inspect after seismic event and check for cracked concrete panel and ruptured water stops. Lower reservoir if appropriate. Review changes to seismicity in the region and update analyses as necessary. | PGA is greater than the design value and could increase with further study. Modes of movement are valid. | Water stops on concrete facing are designed to accommodate movement. Deformation of the crest would be expected but damage to the concrete facing is not. |

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| ROCKFILL | SEISMIC | Slope Stability | Concrete faced rockfill dam. Flexible water stops seal the joint between face slabs. | The right abutment is founded on ancient terrace deposits. A seismic event leads to liquefaction of right abutment foundation materials and downstream abutment. Failure of the natural slope could undermine the toe of the rock fill and lead to embankment failure. | Inspect after seismic event and check for cracked concrete panel and ruptured water stops. Lower reservoir if appropriate. Review changes to seismicity in the region and update analyses as necessary. | PGA is greater than the design value and could increase with further study. Modes of movement are valid. | Terrace deposit is firm clay, sand, gravel, and boulder mix which is not a typical liquefiable deposit. Historically the area has experienced low seismicity. Previous liquefaction analysis under lower PGA did not indicate liquefaction. |
| ROCKFILL | SEISMIC | Slope Stability | Earth and rockfill dam with downstream rockfill with a wide berm, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Seismic event creates a slope failure in the upstream sloping core and exposes the drain and/or cracks the core material exposing the free draining rockfill section of the dam. In addition crest deformation could result in loss of freeboard. Either of these condition or a combination would lead to an uncontrolled release of the reservoir and possible dam failure. | Visual inspection after any felt earthquake | The dumped and sluiced portions of the shells are susceptible to earthquake deformation. | Existing freeboard is adequate to accommodate predicted crest settlement under the MCE. |

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|---|---|---|---|---|---|---|---|
| ROCKFILL | SEISMIC | Spillway Gate | Earth and rockfill dam with downstream rockfill with a wide berm, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Seismic event damages spillway piers, operating system, or the gates themselves rendering gates inoperable. High flows exceeding the capacity of other available outlet works leads to overtopping of the embankment, progressive erosion, and failure. | Visual inspection after any felt earthquake. Develop a procedure for raising the gates with a mobile crane. | lack of a procedure for operating the gates with a mobile crane. High estimated ground motions. | Piers are robust and are expected to withstand the MCE. Unlikely that all three gates would become inoperable simultaneously or independent power sources would fail simultaneously. |
| ROCKFILL | SEISMIC | Spillway Gate | Earth and rockfill dam with downstream rockfill, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Seismic event creates a slope failure in the upstream sloping core and exposes the drain and/or cracks the core material exposing the free draining rockfill section of the dam. In addition crest deformation could result in loss of freeboard. Either of these condition or a combination would lead to an uncontrolled release of the reservoir and possible dam failure. | Visual inspection after any felt earthquake | The dumped and sluiced portions of the shells are susceptible to earthquake deformation. | Existing freeboard is adequate to accommodate predicted crest settlement under the MCE. |

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| ROCKFILL | SEISMIC | Sliding | Earth and rockfill dam with downstream rockfill, upstream sloping core, bounded by filters, and upstream rockfill shell. Spillway founded in rock abutment. | Seismic event leads to sliding failure of the spillway section leading to uncontrolled release of reservoir. | Visual inspection after any felt earthquake | None identified. | Keying of the sidewalls into rock, a grout curtain, strong foundation with contact roughness, proper foundation preparation. |
| ROCKFILL | SEISMIC | Slope Stability | Rockfill core with a thin transition zone separating the upstream sloping impervious zone. A randomly placed rockfill buttress extends from the toe to the crest of the upstream slope. The rockfill dam abuts a concrete gravity powerhouse section and a gated spillway is cut into the opposite abutment bedrock. An RCC emergency spillway is overlays the rockfill dam section. | Under the MCE, slope stability failure of the downstream or upstream slopes occur. Should the slope failure create sufficient loss of crest elevation or separation below the concrete crest cap, water flowing through the breach would create progressive erosion until the reservoir elevation was lowered enough to stop the erosion. | Continue to review seismicity. Inspect after felt earthquakes | None identified. | The dam has experienced two significant earthquakes without damage. RCC overlay adds to the slope stability and would slow the erosion. Discharge capacity could quickly lower the reservoir elevation should damage be detected. |

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| SLAB and BUTTRESS | UNUSUAL | Overtopping | Concrete ambursen structure with an overflow spillway section, a non overflow powerhouse section, and both counterfort and embankment wing dam sections. | Current estimates exceed the design flow and the reservoir levels for the design of the abutment wing dams. Overtopping of the embankment wing dam leads to failure. Loss of the wall could lead to the downward erosion of abutment foundation terrace deposits and an uncontrolled release. | Verify location, condition, and function of the stop logs. Check design calculations to determine adequacy of flood wall. Update operating procedures to ensure staff is not downstream of floodwall during flood above design capacity. | Probable that the design of the floodwall is inadequate. Thirty feet of erodible terrace deposits underlie a the downstream paved area. Head cutting potential exists to the steep slope in this area. Duration of the flood event is long enough for significant erosion to occur. | The downstream area is mostly paved, providing some erosion protection. EAP is activated well before overtopping flows which could mitigate consequences. Center flood wall is considered is known to be weaker than other areas increasing the possibility that this wall would fail first. |
| SLAB and BUTTRESS | UNUSUAL | Sliding | Concrete ambursen structure with an overflow spillway section, a non overflow powerhouse section, and both counterfort and embankment wing dam sections. | Sliding failure along the Dam/Foundation contact at the buttresses under increased flood loading. | Continue collecting survey data and perform routine visual monitoring to detect movement. | There is less mapping of the foundation at this dam section. There are no good records of foundation preparation for the buttress section. Unit stress is greater on an Ambursen dam is greater than a gravity dam due to the buttress concentrating load from the face slabs over a smaller foundation contact area. | As-built drawings indicate the buttresses are founded on rock. Cores indicate good bonding at the contact. Detailed stress analysis for all loading conditions performed and indicate satisfactory results. Buttress dams are not susceptible to uplift pressures. Sloping face of the dam increases stability by utilizing hydrostatic pressures. |

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| SLAB and BUTTRESS | UNUSUAL | Sliding | Concrete ambursen structure with an overflow spillway section, a non overflow powerhouse section, and both counterfort and embankment wing dam sections. | Sliding failure along lift surfaces in the buttresses under increased flood loading, if one buttress is lost, water flows enter the interior of the dam and load the adjacent buttress to failure. | Continue collecting survey data and perform routine visual monitoring to detect movement. | Construction records discuss the possibility of laitance on the lifts, concerns over the quality of the aggregate, and may have been placed wet. No documentation of control tests on the concrete. There is a possibility that joint degradation could occur, during out of place loading, such as during an earthquake. | Construction records indicate that laitance was removed prior to placing the upper lifts. Shear keys were formed in the lift joints as shown in construction photographs. Buttresses are all in good condition with visual indication that lifts are bonded. Seismic analysis is conservative. |
| SLAB and BUTTRESS | UNUSUAL | Structural | Concrete ambursen structure with an overflow spillway section, a non overflow powerhouse section, and both counterfort and embankment wing dam sections. | Failure of face slabs caused by overstressing during flood or earthquake event, should a face slab fail at any location, water flows enter the interior of the dam and cause progressive collapse of adjacent buttresses. | Continue existing surveillance, emphasizing inspection for flexural cracking or new rust staining on the face slabs. | There is evidence of cold joints and some limited spalling. Construction records offer no information on steel reinforcing, and past testing was limited to three samples. Rust stains have been observed on some of the face slabs. | No signs of overstress during historical flood events. Past tests showed rebar and concrete to be in good condition. Construction photographs show conformance with design drawings. Some of the observed rust stains are attributable to embedded form tie wire. |

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| SLAB and BUTTRESS | SEISMIC | Structural | Concrete ambursen structure with an overflow spillway section, a non overflow powerhouse section, and both counterfort and embankment wing dam sections. | Large magnitude earthquake causes cross canyon loads leads to a buckling failure of the spillway buttresses or corbels leading to a collapse of the face slabs. | Continue visual inspections on a regular basis. Perform lift off tests on update relaxation projections every 5 years. | Longer duration earthquake could increase the cumulative damage. Pre-existing reinforcing within the buttresses does not cross the lift joints and provides no flexural capacity against out of place bending. | Diaphragm walls and new struts were added for the expressed purpose of ruling this FM out. The diaphragm walls are reinforced, and tied into the crest slab and founded on massive footings. The design was based on rigorous 3D dynamic FEM modeling and is considered conservative. |
| TIMBER CRIB | USUAL | Sliding | Timber crib dam with upstream concrete facing, central mass concrete section and downstream concrete apron. Central section is overflow with flashboard and gated sections. The abutments have concrete gravity sections, one a waste way and the other the intake section. | Sliding failure of the spillway section during normal and PMF loading along the foundation contact. | Continue with drain maintenance and cleaning, and monitoring and instrumentation surveys. | Some sections of dam known to be on rockfill cribbing with timber cribbing in some monoliths. Potential for shale/weak rock at depth. | Drains are cleaned and plugged drains can discharge to other drains in the system minimizing uplift pressures. Monitoring program in place. Stability analysis shows adequate FS. Flashboards would be removed during PMF. |

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| TIMBER CRIB | USUAL | Piping | Rock filled timber crib with upstream sheet pile cut off wall and a gated concrete reinforced overflow spillway. Concrete slabs are post tensioned to foundation materials. Concrete gravity intake and abutment sections are at one abutment. | Foundation seepage under the spillway section results in the loss of support at the toe of the spillway section resulting in a failure. | Continue monitoring for change in leakage. | Training wall section experienced a loss of material prior to rehabilitation. Although the alluvium is coarse grained it is pervious. The installation depth of the sheet pile wall that lengthens the seepage path is limited by coarse alluvial foundation conditions not allowing cut-off to foundation rock. | Foundation is coarse alluvium and less suseptible to piping. Ongoing monitoring program measures leakage. Fill was placed upstream to reduce leakage. Normal head is also the maximum head. |
| TIMBER CRIB | UNUSUAL | Overtopping | Rock filled timber crib dam, faced with upstream planking. A central flashboard spillway with a reinforced concrete chute. | Overtopping of the timber crib section up to 6 feet could occur during the PMF and overtopping could occur at lower flows if the flashboards are not tripped. Overtopping of non-spillway sections results in uncontrolled release and damage. | A plan for tripping the flashboards early in the flood event to minimize headwater levels. | Flashboard operation is manual and ability to trip during high flows is uncertain. | Timber cribs section has a FS+1.5 during overtopping flows. |

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| TIMBER CRIB | SEISMIC | Rockfall | Rock filled timber crib with upstream sheet pile cut off wall and a gated concrete reinforced overflow spillway. Concrete slabs are post tensioned to foundation materials. Concrete gravity intake and abutment sections are at one abutment. | Earthquake ground motions trigger a large rock fall from the rock mass above one abutment. The rock mass fails a spillway gate panel creating a partial breach and uncontrolled release of the reservoir. | Add more detailed monitoring of the abutment rock face (photographic) and inspect after earthquakes. Investigate and assess the condition at the top of the rock wall. Consider a rock net. | Abutment rock mass has unfavorable joint orientation for stability and has been a concern since construction and potential rock mass is large. Rock joints have been mortared in the past and rock anchors have been installe but the condition of the mortar and anchors is unknown. Past earthquakes have lossened the rock mass. | Rock mass has survived large earthquake events without major rockfalls. Some recent anchoring and scaling has been performed. Rock joints at the top of the slope have been mortared to prevent water infiltration. |
| TIMBER CRIB | SEISMIC | Sliding | Rock filled timber crib with upstream sheet pile cut off wall and a gated concrete reinforced overflow spillway. Concrete slabs are post tensioned to foundation materials. Concrete gravity intake and abutment sections are at one abutment. | A portion of the spillway section deforms under earthquake ground motions. Deformation of the crest causes the gate panels to jam or trip. An uncontrolled release results. | Develop a formal SOP for post seismic inspection procedures. | Stability relies on post tensioned anchors. Deformation of the sheet pile wall could result in it being less effective and water destabilizing timber cribs due to buoyancy. Spillway gate operation could be lost. | Anchors and drains are present in each spillway face making failure of the entire structure unlikely. If load on tendons is lost their presence still holds the structure together. Timber crib is very pervious and can accept flow up to the capacity of the drains . |

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| TIMBER CRIB | SEISMIC | Surge Chamber | Rock filled timber crib with upstream sheet pile cut off wall and a gated concrete reinforced overflow spillway. Concrete slabs are post tensioned to foundation materials. Concrete gravity intake and abutment sections are at one abutment. | Surge chamber collapses as a result of earthquake ground motions. Release of water flow around powerhouse, damaging the structure, and returns to the river. | Conduct and information search about the structure to better quantify this failure mode. Available information is not adequate to analyze the structure. | Level of seismicity is high. Significant damage to the powerhouse nad rick to operators could result. | Surge chamber is fairly robust with mass concrete walls. Surge chamber is concrete lined with an imbedded steel frame, reducing uplift and enhancing stability. Structure is benched into bedrock and cores taken indicate good concrete and rock contact conditions. |
| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
| CONCRETE GRAVITY | USUAL | Drainage | Concrete gravity dam (RCC with concrete facing) with penstock leading to powerhouse. Part of a pumped storage plant with no external drainage to reservoir. | Differential shrinkage between cast-in-place access tunnel and RCC opens a privileged path of seepage. | Add a cutoff collar or grout curtain. Design for construction equipment crossing tunnel and lateral pressure. | No cutoff collar or grout curtain. | There will be sufficient time to correct the problem. |
| CONCRETE GRAVITY | USUAL | Sliding | Concrete gravity dam (RCC with concrete facing) with penstock leading to powerhouse. Part of a pumped storage plant with no external drainage to reservoir. | Leakage though upstream face causes uplift of RCC joints, resulting in sliding and breach. | Address locations of drains and check uplift conditions with piezometers and flow with flumes in the gallery. | Potential for poor construction. Potential for clogging of drains. Downstream facing prevents drainage. | Dam is designed to take full uplift pressures and still meet safety factors. More drains can be added. |

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| CONCRETE GRAVITY | UNUSUAL | Erosion | Earthfill dam including concrete gravity, 5-bay gated spillway with a concrete chute and a stilling basin with baffle blocks, a vertical end sill, and large riprap on the downstream channel. | Over time, erosion of material downstream of stilling basin lowers tailwater level. If tailwater level is too low during spillway discharge, spillway hydraulic jump sweeps out of concrete stilling basin, leading to erosion of soil deposits downstream of stilling basin and potential spillway failure. | Close monitoring of tailwater elevation and re-evaluation of potential failure mode when very large discharges occur in the future. | Uncertainty of performance during large spillway discharges. Largest discharge at the site is less than 1/3 of maximum discharge and was approaching the "Sediment Depoits Eroded" boundary. | Design is based on 10% factor of safety for the computed tailwater level. Erosion and tailwater levels are continually monitored. Condition of stilling basin baffle blocks are monitored by diver inspections after each significant flood. |

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| CONCRETE GRAVITY | UNUSUAL | Erosion | Earthfill and concrete gravity dam including concrete gravity, 5-bay vertical lift-gated spillway. Spillway includes a concrete chute and a stilling basin with a denated end sill. | Spillway is constructed on an erodible foundation and relies on an underdrain system to prevent uplift loads below the stilling basin chute and basin slab. Poor performance of the underdrain system leads to pressures below the slab exceeding the total downward force. This dislodges the chute slabs and leads to high-pressure water beneath the slab, ultimately failing the structure. | Monitor chute and basin slabs. Repair sinkholes adjacent to stilling basin well. | Underdrain system relies on the drainage pipe network below the slab. The drainage pipe is coated steel and likely in poor condition (evidence of failed sections). The drainage system is very difficult to inspect. The chute and basin slabs are independent, thus failure (distruption/blowout and erosion intiation) of a single slab could lead to an overall failure of the structure. There is currently a lack of a credible monitoring system to provide early warning of an impending failure. Sinkholes have developed adjacent to the stilling basin well, indicating that there is a break in the impervious zone, which isolates the tailwater level from the underdrain system. | A significant flood would be required to fail underdrain system. Pump system that keeps drainage system operational has been demonstrated to work effectively and has multiple redundancies. Drainage system has multiple paths to the pump system. Granular drainage blanket below the slab allows pressurized water to flow around distressed pipe sections to locations of pressure relief. If structure shows signs of distress, possible to temporarily shut down spillway and divert flow into the bypass channels. |

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| CONCRETE GRAVITY | UNUSUAL | Overtopping | Concrete gravity dam with an integral powerhouse section and gated spillway section. | The plant shuts downs from any of several different causes and cannot be restarted. The reservoir begins to rise as plant discharge is no longer occuring. Gates fail to open as station service is lost and backup batteries are drained prior to opening. Bad weather, darkness, poor access, small staff, and lack of experience with equipment delays results in overtopping. | Always maintain two remote controlled heated and reliable gates in reserve capacity. Review restart procedures and redundancies to ensure restart is as reliable as possible. Review documentation and ensure procedures for maintaining the most reliable gates are well documented. | Based on past experience this loading condition occurred approxmiately every 3 years. A surge can follow a station shutdown and can cause an immediate, transient forbay rise. Time available to re-establish plant discharge before overtopping occurs is small. Shut downs are usually associated with winter operation when opening gates is more problematic. | If all seven generating units are shut down during a station outage, the two house units are typically running. A number of gates can be operated remotely, shortening response time. Standby diesel and gasoline generators provide levels of redundancy. A station alarm is set and has gone off frequency in the past. |
| CONCRETE GRAVITY | UNUSUAL | Loss of Gate | Concrete gravity dam with 119 gates on gated spillway and an intergral power house and a lock for barge traffic. The dam is a operates as a run of river facility | Ice loading or barge impact causes multiple gates to "pop" out of their guides. | Research past gate failures and research current gate design. | Ice flows are likely, the oldest gates are in poor structural condition. There is a potential for a runaway barge. | Minor downstream impact. Gate replacement program. History of gate performance. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| EARTHFILL | USUAL | Erosion | Earthen and rockfill embankment with a gated concrete spillway, concrete powerhouse, and reservoir containment dykes. | A severe windstorm produces waves that run-up and overtop the main dam or one of the dykes. Erosion of the crest of the dam or dykes progress to the point that the top of the reservoir is reached and a sustained erosional flow begins and the dam or one of the dykes is breached. | Raise the main dam to force wave overtopping (and any possible dam breach) to one of the clay core dyke sections. | Wind speeds for 1:20 and 1:1000 occurances from the record range up to 90 km/hr for the 1:1000 year wind. Wind setup and run-up for extreme winds are in the same order of magnitude as the freeboard on the main dam and centre dyke - as they currently exist. The sand dykes are highly erodible, and the main dam and centre dyke are low in relation to other dykes with respect to wind freeboard. | Wind is a sporadic loading, only 4% to 5% of the waves are at or above the calculated wave height for a given wind condition. The wind set-up can be compensated for by increasing the spillway discharge and drawing down the forebay. Therefore, only wave + run-up must be accounted for. Frequent inspection during periods of high winds along with advance planning for addressing any wave caused erosion can mitigate concerns. |

| Dam Type | Load | PFM Key Word | Dam Description | PFM Description | Risk Reduction Measures | Adverse Conditions (PFM More Probable) | Positive Conditions (PFM Less Probable) |
|---|---|---|---|---|---|---|---|
| EARTHFILL | USUAL | Erosion | Earthen embankment that serves as ancillary control structure for hydroelectric generating station. | Slope failure due to wave erosion that undermines the crest during the IDF, resulting in breach and uncontrolled release of reservoir. | Five year erosion monitoring inspections and weekly visual monitoring during routine operator inspections. | Slight overtopping expected during a 2-year wind with IDF. Upstream slope has minimal riprap. Some erosion has been observed in the past. Spillway rating may be overoptimistic due to the increased roughness and reduced depth of the approach resulting from the rockfill that is buttressing the abutments. IDF assumes the lake is at FSL at the beginning of the flood hydrograph. The lake is often operated above this level. | Freeboard is adequate for FSL with 1000-year wind. Annual geotechnical inspections are conducted. |

# APPENDIX E. SAMPLE FORMS

## Example Schedule for Dam Safety Surveillance and Monitoring

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

| Monitoring Method | Frequency/Schedule | Comments |
|---|---|---|
| Visual Operations Checks | Daily | Note inspection in operator's log. Written report not required unless unusual condition observed. |
| Operations Inspection | Monthly | During winter months, the scope of inspections can be scaled back to what reasonably can be performed based on site conditions. Complete visual inspection checklist. 1/ |
| Engineering Inspection | Annually | Complete visual inspection checklist, evaluate monitoring data, identify corrective maintenance, and prepare written report. |
| Seepage Monitoring Weirs | Weekly | During winter months, obtain readings when this can be reasonably done based on site conditions. 2/ 3/ 4/ 5/ |
| Monitoring Wells | Weekly | During winter months, obtain readings when this can be reasonably done based on site conditions. 2/ 3/ 4/ |
| Embankment and Spillway Crest Survey | On Standby | Immediately following completion of dam rehabilitation. Thereafter, on-standby. Survey only if a specific request is received. |

Reference Drawing(s): ___________________________________________(for plan view of instrumentation locations.)

**Notes and Remarks:**

1/ A copy of each completed "Visual Inspection Checklist" should be transmitted to the Owner's Engineer for review and filing in the dam safety surveillance and monitoring file.
2/ To the extent possible, obtain readings and perform inspections at times when no precipitation or significant snowmelt has occurred in the proceeding 72 hours. If this is not possible, precipitation and/or snowmelt within the last 72 hours should be reported in terms of amount and time.
3/ In the event that the reservoir elevation rises to about Elevation __________, visual inspections and seepage weirs and monitoring well readings are to be performed every day.
4/ Obtain instrument readings and perform a visual operations inspection as soon as possible following significant seismic shaking at the dam site (peak horizontal acceleration in excess of 0.05g) and following a significant flood event (reservoir elevation above Elevation ________)
5/ Whenever flow rates are being read, check for indications of sediments being carried by the flows (discolored water, sediment deposits in front of weirs, etc.) and report immediately if noted.

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## Example Engineer's Dam Safety Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

**Schedule**: Perform **annually** under normal operating conditions for high hazard potential dams. Perform periodically as per proscribed dam safety regulations for intermediate or low hazard potential dams. Perform if unusual conditions are seen during or after a high reservoir event or earthquake.

Inspector: ______________________________ Date: ________________________________

Reservoir Elevation: _____________________ Time: ________________________________

Weather: _______________________________ Temperature: ___________________________

List all persons accompanying Inspector. (Dam Operator and General Maintenance personnel participation is strongly recommended.)

______________________________ ______________________________
Name Title

______________________________ ______________________________
Name Title

______________________________ ______________________________
Name Title

______________________________ ______________________________
Name Title

Additional Information (as appropriate):

Type of Construction: _______________________ Purpose: _______________________________
Year Constructed: __________________________ Drainage Area: __________________________
Federal Dam ID# ___________________________ State/Province Dam ID# ___________________
Location Coordinates: Latitude _______________ Longitude _______________________________
River or Stream: ___________________________ Watershed Basin: _________________________
Dam Length: ______________________________ Dam Width: _____________________________
Spillway Width: ____________________________ Maximum Discharge: ______________________
Normal Storage: ____________________________ Reservoir Surface Area: ___________________

Hazard Potential Category (circle one): High Intermediate Low Null (no hazard assigned)

## Example Visual Operations Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

**Schedule:** Perform **monthly** under normal operating conditions. Perform **immediately** if the reservoir rises above Elevation _______ (2 feet below embankment crest) or after an earthquake that is felt at or near the site. If unusual conditions are seen during or after the high reservoir event or earthquake, perform **daily** until conditions stabilize.

Inspector: ________________________________ Date: _________________________

Reservoir Elevation: ________________________ Time: _________________________

Weather: ________________________________ Temperature: _______________ °F

*A "YES" response should only be given to question(s) below where observed conditions are different from previously observed conditions. Any observed conditions that have previously been reported and are currently unchanged should receive a "NO" response. For any question below answered "YES", please provide additional information describing the situation as completely as possible under item 7 – "Additional Information." Also, take photographs of the situation to be included with this report. A "YES" response indicates unexpected behavior that needs to be investigated.*

1. Crest of Embankment Dam
   a. Any cracks, either transverse or longitudinal? No Yes
   b. Any scarps, sinkholes, or areas of unusual settlement? No Yes
2. Downstream Slope of Embankment Dam
   a. Any new seepage areas or wet areas? No Yes
   b. Any changes in conditions at existing seepage areas or wet areas? No Yes
   c. Any materials being transported by seepage flows at existing or new seepage areas such as discolored seepage water or sediment deposits? No Yes
   d. Any scarps, sinkholes, sloughs, slides or areas of unusual settlement? No Yes
3. Upstream Toe of Embankment Dam
   a. Any significant erosion due to wave action? No Yes
   b. Any scraps, sinkholes, or areas of unusual settlement? No Yes
   c. Any whirlpools in the reservoir? No Yes
4. Downstream Toe Area, Abutments, and Other Areas Downstream
   *Extend the inspection to all areas within 50 feet of the toe of the dam and all the way up both abutment groins and to within 50 feet of either side of the groins. Inspection for seepage and sediment in the river channel should be performed during low flows and be extended along the river channel for at least 300 feet.*
   a. Any new seepage areas or wet areas? No Yes

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## Example Visual Operations Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

| | | |
|---|---|---|
| b. Any changes in conditions at existing seepage areas or wet areas? | No | Yes |
| c. Any cracks, sinkholes, sloughs, or areas of unusual settlement? | No | Yes |
| d. Any new seepage areas along the banks of the river channel? | No | Yes |
| e. Any new sediment deposits along the banks of the river channel? | No | Yes |

5. Low Level Outlet Works

| | | |
|---|---|---|
| a. Any new or enlarged cracks or spalls in the concrete? | No | Yes |
| b. Any unusual deformations or displacements? | No | Yes |
| c. Any unusual flow patterns or conditions during releases? | No | Yes |
| d. Any new seepage into the gatehouse chamber or impact stilling basin? | No | Yes |

6. Spillway

| | | |
|---|---|---|
| a. Any new or enlarged cracks or spalls in the concrete? | No | Yes |
| b. Any unusual deformations or displacements? | No | Yes |
| c. Any unusual flow patterns or conditions during releases? | No | Yes |

7. Additional Information

*All descriptions should include specific location information and all other seemingly relevant information. Seepage area descriptions should include: estimated seepage amount and water clarity description, i.e. clear/cloudy/muddy, etc. Crack descriptions should include orientation and dimensions. Descriptions of changes at cracks should include the estimated amount of movement, and movement direction. Deteriorated or spalled concrete descriptions should include degree of deterioration and approximate dimensions of the affected area. Provide sketches and/or photos as appropriate.*

**Example Engineer's Dam Safety Inspection Checklist**
Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

**EXISTING DOCUMENTS AND INSPECTION PROGRAM**

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| EMERGENCY ACTION PLAN | | | |
| | | | |
| 1. Current plan posted? | | | |
| 2. Understood by operator? | | | |
| 3. Warning systems? | | | |
| 4. Certification of last test? | | | |
| 5. Adequate? | | | |
| 6. Habitable structures? | | | |
| 7. Recreation areas? | | | |
| 8. Changed hazard potential? | | | |
| 9. New development? | | | |
| 10. Other? | | | |
| | | | |
| INSPECTION & MAINTENANCE PLAN | | | |
| | | | |
| 1. Current plan posted? | | | |
| 2. Understood by operator? | | | |
| 3. Adequate | | | |
| 4. Other? | | | |
| | | | |
| OWNER'S INSPECTION PROGRAM | | | |
| | | | |
| 1. Does one exist? | | | |
| 2. Adequate surveillance? | | | |
| a. Project structures? | | | |
| c. Conduits through dams? | | | |
| d. Drainage systems? | | | |
| e. Other? | | | |
| 3. Frequency? | | | |
| 4. Documentation? | | | |
| 5. Performed by whom? | | | |
| | | | |
| DATE OF THE LAST SAFETY INSPECTION | | | |

Other comments:

T092700-0210 Inspection & Monitoring Plan Page 2 of 7 Date Inspected: ___________

**Example Engineer's Dam Safety Inspection Checklist**

Modify to Suit Site Specific Conditions at Any Dam

Town/Village, State/Province

**OBSERVATION CHECKLIST NO.1 – RESERVOIR**

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| RESERVOIR | | | |
| | | | |
| 1. Signs of shoreline instability? | | | |
| 2. Sedimentation? | | | |
| 3. Debris? | | | |
| 4. Ice related problems? | | | |
| 5. Operating constraints? | | | |
| 6. Environmental concerns? | | | |
| 7. Rim stability? | | | |
| 8. Other? | | | |
| | | | |

Other Comments:

**OBSERVATION CHECKLIST NO.2 – CONCRETE OR MASONRY DAM**

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| CONCRETE OR MASONRY DAM | | | |
| | | | |
| 1. Crest | | | |
| a. Alignment? | | | |
| b. Displacement? | | | |
| c. Spalling | | | |
| d. Condition of joints? | | | |
| 2. Upstream face (vertical) | | | |
| a. Alignment? | | | |
| b. Condition of joints? | | | |
| c. Missing stones? | | | |
| c. Vegetation? | | | |
| 2. Downstream face (vertical) | | | |
| a. Alignment? | | | |
| b. Condition of joints? | | | |
| c. Vegetation? | | | |

Other comments:

T092700-0210 Inspection & Monitoring Plan Page 3 of 7 Date Inspected: ____________

**Example Engineer's Dam Safety Inspection Checklist**

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

**OBSERVATION CHECKLIST NO.2 – CONCRETE OR MASONRY DAM (CONTINUED)**

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| 3. Seepage | | | |
| a. Where? | | | |
| b. Quantity? | | | |
| 5. Abutment Contacts | | | |
| a. Abutment instability? | | | |
| b. Erosion? | | | |
| c. Visible displacement? | | | |
| d. Seepage from contact? | | | |
| 7. Instrumentation | | | |
| a. Are there.... | | | |
| (1) Piezometers? | | | |
| (2) Weirs? | | | |
| (3) Settlement monuments? | | | |
| (4) Observation wells? | | | |
| (5) Other? | | | |
| b. Are readings.... | | | |
| (1) Available? | | | |
| (2) Plotted? | | | |
| (3) Taken periodically? | | | |
| (4) Submitted periodically? | | | |
| c. Evaluated? | | | |
| 8. Other? | | | |
| | | | |

Other comments:

**OBSERVATION CHECKLIST NO.3 - -SERVICE SPILLWAY**

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| SERVICE SPILLWAY | | | |
| | | | |
| 1. Approach Channel | | | |
| a. Trash boom? | | | |
| b. Debris? | | | |
| c. Vegetation and trees? | | | |
| d. Sedimentation? | | | |
| 2. Crest | | | |
| a. Settlement? | | | |
| b. Displacements? | | | |
| c. Cracking? | | | |
| d. Deterioration? | | | |

Other comments:

T092700-0210 Inspection & Monitoring Plan Page 4 of 7 Date Inspected: ___________

## Example Engineer's Dam Safety Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

### OBSERVATION CHECKLIST NO.3 - SERVICE SPILLWAY (CONTINUED)

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| e. Seepage? | | | |
| f. Vegetation and debris? | | | |
| 3. Energy Dissipators | | | |
| a. Deterioration? | | | |
| b. Erosion? | | | |
| 4. Receiving Stream | | | |
| a. Undercutting? | | | |
| b. Erosion? | | | |
| c. Obstruction? | | | |
| d. Concrete/Masonry sidewalls damaged? | | | |
| 5. Other? | | | |
| | | | |

Other comments:

### OBSERVATION CHECKLIST NO.4 - LOW LEVEL OUTLETS

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| LOW LEVEL OUTLETS | | | |
| | | | |
| 1. Gates | | | |
| a. Mechanical equipment operable? | | | |
| b. Are valves remotely controlled? | | | |
| c. Are valves maintained? | | | |
| 2. Metal Conduits | | | |
| a. Intake structures damaged? | | | |
| b. Hydraulic Capability? | | | |
| c. Is metal corroded? | | | |
| d. Is conduit cracked? | | | |
| e. Are joints displaced, leaking? | | | |
| 3. Metal Appurtenances | | | |
| a. Corrosion? | | | |
| b. Breakage? | | | |
| c. Secure Anchorages | | | |

Other comments:

T092700-0210 Inspection & Monitoring Plan Page 5 of 7 Date Inspected: ____________

# Example Engineer's Dam Safety Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

## OBSERVATION CHECKLIST NO.4 - LOW LEVEL OUTLETS (CONTINUED)

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| 4. Discharge Channel | | | |
| 5. Energy Dissipators | | | |
| a. Deterioration? | | | |
| b. Erosion? | | | |
| 6. Other? | | | |
| | | | |

Other comments:

## OBSERVATION CHECKLIST NO.5 – EARTH EMBANKMENTS AND BERMS

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| EARTH EMBANKMENTS AND BERMS | | | |
| | | | |
| 1. Alignment | | | |
| a. Alignment? | | | |
| b. Displacement? | | | |
| c. Settlement? | | | |
| 2. Deterioration | | | |
| a. Slope vegetation condition? | | | |
| b. Erosion? | | | |
| c. Sloughs or Slumps? | | | |
| d. Animal burrow? | | | |
| e. Riprap? | | | |
| 3. Seepage | | | |
| a. Where? | | | |
| b. Quantity? | | | |
| 4. Abutment Contacts | | | |
| a. Abutment instability? | | | |
| b. Erosion? | | | |
| d. Visible displacement? | | | |
| e. Seepage from contact? | | | |
| 5. Instrumentation | | | |
| a. Are there | | | |
| (1) Piezometers? | | | |
| (2) Weirs? | | | |
| (3) Settlement monuments? | | | |
| (4) Observation wells? | | | |
| b. Are readings | | | |
| (1) Available? | | | |

T092700-0210 Inspection & Monitoring Plan    Page 6 of 7    Date Inspected: ____________

## Example Engineer's Dam Safety Inspection Checklist

Modify to Suit Site Specific Conditions at Any Dam
Town/Village, State/Province

### OBSERVATION CHECKLIST NO.5 – EARTH EMBANKMENTS AND BERMS (CONTINUED)

| ITEMS | YES | NO | REMARKS |
|---|---|---|---|
| | | | |
| (2) Plotted? | | | |
| (3) Taken and submitted periodically? | | | |
| c. Evaluated? | | | |
| 6. Other? | | | |
| | | | |

Other comments:

Geocomp CORPORATION

## Installation Log

Client: ____________________
Project: ____________________
Location: ____________________

Instrument Type: ____________________
Manufacturer: ____________________

Unique Assigned ID #: ____________

Casing Length (ft): ____________

| Magnet | Initial Readings Depth(f) |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |
| 7 | |
| 8 | |

Planned Installation:
Casing Bottom (depth GL): ________
BH Bottom (depth GL): ________
Grout (cf): ________
Casing O.D. (in): ________
Casing Length (ft): ________

Actual Installation:
Casing Bottom (depth GL): ________
BH Bottom (depth GL): ________
Grout (cf): ________
Casing O.D. (in): ________
Casing Length (ft): ________

Top of Casing Elevation (ft): ________
(per Project Datum)

Sketch: Elevation

Depth (ft)
0
10
20
30
40
>I< Magnet
50
>I< Magnet
60
>I< Magnet
70
>I< Magnet
80
>I< Magnet
90
>I< Magnet
100
>I< Magnet
110
>I< Magnet
120

Not to Scale

Plan

N

Not to Scale

Comments:

Geocomp CORPORATION

## Inclinometer Installation Log

Client: ____________ Unique Assigned ID #: ____________

Project: ____________

Location: ____________

Instrument Type: ____________

Manufacturer: ____________

Model No.: ____________

Serial No.: ____________

Installation Start Date: ____________

Installation Finish Date: ____________

Weather: ____________

Driller: ____________

Installer: ____________

Supervisor: ____________

Initial Reading: ____________

Planned Installation:

Casing Bottom (depth GL): ____________

BH Bottom (depth GL): ____________

Grout (cf): ____________

Casing O.D. (in): ____________

Casing Length (ft): ____________

Actual Installation:

Casing Bottom (depth GL): ____________

BH Bottom (depth GL): ____________

Grout (cf): ____________

Casing O.D. (in): ____________

Casing Length (ft): ____________

Top of Casing Elevation (ft): ____________
(per Project Datum)

| Sketch Elevation | Plan |
|---|---|
| Not to Scale | Not to Scale |

**Comments:** (Attach formal initial readings)

...Consulting\Active Projects\2003\installation forms\Install_Log_Form

Geocomp
CORPORATION

## Installation Log

Client: ____________
Project: ____________
Location: ____________

Unique Assigned ID #: ____________

Casing Length (ft): ____________

Instrument Type: ____________
Manufacturer: ____________
Model No.:

Top of Casing Elevation (ft): ____________
(per Project Datum)

Installation Start Date: ____________
Installation Finish Date: ____________
Weather: Sunny, Hot

Installers: AH

| Sensor | Serial No. | Initial Readings X | Y | Temp |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |

Sketch: Elevation

0 >|< PIVOT
SENSOR 1
10 >|< PIVOT
SENSOR 2
20 >|< PIVOT
SENSOR 3
30 >|< PIVOT
SENSOR 4
40 >|< PIVOT
SENSOR 5
50 >|< PIVOT
SENSOR 6
60 >|< PIVOT
SENSOR 7
70 >|< PIVOT
SENSOR 8
80 >|< PIVOT
SENSOR 9
90 >|< PIVOT
SENSOR 10
100 >|< PIVOT
SENSOR 11
110 >|< PIVOT
SENSOR 12
120 >|< PIVOT
SENSOR 13
130 >|< FIXED BRACKET

Not to Scale

N

Plan

Not to Scale

**Comments:**

Geocomp CORPORATION

## Observation Well Installation Log

Client: ____________________ Unique Assigned ID #: ________
Project: ____________________
Location: ____________________

Instrument Type: ______________
Manufacturer: ______________
Model No.: ______________
Serial No.: ______________

Installation Start Date: ______________
Installation Finish Date: ______________
Weather: ______________

Driller: ______________
Installer: ______________
Supervisor: ______________

Initial Reading: ______________

Planned Installation:
BH Bottom (ft): ________
Casing Bottom (ft): ________
Grout (cf): ________
Casing O.D. (in): ________
Casing Length (ft): ________
filter/screen depth (ft) ________

Actual Installation:
BH Bottom (ft): ________
Casing Bottom (ft): ________
Grout (cf): ________
Casing O.D. (in): ________
Casing Length (ft): ________
filter/screen depth (ft) ________

Top of Casing Elevation (ft): ________
(per Project Datum)

| Sketch Elevation | Plan |
|---|---|
| Not to Scale | Not to Scale |

Comments: (Attach formal initial readings)

Geocomp CORPORATION

## Vibrating Wire Piezometer Installation Log

Client: ____________
Project: ____________
Location: ____________

Unique Assigned ID #: ________

Ground Elevation Elevation (ft): ________
(per Project Datum)

Instrument Type: ____________
Manufacturer: ____________
Model No.: ____________

Installation Start Date: ____________
Installation Finish Date: ____________
Weather: ____________

Installer: ____________
Supervisor: ____________

**Planned Installation:** BH Bottom (ft): ________

| Sensor | depth ft | Sand bottom (ft) | Sand top (ft) | Bentonite top (ft) |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |

**Actual Installation:** BH Bottom (ft): ________

| Sensor | depth ft | Sand bottom (ft) | Sand top (ft) | Bentonite top (ft) |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |

| Sensor | s/n | Reading (digits) zero | Reading (digits) initial |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |

| Sketch Elevation | Plan |
|---|---|
| Not to Scale | Not to Scale |

**Comments:**

________________________________________
________________________________________
________________________________________
________________________________________
________________________________________
________________________________________
________________________________________