CHAPTER IX

INSTRUMENTATION AND MONITORING

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Instrumentation and Monitoring

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9-1.1 General

The majority of FERC licensed dams have been evaluated and, where necessary, have been or are being modified to meet current criteria. The next logical step is to concentrate on dam safety monitoring programs, which consist of collecting data from visual observations and instrumentation and evaluating the data with respect to dam performance and safety. *Visual observation* consists of the thorough inspection of conditions at the dam and appurtenant structures, noting any abnormal or unusual conditions that could jeopardize the safety of the dam. *Instrumentation* consists of the various electrical and mechanical instruments or systems used to measure pressure, flow, movement, stress, strain, and temperature. *Monitoring* is the collection, reduction, presentation, and evaluation of the instrumentation data. Instrumentation and monitoring are tools that must be used with a vigilant inspection program to continually evaluate the safety of dams.

9-1.2 Purpose and Scope

The purpose of this chapter is to provide staff engineers with recommended guidelines to use in reviewing and evaluating the adequacy of instrumentation and monitoring programs in license applications, supporting design reports, FERC Part-12 consultants reports, or programs recommended by the regional office inspector following operation or construction inspections. There are no simple rules for determining the appropriate level of instrumentation and monitoring because it depends on the size and hazard potential classification of the dam, the complexity of the dam and foundation, known problems and concerns, and the degree of conservatism in the design criteria. Therefore, evaluation of instrumentation and monitoring programs requires staff to apply engineering judgement and common sense.

A major change in the extent of existing instrumentation programs at most projects is not anticipated, though some dams will require additional instrumentation. Many monitoring programs may need to be improved. Emphasis should be placed on timely collection and evaluation of the instrumentation data. This chapter discusses the philosophy of instrumentation and monitoring, commonly used instruments, minimum instrumentation guidelines, instrumentation system design, monitoring schedule guidelines, data processing and evaluation, automated data acquisition, and examples of acceptable instrumentation and data presentation.

9-2 Philosophy of Instrumentation and Monitoring

The purpose of instrumentation and monitoring is to maintain and improve dam safety by providing information to 1) evaluate whether a dam is performing as expected and 2) warn of changes that could endanger the safety of a dam.

The causes of dam failures and incidents have been catalogued (ASCE 1975 and 1988, Jansen 1980, National Research Council 1983, ICOLD 1992). The common causes of concrete dam failures and incidents are:

- 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 leakage and piping in pervious strata, soluble lenses, and rock discontinuities; and
- sliding along weak discontinuities in foundations.

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, or rainfall;
- sliding along clay seams in foundations;
- cracking due to differential settlements; and
- liquefaction.

Instrumentation and monitoring, combined with vigilant visual observation, can provide early warning of many conditions that could 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 piping; settlement of an embankment crest or bulging of embankment slopes could indicate sliding or deformation; inelastic movement of concrete structures could indicate sliding or alkali-aggregate reaction. Conversely, lack of normally expected natural phenomena may also indicate potential problems. For example, lack of seepage in a drainage system could indicate that seepage is occurring at a location where it was not expected or contemplated by the designer.

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 or it should be abandoned. Instrumentation for long-term monitoring should be rugged and easy to maintain and should be capable of being verified or calibrated. Instrumentation typically provides data to:

- characterize site conditions before construction;
- verify design and analysis assumptions;
- evaluate behavior during construction, first filling, and operation of the structure;
- evaluate performance of specific design features;
- observe performance of known geological and structural anomalies; and
- evaluate performance with respect to potential site-specific failure modes.

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. Data must be conscientiously collected, meticulously reduced, tabulated, and plotted, and must be judiciously evaluated with respect to the safety of the dam in a timely manner. A poorly planned program will produce unnecessary data that the dam owner will waste time and money collecting and interpreting, often resulting in disillusionment and abandonment of the program.

9-2.1 Visual Observation

Visual observation of all structures should be made in conjunction with instrumentation monitoring to adequately assess the safety of a dam. Visual observation can readily 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 these features.

Most visual observation provides qualitative rather than quantitative information, while instruments provide detailed quantitative information. Visual observation and instrumentation data are natural complements and when used together they provide the primary means for engineers to evaluate the safety of a dam.

9-2.2 Purpose of Minimum Instrumentation

Though only a small percentage of dams develop problems, it is impossible to predict those that will develop problems because of the highly indeterminate nature of the structures and the infinite number of possible variations in conditions that could affect the safety of a dam or appurtenant structures. Therefore, it is prudent that any dam that may affect the public safety has basic instrumentation to monitor vital signs.

The minimum recommended instrumentation is limited to that which clearly provides useful information for evaluating dam safety and is also readily installed and monitored. In these guidelines, minimum instrumentation varies from visual observation of low-hazard potential dams, to instruments for the measurement of pore pressures, uplift pressures, surface movement, internal movement, and foundation deformation on proposed, large, high-hazard potential structures. Minimum instrumentation should be located where it will provide data that are representative of the entire structure.

9-3 Types of Instrumentation

Common types of instruments are summarized in this section. For each type of measurement, basic engineering concepts and specific types of instruments are discussed. Emphasis is placed on types of measurements recommended by these guidelines. For other types of instrumentation, only a general discussion and a list of references is provided. More detailed information for all types of instrumentation is available in the literature (Dunnicliff 1981 and 1988, MESA 1973, Sherard 1981, USACE 1971, 1976, and 1987c, and USBR 1976, 1977, 1987a, 1987b, and 1990).

9-3.1 Water Level and Pressure

Water level is commonly measured with staff gages, float-type water level gages, and ultrasonic sensors. Water pressure is commonly measured with bubblers, observation wells, and several types of piezometers, that are discussed below. Other types of water level and water pressure measuring devices may be appropriate in special circumstances.

The USACE (1971 and 1987c) and the USBR (1987a, 1987b, and 1990) provide a more detailed discussion of water level measuring devices. Advantages and limitations of water level and water pressure instruments are listed in Table 9-3.1.1.

9-3.1.1 Engineering Concepts

Water pressure is a general term that includes pressure within a reservoir or other body of water, pore pressure, and uplift pressure. Water pressure within soils and within concrete is commonly referred to as pore pressure. Water pressure acting upward on the base of concrete dams is commonly known as uplift pressure.

Water level and water pressure are directly related by the depth below the water surface or phreatic surface. Thus, measurements or water pressure can be readily converted to water level and vice-versa.

Water pressure usually varies from headwater level on the upstream side of a dam to tailwater level, ground water level, or atmospheric pressure on the downstream side of a dam. The headwater, tailwater, and varying pressure across the dam produce forces on a dam that must be properly accounted for in stability analyses.

TABLE 9-3.1.1
ADVANTAGES AND LIMITATIONS OF COMMON WATER LEVEL AND PRESSURE INSTRUMENTS

TYPE	ADVANTAGES	LIMITATIONS
Staff Gage	Simple device, inexpensive, reliable.	Cannot be automated.
Float-Type Water Level Gage	Simple device, inexpensive, reliable. Easily automated.	Requires readout device. Sensor must be in water. Must be protected from ice.
Ultrasonic Water Level Sensor	Simple device, inexpensive, reliable. Sensor does not touch water. Easily automated.	Requires readout device. Must be corrected for air temperature. Debris, foam, and ice can cause false readings.
Bubbler	Simple device, inexpensive, reliable. Easily automated.	Requires readout device. Sensor must be submerged in water.
Observation Well	Simple device, inexpensive. Easily automated.	Applicable only in uniform materials, not reliable for stratified materials. Long lag time in impervious soils.
Open Standpipe Piezometer	Simple device, inexpensive, reliable. Simple to monitor and maintain. Standard against which all other piezometers are measured. Can be subjected to rising or falling head tests to confirm function. Easily automated.	Long lag time in impervious soils. Potential freezing problems if water near surface. Porous tips can clog due to repeated inflow and outflow. Not appropriate for artesian conditions where phreatic surface extends significantly above top of pipe. Interferes with material placement and compaction during construction. Can be damaged by consolidation of soil around standpipe.
Closed Standpipe Piezometer	Same as for open standpipe piezometers.	Same as open standpipe piezometer but appropriate for artesian conditions.
Twin-tube Hydraulic Piezometer	Simple device, moderately expensive, reliable, long experience record. Short lag time. Minimal interference with construction operations.	Cannot be installed in a borehole, therefore, generally not appropriate for retrofitting. Readout location must be protected from freezing. Moderately complex monitoring and maintenance. Periodic de-airing required. Elevation of tubing and of readout must be less than 10 to 15 feet above piezometric elevation. Can be automated, but moderately complex.
Pneumatic Piezometer	Moderately simple transducer, moderately expensive, reliable, fairly long experience record. Very short lag time. Elevation of readout independent of elevation of tips and piezometric levels. No freezing problems.	Moderately complex monitoring and maintenance. Dry air and readout device required. Can be automated, but not over long distances. Sensitive to barometric pressure. Automation is complex. Moderately expensive readout.
Vibrating Wire Piezometer	Moderately complex transducer. Simple to monitor. Very short lag time. Elevation of readout independent of elevation of tips and piezometric levels. No freezing problems. Frequency output signal permits transmission over long distances. Easily automated.	Lightning protection required. Expensive transducer and readout. Sensitive to temperature and barometric pressure changes. Risk of zero drift, but some models available with in-situ calibration check.
Bonded Resistance Strain Gage (Electronic) Piezometer	Moderately complex device, expensive. Simple to monitor. Very short lag time. Elevation of readout independent of elevation of tips and piezometric levels. No freezing problems. Easily automated.	Lightning protection required. Subject to zero-drift, therefore, not recommended for long-term monitoring. Expensive transducer and readout. Voltage or current output signal sensitive to cable length, splices, moisture, etc.

The primary factors influencing the distribution of water pressures in soil are the permeability of the soil, the ratio of horizontal to vertical permeability, and the variation of permeability within different zones and strata. The primary factors influencing the distribution of water pressures in rock are the joint permeability and the variation of the permeability due to the variation of the orientation, spacing, persistence, interconnection, and aperture of the joints. Where impervious strata exist in soil or rock, different pressures may occur in adjacent strata. Water pressure distribution is also affected by drains, abutment water tables, strata variations, and occasionally grout curtains. Rainfall and regional water levels may change local water levels, which in turn may affect water pressure distribution. All these aspects must be properly understood and accounted for when selecting and locating piezometers.

Relatively high excess pore water pressures may develop in impervious zones and compressible foundation strata during construction of embankment dams as the height of the dam increases. The inability of the dam or foundation to maintain effective strength during construction may lead to deformation or, in extreme cases, slope or bearing capacity failures. Consolidation testing and analyses, and pore pressure measurements during construction provide guidance for regulating the rate of fill placement and/or moisture control in the fill during construction to prevent instability. These pressures change to steady-state seepage pressures with time, depending on the permeability and length of drainage paths of the system.

The location of the phreatic surface for steady state seepage conditions in embankment dams is commonly established by theoretical analyses, and the variation of pressure beneath the phreatic surface is estimated by flow nets or is assumed to vary hydrostatically. Alternatively, pressures are estimated by finite element or finite difference models. Steady state seepage conditions may take years to develop.

Uplift pressure beneath concrete structures is generally assumed to vary linearly from headwater to tailwater or downstream ground surface. If foundation drains exist and are adequately maintained, the uplift pressure is usually reduced at the line of drains in accordance with the effectiveness of the drainage system. The linear pressure distribution can be affected by the factors influencing the distribution of water pressures in soil and rock that are discussed above. Common uplift pressure assumptions are illustrated in Chapter III of these guidelines.

Seasonal water pressure variations can occur as a result of seasonal reservoir level and temperature variations. Concrete dams and foundations deform slightly to adjust to these changing loads. In some cases, the deformations are sufficient to alter the aperture and permeability of foundation rock joints, which changes the pressure distribution. In a closed, perfectly rigid hydraulic system, changes in water pressure are transmitted, nearly instantaneously, by pressure waves. Piezometers are not perfectly rigid, or closed. Therefore, some water must flow for a pressure change to be measured. The time required for the flow to occur is known as lag time. Lag time is influenced by the degree of saturation, the permeability of the materials surrounding the piezometer, the design of the instrument, and the magnitude of change in pressure. Open standpipe piezometers require a relatively large volume of water to fill the standpipe and, in low permeability soils, lag time can range up to several months. Pneumatic and diaphragm type piezometers installed in sealed and saturated zones require negligible flow, and lag time for these types of piezometers is generally short. If the sensor is not sealed in a saturated zone, the lag time is controlled by the filter pack or material surrounding the piezometer. Lag time is usually only significant for piezometers installed in impervious materials.

Below the phreatic surface, soils are usually assumed to be saturated. Above the phreatic surface, soils contain both gas and water within the pore spaces. In partially saturated soils, piezometers measure pore air pressure rather than pore water pressure, unless high air entry porous tips are used. In cohesionless materials, the difference between pore air pressure and pore water pressure is minimal. In fine grained cohesive materials with high capillary pressure, pore air is always greater than pore water pressure. In some instances the difference can be significant with respect to evaluating the stability of a dam (Sherard 1981).

Piezometer tubing and cables should be installed to avoid development of seepage paths along them, or through them as they deteriorate. Special attention must be paid to sealing tubing and cables where they cross zones of an embankment dam. Adequate filters must be used around tubing located outside of the core and where tubing exits from the dam to prevent piping along the tubing or through damaged or deteriorated tubing.

9-3.1.2 Water Level Gages

Staff gages are the simplest method for measuring reservoir and tailwater levels. Staff gages are reliable and durable. For automated monitoring, a float and recorder, ultrasonic sensor, bubbler, or one of the other instruments discussed below is necessary.

Water level gages can be used to measure flow in rivers (e.g. minimum instream flow), when the relationship between river flow and river stage is known. Stream bed erosion or sedimentation can change the calibration and cause inaccurate measurements. Water level gages used for flow measurements in channels with moveable beds should be periodically re-calibrated.

9-3.1.3 Observation Wells

Observation wells are usually vertical pipes with a slotted section at the bottom or a tube with a porous tip at the bottom. They are typically installed in boreholes with a seal at the surface to prevent surface water from entering the borehole. The depth to the water level is measured by lowering an electronic probe or weighted tape into the pipe.

Observation wells are appropriate only in a uniform, pervious material. In a stratified material, observation wells create a hydraulic connection between strata. As a result, the water level in the well is an ambiguous combination of the water pressure and permeability in all strata intersected by the borehole. Observation well data may lead to erroneous conclusions regarding actual water pressures within the dam and foundation.

9-3.1.4 Open Standpipe Piezometers

Open standpipe piezometers are observation wells with subsurface seals that isolate the strata to be measured. Open standpipe piezometers are also known as Casagrande-type piezometers and, in concrete dams, as pore pressure cells. The seals are usually made of bentonite clay or cement grout and care must be taken during installation to develop a good seal. Riser pipe joints should be watertight to prevent leakage into or out of the pipe, which could change the water level in the pipe. The top of the standpipe should be vented and the inside diameter should be greater than about 8 mm (0.3 inch) to be self de-airing.

A common version of the open standpipe piezometer is a wellpoint, which is a prefabricated screened section and riser pipe that is pushed into place. If the screened section is not adequately sealed, it will act like an observation well rather than a piezometer. Dunnicliff (1988) discusses methods of sealing well points.

The sensing zone (screened length or porous tip) of observation wells and open standpipe piezometers is susceptible to clogging, which can increase lag time or result in failure of the instrument. This susceptibility can be diminished by a properly designed filter pack that meets filter criteria with the surrounding soil and properly sized perforations that are compatible with the filter pack.

Open standpipe piezometers are the standard against which all other piezometers are judged. They are simple, reliable, inexpensive, and easy to monitor.

9-3.1.5 Closed Standpipe Piezometers

Closed standpipe piezometers are identical to open standpipe piezometers, except that the water level being measured is above the top of the standpipe (artesian condition) and the pressure is measured with a pressure gage (or pneumatic, or vibrating wire piezometer) fitted to the top of the pipe. In concrete dams they are also known as pore pressure cells. Closed standpipe piezometers installed in concrete dams during construction usually have riser pipes that are not vertical, but rather routed to a gallery for ease of monitoring. Provisions for venting gas trapped inside of the riser pipe are often made, but are not required on most common sizes of riser pipes.

9-3.1.6 Twin-tube Hydraulic Piezometers

Twin-tube hydraulic piezometers are similar in principal to closed standpipe piezometers. They consist of a porous filter element connected to two flexible tubes. The tubes are extended more or less horizontally in trenches through the fill or foundation to a readout point. Two tubes are used to allow the system to be flushed to remove trapped air. Water pressure is calculated using the average pressure head of the gages on each tube.

9-3.1.7 Pneumatic Piezometers

Pneumatic piezometers consist of a porous filter connected to two tubes which have a flexible diaphragm between. The diaphragm is held closed by the external water pressure. The end of one of the tubes is attached to a dry air supply and a pressure gage. Air pressure is applied until it exceeds the external water pressure acting on the diaphragm, which deflects the diaphragm and allows the air to vent through the other tube. The air supply is shut off, and the external water pressure and internal pressure equalize allowing the diaphragm to close. The residual internal air pressure is taken as the external water pressure. Alternatively, the water pressure can be taken as the air pressure required to maintain a constant flow through the tubes. Some constant flow types use a third tube connected to a pressure gage to measure pressure at the diaphragm rather than at the inlet to reduce potential errors and eliminate the need for individual calibration curves.

9-3.1.8 Vibrating Wire Piezometers

Vibrating wire piezometers consist of a porous stone connected to a sealed metal chamber with a diaphragm adjacent to the stone. Inside the chamber, a wire is stretched between the diaphragm and a fixed point at the other end of the chamber. The chamber is connected to an electronic readout device. Water pressure deflects the diaphragm, which changes the tension and resonant frequency of the wire. Pressure is measured by electronically vibrating the wire, measuring the frequency of vibration, and relating frequency to water pressure using calibration data. Modern readouts perform the calibration automatically.

9-3.1.9 Bonded Resistance Strain Gage Piezometers

Bonded resistance strain gage piezometers (a.k.a. electronic piezometers) consist of a porous stone connected to a sealed metal chamber with a diaphragm adjacent to the stone, similar to vibrating wire piezometers. Inside the chamber, a strain gage is bonded to the diaphragm. Wires extend from the chamber to an electronic readout device. Water pressure deflects the diaphragm and the magnitude of the deflection is measured by the strain gage. Water pressure is determined by relating strain gage output to water pressure using calibration curves. These piezometers are subject to zero drift, and therefore are not appropriate for long-term monitoring.

9-3.2 Seepage and Leakage

Seepage is defined as interstitial movement of water through a dam, the foundation, or the abutments. It is differentiated from *leakage*, which is flow of water through holes or cracks. Seepage and leakage are commonly measured with weirs, Parshall flumes, and calibrated containers. Other types of flow measuring devices such as flow meters may be appropriate in special circumstances. Geophysical surveys can be used to determine flow direction. USBR references (1987a, 1987b, and 1990) provide a more detailed discussion of seepage and leakage measuring devices.

9-3.2.1 Engineering Concepts

The difference in water levels between the upstream and downstream sides of a dam causes seepage and leakage. The primary factors influencing the amount of seepage and leakage are the same as those influencing pressure distribution discussed in section 9-3.2.1. The amount of seepage or leakage is directly proportional to permeability and pressure. It is possible to have large flow with high pressure, large flow with low pressure, low flow with high pressure, or low flow with low pressure.

Most of the factors that influence the amount of seepage or leakage do not change during the life of a project. Usually the main variable is the reservoir level, and typically seepage and leakage volume are directly related to the reservoir level. Any change in seepage or leakage volume not related to reservoir level must be evaluated immediately. Significant or rapid changes in seepage or leakage related to the reservoir level should also be investigated. An increase in seepage or leakage may be an indication of piping.

A decrease in seepage or leakage may indicate clogged drains. A decrease in seepage may also indicate that seepage is increasing at a location other than that being measured, which could lead to piping. Cloudy or turbid seepage may indicate piping. New seeps or leaks may also be indications of developing problems.

Another variable that affects the amount of seepage or leakage is the development of the steady-state phreatic surface in a newly constructed project. The steady-state phreatic surface can take years, during which, a gradual increase in seepage or leakage may occur.

For dams on soluble rock foundations (e.g. gypsum or halite), seepage may increase with time due to dissolution of the rock. In these cases a slow steady increase in seepage may indicate developing problems.

Water quality measurements can provide data to evaluate the dissolution of the foundation rock, the source of seepage, or piping. Common water quality measurements include field measurements of Ph, temperature, and conductivity, and laboratory measurements of total dissolved solids, total suspended solids, and a variety of minerals (e.g. sodium, potassium, carbonate, bicarbonate, sulfate, and chloride). Standard test methods are given by the American Society for Testing and Materials (ASTM), the American Water Works Association (AWWA), and the U.S. Environmental Protection Agency (EPA). The USBR (1987) discusses application of the standard test methods to evaluating seepage from dams.

9-3.2.2 Weirs

Weirs are usually metal or plastic plates with a notch in the top edge. They are installed in a ditch, gutter, pipe, or in manholes in the relief well collection system. The quantity of water flowing through the notch is calculated by measuring the depth of water from the invert of the notch to the upstream water surface and using the measurement in the appropriate hydraulic equation.

The notch can be triangular, rectangular, or trapezoidal. Triangular notches are appropriate for low flows (less than about 0.05 m^3/s [10 cfs]). Rectangular or trapezoidal weirs are appropriate for larger flows. The crest of the weir should be thin enough that the nappe springs clear. Standard weir dimensions and calibrations are readily available (USBR 1984).

Weirs are simple, reliable, inexpensive, and require little maintenance. Limitations are the severe restriction of the flow channel, relatively high head loss, and the need for sufficient elevation change to prevent the tailwater from submerging the weir.

9-3.2.3 Parshall Flumes

Parshall flumes are specially shaped open channel sections. They consist of a converging upstream section, a downward sloping throat, and an upward sloping and diverging downstream section. They are usually permanent installations made of reinforced concrete, metal, or prefabricated fiberglass and can be sized to measure a wide range of flows. Throat widths from 25 mm (1 inch) to 10 m (33 feet) are common. Standard flume dimensions are in USBR (1984). The quantity of water flowing through the throat is calculated by measuring the depth of water upstream and using the measurement in the appropriate hydraulic equation. Parshall flumes should be installed level and ideally at a site free of downstream submergence.

Parshall flumes are simple, reliable, and require little maintenance. They cause minimal restriction to the flow channel and low head loss. The primary limitation is the relatively expensive installation.

9-3.2.4 Calibrated Containers

Containers of known volume can be used to measure low flows that are concentrated and free-falling. The flow rate is computed as the volume of the container divided by the time required to fill the container.

Extremely low flow rates can be measured accurately. The maximum flow rate is limited by the size of the container that can be maneuvered quickly into and out of the flow or into which flow can readily be diverted. Typically, calibrated containers are appropriate for flows less than about 0.003 m^3/S (50 gpm).
Calibrated containers are reliable for low flows and are inexpensive. They have limited application because of the requirement for a free-falling flow, they are not accurate for large flows, and are labor intensive.

9-3.3 Movement

Movement can be divided into three types: surface movement, internal movement, and crack or joint movement. Since it can occur in any direction, measurements in three mutually perpendicular directions are necessary to accurately determine vector movement. Measurements are typically made in vertical, transverse horizontal, and longitudinal horizontal directions. Movement in one or more of these directions is often judged to be negligible and is not measured.

Surface movement is defined as horizontal or vertical movement of a point on the surface of a structure relative to a fixed point off of the structure. It is usually determined by some type of surveying. Modern surveying equipment has increased the number and type of surveys that are available.

Internal movement is defined as horizontal or vertical movement within the structure. It is usually determined relative to some point on the structure or in the foundation.

Joint or crack movement is defined as horizontal or vertical movement of one part of a structure relative to another part of a structure. It is usually measured across block joints or cracks in concrete structures or cracks in earth structures.

Tubing or cables for movement measuring devices should be installed to avoid development of seepage paths along them, or through them, as they deteriorate. As for piezometer tubing discussed on Section 9-3.1.1., special attention must be paid to sealing tubing and cables where they cross zones of an embankment dam.

Commonly used techniques for measuring movement are summarized below. More detailed information may be found in ICOLD (1993), ISRM (1981), USACE (1987a and 1987c) and USBR (1987a and 1987b).

9-3.3.1 Engineering Concepts

All structures move as the result of applied loads. Embankments settle and spread over time as the result of consolidation and secondary settlement of the dam and foundation from self weight. Embankments also deform due to external loads produced by reservoir water, rapid drawdown, earthquakes, undermining, swelling clays, and piping. Concrete structures deform due to internal loads such as pore pressure, cooling, and alkali aggregate reaction of concrete; and external loads caused by air and reservoir temperature, solar radiation, reservoir levels, uplift pressure, wind, earthquakes, undermining, ice, overflowing water, swelling clay, and foundation settlement.

Movements in response to such loads are normal and acceptable, provided they are within tolerable ranges and do not cause structural distress. Embankments are less brittle than concrete structures and can undergo larger movements without distress. As a result, measurements of surface movements of embankment dams are typically less precise than those for concrete structures. Sudden or unexpected direction, magnitude, or trend of surface movement could indicate developing problems. Internal movement measurements of both concrete and embankment dams and their foundations should be detailed and precise.

Measuring points for all movement surveys should be installed so that they are not subject to movement from freeze-thaw action or traffic.

9-3.3.2 Level Surveys

Vertical surface movements are commonly measured by conventional differential leveling surveys. Measuring points are established on the crest or slopes of the dam. Embankment measuring points are usually steel bars embedded in concrete placed in the fill. Concrete dam measuring points are usually bronze markers set in the concrete or scratch marks. The change in elevation between the measuring points and survey control monuments off of the dam are measured using levels and rods. Typically, survey methods and equipment for measurements of embankments should be sufficiently accurate to discern movement on the order of 30 mm (0.1 foot). A conventional level and rod are usually adequate for embankment dams. Typically, survey methods and equipment for measurements of concrete structures should be sufficiently accurate to discern movement on the order of 3 mm (0.1 inch). Precision levels and rods equipped with micrometer targets are usually used for concrete structures.

Level surveys are the simplest and most accurate method for determining vertical movement of a dam. A limitation of level surveys is the labor cost, though modern surveying equipment has reduced the time required to perform a survey and reduce the data.

9-3.3.3 Alignment Surveys

Horizontal surface movements are commonly measured as offsets from a baseline. The same measuring points used for the level surveys are normally used for alignment surveys. The method and equipment used depends on the type of dam and the desired accuracy.

For embankment dams, one or more lines of measuring points are established along the crest and on the slopes parallel to the crest. Instrument and target monuments are established at the ends of the lines on the abutments beyond the dam. To measure movement, a theodolite is set up on the instrument monument on one abutment and sighted to the target monument on the opposite abutment. Offsets from the line-of-sight are then measured to each measuring point using a plumb bob and tape. Typically, survey methods and equipment should be sufficiently accurate to discern movement on the order of 30 mm (0.1 foot).

For concrete dams a similar procedure is employed, but with refinements to increase the accuracy of the measurements. These surveys are also known as collimation surveys. Measuring points are established along straight lines on the crest and, in some cases, along the face of the dam. The measuring points are markers set in the dam concrete. Instrument and target monuments are established outside the limits of the dam at the ends of the lines of measurement points. The monuments are usually 200- to 250-mm- (8- to 10-inch-) diameter concrete-filled pipes buried at least 3 m (10 feet) into the ground. The top of the instrument monument is fitted with a threaded plate to fit a theodolite. The target monument is fitted with a threaded plate to fit a target. The line-of-sight is established using a high precision theodolite set on the instrument monument and sighted to the target on the target monument. Offsets from the base line are measured with a micrometer attached to a moveable target leveled over each measuring point. Typically, survey methods and equipment should be sufficiently accurate to discern movement on the order of 3 mm (0.1 inch).

Alignment surveys are the simplest and most accurate method for determining horizontal movement in straight dams. Their application is limited for curved dams, irregularly shaped dams, or where the line-of-sight is limited, because the number of measurement points along any one line is small. A limitation of alignment surveys is the labor cost, although modern surveying equipment has reduced the time required to perform a survey and reduce the data

9-3.3.4 Triangulation and Trilateration

Triangulation and trilateration use trigonometric principles of triangles to measure the location of points on a dam. In triangulation surveys, angles to a measuring point on the dam are determined from two locations on a base line. Using the known distance between, and the elevation of base line monuments, the triangle between the three points is solved trigonometrically to determine the location (horizontal and vertical) of the measuring point. Angles are measured with precise theodolites.

In trilateration surveys, the distances between a measuring point on the dam and two locations on a base line are determined. Using the known distance between, and the elevation of monuments on the baseline, the triangle between the three points is solved trigonometrically to determine the location (horizontal and vertical) of the measuring point. Since distances can be measured more precisely than angles, trilateration surveys are more precise than triangulation surveys.

Distances are measured with electronic distance measurement (EDM) equipment. EDMs determine distance by measuring the time it takes for light to travel from the source to a reflector and back and then multiplying by the speed of light. Extremely high accuracies can be obtained with this equipment. Measurements must be corrected for barometric pressure, temperature, and the curvature of the earth.

Baseline monuments are similar to instrument monuments used for alignment surveys of concrete dams. Triangulation and trilateration are useful when measuring points do not lie along a straight line or when lines of sight are obstructed. Vertical movements can be measured with both surveys if the base line has a significant vertical component. The surveys are highly accurate, but require an experienced crew. Disadvantages are the cost of the survey crew labor, the cost of establishing the baseline, the need for specialized equipment, and the relatively complex calculations.

9-3.3.5 Internal Movement

Internal settlement of an embankment or foundation can be measured with a variety of instruments including settlement plates, cross-arm devices, magnetic- or inductance-type probe extensometers, fluid leveling devices, pneumatic settlement sensors, vibrating-wire settlement sensors, and various other mechanical and electrical sounding devices. Internal horizontal and vertical movements are commonly measured with inclinometers and extensometers. Internal movements of concrete structures are commonly measured with plumblines, tiltmeters, inclinometers, and extensometers. The operation, advantages, and limitations of these devices are well described in the references for section 9-3.3. Some common types of internal movement instruments are described below.

Plumblines consist of a plumb bob suspended from a wire in a vertical shaft in a dam. Measurements of the location of the wire relative to the suspension point are taken at one or more elevations along the shaft. They are simple, inexpensive, accurate, and reliable.

Tiltmeters consist of a base plate, sensor, and readout device. They are commonly attached to a surface (internal or external) of a structure and measure vertical rotation of the surface. They are portable, accurate, and precise.

Inclinometers consist of specially shaped casing, a probe and readout device. They are commonly installed in vertical drill holes in dams, foundations and abutments, although they may be installed in a dam during construction. Inclination of the casing is measured at regular intervals and lateral movement with respect to the bottom of the casing is calculated. They are reliable and accurate.

Extensometers consist of one or more rods anchored at different depths in a borehole and a reference head at the surface. They are commonly installed vertically to measure vertical movement of the reference head relative to the anchor zone(s), though they may be installed in other orientations. They are accurate and can be used to measure small movements.

9-3.3.6 Crack and Joint Measuring Devices

Movement of one side of a crack or joint in a concrete structure relative to the other side of the joint or crack is commonly measured with reference points or crack meters. Grout or plaster patches can be used to evaluate whether or not movement is occurring. Many variations are used.

Reference points can be scratch marks in the concrete, metal pins, or metal plates on opposite sides of a joint or crack. The distance between the scratch marks is measured with a micrometer or dial gage to determine movement. Sometimes three points are used in a triangle to measure both horizontal and vertical movement.

Crack meters are commercially available devices that allow movement in two directions to be measured. A common device consists of two plastic plates. One plate is opaque and contains a grid. The other plate is translucent and contains a set of cross hairs. One plate is fixed on each side of the crack or joint with the cross hairs set over the center of the grid. Movement is measured by noting the location of the cross hairs with respect to the grid. A variety of other crack meters including Carlson and vibrating-wire sensors, dial gages, and mechanics feeler gages may be used to measure movement of cracks.

All these devices are simple to install and monitor. The accuracy and reliability varies depending on the details of the devices and measurements. Mineral deposits, iron staining, or efflorescence obscuring the instruments are a common problem if seepage or leakage flow is present.

9-3.4 Stress and Strain

Earth pressures within fill and against concrete structures are commonly measured with earth pressure cells. These are also known as total pressure cells. They consist of two flexible diaphragms sealed around the periphery, with a fluid in the annular space between the diaphragms. Pressure is determined by measuring the increase in fluid pressure behind the diaphragm with pneumatic or vibrating-wire sensors. Earth pressure cells should have similar stiffness as the surrounding soil to avoid inaccurate measurements of in-situ stress caused by arching. Soil pressures against structures can also be measured with a Carlson-type cell. It consists of a chamber with a diaphragm on the end. Deflection of the diaphragm is measured by a Carlson-type transducer and is converted to stress. Stress in concrete structures can be measured with total pressure cells or Carlson-type cells designed to have a stiffness similar to concrete. It can also be measured by overcoring.

The modulus of elasticity, creep coefficient, and the Poisson's ratio for concrete can be determined from the laboratory testing of concrete field cylinders. These values are required for converting strain measurements to stress.

A variety of mechanical and electrical strain gages are used to measure strain in concrete structures. Some of the instruments are designed to be embedded in the dam during construction and others are surface mounted following construction. Strain gages are often installed in groups so that the three-dimensional state of strain can be evaluated.

The operation and limitations of stress and strain instruments are discussed by Dunnicliff (1988), USACE (1976, and 1987c), and USBR (1976, 1977, 1987a, and 1987b).

9-3.5 Temperature

Temperature measurements of a dam, foundation, or instruments, are often required to reduce data from instruments, increase precision, or to interpret results. For example, movements of concrete dams and changes in leakage at concrete dams are commonly related to changes in temperature. Temperature is also commonly measured in concrete dams under construction to evaluate mix design, placement rates, and block and lift sizes; to time grouting of block joints; and to evaluate thermal loads.

Temperatures can be measured with resistance thermometers or thermocouples. The operation and limitations of these devices are discussed by Dunnicliff (1988), USACE (1987c), and USBR (1976, 1977 and 1987b).

Temperature measurements of seepage and leakage may indicate the source of seepage.

9-3.6 Seismic Loads

Seismic strong motion instrumentation records acceleration from earthquake shaking. The data are used to evaluate the dynamic response of dams. Seismic acceleration and velocity are usually recorded with strong-motion accelerographs. These devices typically consist of three mutually-perpendicular accelerometers, a recording system, and triggering mechanism. To prevent accumulation of unwanted data, the instruments are usually set to be triggered at accelerations generated by nearby small earthquakes or more distant, larger earthquakes. They are expensive, especially considering that multiple instruments are necessary to record dynamic response at several locations on a structure, a foundation, or abutments. The devices must be properly maintained, so that they operate if an earthquake occurs. These devices are discussed by USACE (1987c) and USBR (1987a and 1987b).

9-3.7 Loads in Post-Tensioned Anchors

Post-tensioned anchors consist of single or multiple wires, strands, or bars installed in drilled holes. The bottom end is grouted in the dam or foundation and the top end is fitted with a head that allows the anchor to be post-tensioned. The section between the grouted end and the head is known as the stressing length. It may be free (ungrouted) or grouted. Post-tensioned anchors are commonly used to improve the stability of concrete dams. Installation, design, and testing of post-tensioned anchors in discussed by Littlejohn and Bruce (1976), Hanna (1982), the FHA (1984), and the Post-Tensioning Institute (1994).

There is no practical method of measuring loads in fully grouted anchors.

Loads in post-tensioned anchors that have a free length can be evaluated by lift-off tests, load cells, extensometers, and fiber-optic cables.

In lift-off tests, a jack is attached to the head of an anchor and the pressure required to lift the head is measured by a pressure cell. This type of test requires that the anchor head be accessible and be capable of being connected to a jack.

Load cells can be located beneath the anchor head to measure the load in the anchor. Hydraulic and vibrating-wire cells have been used successfully. Electrical resistance strain gage load cells have not had good performance records. Load cells can be permanently installed in new anchors and in some cases can be placed under the heads of existing anchors.

Extensometers and fiber-optic cables can be installed integral with multiple strand or wire anchors to measure change in length. The length can be converted to load with elastic constants, assuming no slippage at the head.

Water pressure, seepage, leakage, movement, stress, and strain data taken before and after installation of anchors may be useful in evaluating the response of the dam to anchor loads.

9-4 Minimum Instrumentation Recommendations

Minimum instrumentation recommendations for all dams are established in this section. The recommended minimums are considered to be generally applicable; however, since each dam is unique, the recommendations should be applied using engineering judgement and common sense.

Minimum recommended instrumentation is separated into categories of existing and proposed dams and further subdivided depending on the hazard potential classification and the type of structure. Tables 9-4a and 9-4b summarize the recommended minimum instrumentation. For simplicity, types of measurements rather than specific instruments are shown in the tables. Instruments for each type of measurement are discussed in Section 9-3.

TABLE 9-4a
MINIMUM RECOMMENDED INSTRUMENTATION FOR EXISTING DAMS [1]

TYPE OF MEASUREMENT	LOW-HAZARD POTENTIAL DAMS — ALL TYPES	SIGNIFICANT AND HIGH-HAZARD POTENTIAL DAMS					
		EMBANKMENT	CONCRETE GRAVITY	ARCH	BUTTRESS	SEPARATE SPILLWAY AND/OR OUTLET	INTEGRAL POWERHOUSE
VISUAL OBSERVATION [2]	X	X	X	X	X	X	X
RESERVOIR LEVEL		X	X	X	X	X	X
TAILWATER LEVEL		X	X	X	X	X	X
DRAIN FLOW, SEEPAGE, AND LEAKAGE		X	X	X	X	X	X
PORE/UPLIFT PRESSURE [3]		X	X			X	X
SURFACE SETTLEMENT							
SURFACE ALIGNMENT			X	X	X	X	X
INTERNAL MOVEMENT							
JOINT/CRACK [4] DISPLACEMENT			X	X	X	X	X
FOUNDATION MOVEMENT [5]		X	X	X	X	X	X
SEISMIC LOADS [6]		X	X	X	X	X	X
LOADS IN POST-TENSIONED ANCHORS [7]			X	X	X	X	X

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[1] This table is provided to help explain the guidelines. Refer to the text of Section 9-4 for more detailed discussion of minimum recommendations. Additional instrumentation should be used to address specific concerns.

[2] Visual observation consists of walking tours of the crest, toes, abutments, etc.

[3] Using existing piezometers, observation wells, or foundation drains; or using existing or new piezometers or observation wells from dams with reduced uplift assumed in stability analysis or that do not meet criteria using conservative estimate of the phreatic surface.

[4] Only on structurally significant joints or cracks that have visible displacement.

[5] Should be considered for dams on compressible or weak foundations.

[6] Should be considered on a case-by-case basis for dams in seismic zones 3 and 4.

[7] For anchors that are required to meet stability criteria, loads should be measured wherever it is possible to measure anchor loads, or anchors should be modified to measure loads.

TABLE 9-4b
MINIMUM RECOMMENDED INSTRUMENTATION FOR PROPOSED DAMS [1]

TYPE OF MEASUREMENT	LOW-HAZARD POTENTIAL DAMS - ALL TYPES	SIGNIFICANT AND HIGH-HAZARD POTENTIAL DAMS					
		EMBANK-MENT	CONCRETE GRAVITY	ARCH	BUTTRESS	SEPARATE SPILLWAY AND/OR OUTLET	INTEGRAL POWER-HOUSE
VISUAL OBSERVATION [2]	X	X	X	X	X	X	X
RESERVOIR LEVEL		X	X	X	X	X	X
TAILWATER LEVEL		X	X	X	X	X	X
DRAIN FLOW, SEEPAGE, AND LEAKAGE		X	X	X	X	X	X
PORE/UPLIFT PRESSURE		X	X			X	X
SURFACE SETTLEMENT		X					
SURFACE ALIGNMENT		X	X	X	X	X	X
INTERNAL MOVEMENT [3,5]			X	X	X		
JOINT/CRACK [4] DISPLACEMENT			X	X	X	X	X
FOUNDATION MOVEMENT [5]		X	X	X	X	X	X
TEMPERATURE			X	X	X		
SEISMIC LOADS [6]		X	X	X	X	X	X
LOADS IN POST-TENSIONED ANCHORS [7]			X	X	X	X	X

[1] This table is provided to help explain the guidelines. Refer to the text of Section 9-4 for more detailed discussion of minimum recommendations. Additional instrumentation should be used to address specific concerns.

[2] Visual observation consists of walking tours of the crest, toes, abutments, etc.

[3] For concrete dams greater than about 100 feet high.

[4] Only on structurally significant joints or cracks that have visible displacement.

[5] Should be considered for dams on compressible or weak foundations.

[6] Should be considered on a case-by-case basis for dams in seismic zones 3 and 4.

[7] Loads should be measured in anchors that are required to meet stability criteria.

The minimum instrumentation applies to separate spillway and outlet works only if they are substantial and independent water-retaining structures. Instrumentation for separate spillway and outlet structures that retain only minimal water should be evaluated on a case-by-case basis. In most cases, these types of structures will require little or no instrumentation.

Instrumentation in addition to the minimum recommended should be used wherever it will help to resolve a dam safety concern. The minimum instrumentation assumes a geometrically simple dam on a sound foundation. Instrumentation in addition to the minimum should be tailored to known or suspected site-specific conditions. For example, a low dam on a pervious, weak, compressible, jointed, or similar problem foundation may require more instrumentation than a higher dam on a sound foundation.

Possible causes of, and remedial measures for a wide variety of problems and concerns are tabulated in reports by the EPRI (1986) and the National Research Council (1983). Case histories of dam incidents and remedial measures are discussed in reports by the ASCE (1975, 1988). Instrumentation is often installed to help evaluate causes of problems and concerns. Table 9-4c summarizes typical instrumentation that can be used to help evaluate common problems and concerns.

9-4.1 Visual Observation

Though not strictly instrumentation, visual observation is included as a type of measurement in the tables to stress its importance. Visual observation of all structures should be made in conjunction with instrument monitoring. It typically consists of walking tours of the dam crest, toes, and abutments in order to identify any unusual or abnormal conditions that could jeopardize the safety of the dam. Photographs or videos are often useful to document existing conditions and to help evaluate whether or not there has been any change from the previous conditions. Visual observation is discussed in many publications including USBR (1983), USACE (1977), National Research Council (1983), EPRI (1986), and ICOLD (1987).

9-4.2 Existing Dams

Minimum instrumentation recommendations for existing dams are less than for proposed dams, because instrumentation to monitor construction and first filling is not appropriate, retrofitting instrumentation can be expensive, and the performance of the dam is known. Minimum recommended instrumentation for existing dams is listed in Table 9-4a.

Existing instruments should continue to be monitored if they still provide useful information (even if they exceed minimum instrumentation recommendations). However, if existing instrumentation no longer provides useful or meaningful information, it should be abandoned as discussed in Section 9-7.4.

TABLE 9-4c
TYPICAL INSTRUMENTATION AND MONITORING USED IN EVALUATING CAUSES OF COMMON PROBLEMS/CONCERNS [1]

PROBLEM/CONCERN	TYPICAL INSTRUMENTATION
Seepage or leakage	Visual observation, weirs, flowmeters, flumes, calibrated containers, observation wells, piezometers
Boils or piping	Visual observation, piezometers, weirs
Uplift pressure, pore pressure, or phreatic surface	Visual observation, observation wells, piezometers
Drain function or adequacy	Visual observation, pressure and flow measurements, piezometers
Erosion, scour, or sedimentation	Visual observation, sounding, underwater inspection, photogrametric survey
Dissolution of foundation strata	Water quality tests
Total or surface movement (translation, rotation)	Visual observation, precise position and level surveys, plumb measurements, tiltmeters
Internal movement or deformation in embankments	Settlement plates, cross-arm devices, fluid leveling devices, pneumatic settlement sensors, vibrating wire settlement sensor, mechanical and electrical sounding devices, inclinometers, extensometers, shear strips
Internal movement or deformation in concrete structures	Plumblines, tiltmeters, inclinometers, extensometers, jointmeters, calibrated tapes
Foundation or abutment movement	Visual observation, precise surveys, inclinometers, extensometers, piezometers
Poor quality rock foundation or abutment	Visual observation, pressure and flow measurements, piezometers, precise surveys, extensometers, inclinometers
Slope stability	Visual observation, precise surveys, inclinometers, extensometers, observation wells, piezometers, shear strips
Joint or crack movement	Crack meters, reference points, plaster or grout patches
Stresses or strains	Earth pressure cells, stress meters, strain meters, overcoring
Seismic loading	Accelerographs
Relaxation of post-tension anchors	Jacking tests, load cells, extensometers, fiber-optic cables
Concrete deterioration	Visual observation, loss of section survey, laboratory and petrographic analyses
Concrete growth	Visual observation, precise position and level surveys, plumb measurements, tiltmeters, plumblines, inclinometers, extensometers, jointmeters, calibrated tapes, petrographic analyses
Steel deterioration	Visual observation, sonic thickness measurements, test coupons

[1] Appropriate remedial measures should be taken for all problems and concerns. Possible remedial measures for a wide variety of problems and concerns are discussed in EPRI (1986), National Research Council (1983), ASCE (1975 and 1988) and USACE (1986a).

9-4.2.1 Low-hazard Potential Dams

Extensive instrumentation on low-hazard potential dams is not required. Minimum recommended instrumentation for low-hazard potential dams consists of visual observation.

Some low-hazard potential dams are a critical source of municipal water, may cause unacceptable environmental impacts if they fail (e.g. release of heavy metals in sediments), or are important to public safety for other reasons. Instrumentation at these dams should be reviewed on a case-by-case basis and increased as appropriate.

9-4.2.2 Significant and High-hazard Potential Dams

Minimum instrumentation for significant and high-hazard potential dams includes that recommended for low-hazard potential dams plus additional instrumentation to monitor headwater and tailwater levels, significant seepage and leakage, pore pressure or uplift pressure, loads in post-tensioned anchors, and movement. Strong motion instrumentation should be considered on a case-by-case basis for dams in seismic zones 3 and 4.

9-4.2.2.1 Water Level

One measurement site for headwater level and one for tailwater level is usually sufficient. The instruments should be located where the levels are representative of project conditions and where they are easily and safely accessed.

9-4.2.2.2 Seepage and Leakage

Seepage flow from embankment toe drains, concrete gravity or arch foundation drains, and foundation relief wells are usually collected in a drainage system and routed to the downstream channel. Flow measurements should be taken near the system outfall where the combined flow can be measured. Additional measurements at intermediate locations may be appropriate on a case-by-case basis. Measurements of seepage or leakage from other sources should be made at locations where the flow is representative and readily measured. If the foundation has soluble strata, water quality tests should be considered.

9-4.2.2.3 Pore/Uplift Pressure

Pore pressures and uplift pressures are typically the least certain loads on a dam. Wherever reasonable, estimates of the pressures used in stability analyses should be verified by measurements. Redundant piezometers should be considered as discussed in

Section 9-5.5.
Embankments. Pore pressures should be measured in all existing observation wells and piezometers within an embankment and within the foundation. Installation of pore pressure instrumentation at existing dams is not required unless they do not meet stability criteria using a conservative estimate of the phreatic surface or anomalous conditions are suspected.

Existing dams that do not meet stability criteria using a conservative estimate of the phreatic surface should have instruments to locate the phreatic surface. If existing instrumentation is not adequate to do so, additional instruments should be installed. Instrumentation should be located based on the site-specific geotechnical characteristics of the embankment, foundation, and abutments. Typically, a minimum of two or three piezometers along a transverse line through the maximum section are sufficient. Additional transverse lines may be appropriate for long dams or for complex foundations.

Concrete Gravity Dams. Uplift pressure should be measured in all existing instruments at existing concrete gravity dams. If existing instruments no longer provide useful information, they should be abandoned as discussed in Section 9-7.4.

Installation of uplift pressure instrumentation at existing dams is not required unless a reduction in uplift is needed to meet stability criteria or anomalous conditions are suspected.

Dams that require a reduction in uplift below a linear variation between headwater and tailwater to meet stability criteria have instrumentation to verify the uplift reduction. If existing instrumentation is not adequate to demonstrate the uplift reduction, additional instruments should be installed. Instrumentation should be located based on the site-specific geotechnical characteristics of the foundation and abutments. Typically, a minimum of two or three piezometers along a transverse line through the maximum section are sufficient. Additional transverse lines may be appropriate for long dams or for complex foundations.

Uplift pressure measurements should be made in foundation drains of existing concrete gravity dams if no other means to measure uplift exists and if additional instrumentation is not required. Measurements should be made in selected drains that are judged to provide representative uplift pressures beneath sections of the dam that are critical for stability. Drains should be clear the full length of their depth. Pressure measurements should be made in only one or two drains at one time because plugging a large number of drains may significantly increase the uplift pressure and possibly jeopardize the stability of the dam.

Uplift pressures measured in foundation drains may be greater or less than actual uplift pressures on potential failure surfaces. In a uniform foundation they tend to be greater than actual uplift pressures because the measuring device prevents the drainage and pressure reduction normally provided by the drain. In stratified foundations pressures measured in drains may be less than actual uplift pressures. This is because the pressure in various strata intersected by the drain are combined in an ambiguous manner, depending on the pressure and permeability of each strata. In this case, pressures should be measured in isolated lengths of the drain to identify the location of high and low pressure strata.

Arch and Buttress Dams, Spillways, Outlet Structures, and Powerhouses. Uplift pressure should be measured in all existing instruments at existing arch dams, buttress dams, separate spillways and/or outlet structures, and integral powerhouses. Installation of uplift pressure instrumentation at existing dams is not required unless a reduction of uplift is needed to meet stability criteria or anomalous conditions are suspected.

For thin arch dams and buttress dams that are not founded on slabs, uplift pressures generally have a minimal effect on stability and need not be measured. All other dams that require a reduction in uplift below a linear variation between headwater and tailwater to meet stability criteria should have instrumentation to verify the uplift reduction. If existing instrumentation is not adequate to demonstrate the uplift reduction, additional instruments should be installed. Instrumentation should be located based on the site-specific geotechnical characteristics of the foundation and abutments. Typically, a minimum of two or three piezometers along a transverse line through the maximum section are sufficient. Additional lines may be appropriate for long dams or for complex foundations.

9-4.2.2.4 Movement

Movement is perhaps the most important indicator of structural distress. Though all dams deform in response to applied loads, excessive movement may indicate developing problems.

Embankments. For existing embankment dams, settlement of the crest or bulging of the slopes might indicate developing problems. Visual observation by a trained inspector should be sufficient to identify significant movements of embankments that have a satisfactory performance record with respect to movement.

Concrete Gravity, Arch, and Buttress Dams. Concrete gravity, arch, and buttress dams deform elastically in response to changing reservoir loads and seasonal temperature changes. However, inelastic movements might indicate potential instability. Transverse horizontal movement of the crest of the dam should be monitored. Longitudinal horizontal and vertical movements are usually small and generally do not need to be routinely monitored. The measurements should be sufficiently precise to clearly identify cyclical seasonal movements from water level and temperature loadings and any inelastic trends. One line of four or five measuring points along the crest is typically sufficient. Measuring points should be spaced close enough to allow measurement of all significant deformation. At least two survey monuments (survey control points) should be permanently established off the dam structure.

Contraction joints between blocks of concrete gravity and buttress dams are a plane of weakness and if not keyed or grouted, movement will first become visible at the joints. Small elastic movements in response to seasonal temperature and reservoir levels changes are normal and do not require instrumentation to monitor them. Wherever there is indication of significant inelastic movement, instrumentation to measure relative movement between blocks should be installed.

Almost all existing concrete dams have a variety of cracks. Most cracks are not important with respect to the structural stability or integrity of the dam. Nevertheless, large, recently formed, growing, or critically oriented cracks may be an indication of structural distress. As with block joints, deformation will first become visible at cracks. Instrumentation should be installed to measure relative movement across cracks that are judged to be a potential indication of structural distress. The measurements should be sufficiently precise to clearly identify seasonal trends and any inelastic movements.

Arch dams are designed to act monolithically and measurement of relative movements, except at significant cracks, is usually not warranted. Arch dams can impose higher stresses on foundations and abutments than other types of dams. Existing arch dams on foundations or abutments that are expected to have significant deformation should have instrumentation to measure the deformation of the foundation and abutments. The appropriate number and location of instruments depends on the specific foundation conditions.

Spillways, Outlet Structures, and Powerhouses. Recommended minimum movement instrumentation for significant water-retaining spillway and outlet structures and integral powerhouses consists of that appropriate to measure transverse horizontal surface movements. Two measuring points are typically sufficient. At least two survey monuments (survey control points) should be permanently established off the dam structure.

9-4.2.2.5 Seismic Loads

Seismic strong motion instrumentation should be considered on a case-by-case basis for dams in seismic zones 3 and 4 shown on the seismic zone maps in Chapters III and IV of these guidelines. Dam design, foundation materials, and methods of construction, and any site-specific seismotectonic studies should be weighed against any potential benefits before seismic strong motion instrumentation is required.

9-4.2.2.6 Loads in Post-Tensioned Anchors

Loads should be monitored in post-tensioned anchors that are required to meet stability criteria. The number of anchors to be monitored should be evaluated on a case-by-case basis, but should typically be between 5 and 10 percent of the total number of anchors.

All existing post-tensioned anchor installations that do not have provisions to measure loads in representative anchors should be modified, wherever possible, to have such provisions. Existing post-tensioned anchors that cannot be modified to measure loads should be evaluated on a case-by-case basis. The possibility of loss of load from corrosion, creep of the grouted anchorage, and movements that may have locally yielded the anchor should be evaluated.

All new post-tensioned anchor installations in existing dams should have provisions for long-term measurement of loads in a representative number of anchors.

9-4.3 Proposed Dams

Minimum instrumentation for proposed dams includes that recommended for existing dams plus additional instrumentation to monitor conditions during construction, first filling, and the early life of the project. The minimum recommended instrumentation is shown in Table 9-4b.

The recommended minimum instrumentation is limited to that which clearly provides information useful in confirming key design assumptions and evaluating the stability of the structures. Instrumentation is often included in proposed dams for reasons other than dam safety such as to guide timing of construction operations or to provide information for various studies. While this type of instrumentation is necessary and encouraged, it is not included in the minimum.

9-4.3.1 Low-hazard Potential Dams

Minimum recommended instrumentation for proposed low-hazard potential dams is the same as recommended for existing low-hazard potential dams — that is, visual observation.

Instrumentation similar to that for proposed significant and high-hazard potential dams should be considered for proposed low-hazard potential dams that are likely to become high-hazard potential dams from downstream development.

9-4.3.2 Significant and High-hazard Potential Dams

Minimum instrumentation recommended for proposed significant and high-hazard potential dams includes that recommended for existing significant and high-hazard potential dams plus additional instrumentation to monitor uplift or pore pressures, internal movement, foundation movement, and loads in post-tensioned anchors. Strong motion instrumentation should be considered on a case-by-case basis for dams in seismic zones 3 and 4.

9-4.3.2.1 Pore/Uplift Pressure

All proposed significant and high-hazard potential dams should have instrumentation to measure pore pressures or uplift pressures to confirm design assumptions, evaluate pore pressures during construction, check seepage conditions, check performance of the drainage system, and measure the uplift pressure distribution. The number and location of the instruments depends on the type of dam and site-specific geotechnical characteristics. Redundant piezometers should be considered as discussed in Section 9-5.5.

<u>Embankments.</u> Embankments should have piezometers included in the dam and foundation to confirm design assumptions during construction and first filling, and for long-term monitoring during operation.

<u>Embankments During Construction and First Filling.</u> The need for piezometers in impervious cores of embankment dams should be left to the discretion of the design engineer. Problems have occurred in the past from seepage developing along the piezometer cables and tubing. Piezometers are not essential in moderate to thin, impervious cores of low- to moderate-height dams that are constructed with good moisture control. The appropriateness of piezometers in thick core zones or unusually high dams should be evaluated on a case-by-case basis. If used, special attention should be given to sealing the piezometer cables and tubing to prevent development of seepage

paths and using filter material around tubing located outside of the core to protect against piping.

Piezometers should be located downstream of the impervious core to monitor the effectiveness of the drainage system during filling.

Where the foundation contains compressible, low permeability strata, piezometers should extend into the foundation. Sufficient piezometers should be installed to measure induced pore pressures in the foundation beneath the dam and also for an appropriate distance upstream of and downstream from the dam.

Embankments During Operation. More piezometers are commonly installed to monitor construction and first filling than are required for long-term operation. Instrumentation should be planned such that some of the construction/first filling instruments will be used for long- term monitoring. At least one line of pore pressure instruments located along a transverse plane through the maximum section is recommended for long-term monitoring of embankment dams. Additional transverse lines of instruments may be appropriate for long dams or for complex foundations. Sufficient instruments should be installed along each line to define the phreatic surface through the dam and in the foundation. Three or four piezometers are usually sufficient. Specific locations should be based on the embankment zoning, foundation, and abutments. If relief wells are used, the line of piezometers should extend downstream from the line of relief wells and additional piezometers should be located at midpoints between selected relief wells.

Concrete Gravity Dams. All proposed concrete gravity dams should have instruments installed at the base to monitor uplift pressures. At least one line of piezometers located along a transverse plane through the maximum section is recommended. Additional lines may be appropriate for long dams or for complex foundations. Sufficient piezometers should be located along the line to adequately measure the uplift pressure distribution. Two or three piezometers are typically sufficient. If foundation drains are included in the proposed dam, at least one piezometer should be located along the line of drains, midway between two drains, to provide data to evaluate drain spacing.

Piezometers within the foundation are appropriate if the foundation is soil, soft rock, or if it contains relatively impervious, adversely oriented strata that may act as an aquiclude or be a potential plane of sliding. Sufficient piezometers should be installed to adequately measure the uplift pressure distribution.

Arch and Buttress Dams, Spillways and Powerhouses. Uplift pressures beneath thin arch dams and buttress dams not founded on slabs are less important than for concrete gravity dams because of the smaller base area on which uplift can act. The appropriateness of piezometers should be evaluated on a case-by-case basis for these structures. For thick arch and buttress dams that are founded on slabs, piezometers should be installed in the foundation and in the abutments to verify design assumptions. The number and location of the piezometers depends on the specific conditions at the site. Piezometers within the foundation are appropriate if the foundation is soil, soft rock, or if it contains relatively impervious, adversely oriented strata that may act as an aquiclude or be a potential plane of sliding. Enough piezometers should be installed to adequately measure the uplift pressure distribution.

Separate spillways, outlets, and integral powerhouses should have one transverse line of piezometers similar to that for concrete gravity dams.

9-4.3.2.2 Movement

Movement instrumentation recommended for proposed dams includes that recommended for existing dams plus additional instrumentation to monitor surface movement of embankment dams and internal movement of concrete dams.

<u>Embankments.</u> Horizontal (longitudinal and transverse) and vertical surface movement of proposed embankment dams should be monitored. One line of measuring points along the crest of an embankment dam is usually sufficient. For large embankments or those on soft foundations, an additional longitudinal line(s) on the downstream slope is appropriate. Measurement points should be spaced sufficiently close to allow measurement of all significant deformation. Five to 10 measuring points are typically sufficient. At least two survey monuments (survey control points) should be permanently established off the dam structure.

The need for instruments to monitor internal movement should be evaluated on a case-by-case basis. For example, there may be little value in monitoring internal movement of small to moderate height embankment dams on good foundations or of rockfill dams on good foundations. Internal movement instrumentation would be appropriate for high dams, those with wide impervious zones, or those on compressible or weak foundations.

Proposed embankments on foundations that contain compressible strata should have additional instrumentation installed to monitor foundation deformation. The appropriate number and location of instruments depends on the specific foundation conditions.

<u>All Other Structures.</u> Concrete gravity, arch, and buttress dams should have transverse horizontal surface movement instrumentation as recommended for existing concrete gravity dams. In addition, proposed dams that are greater than about 100 feet high should have instrumentation to monitor transverse horizontal internal movement. Internal

movement should be monitored along a transverse line through the maximum section. For long dams, additional transverse lines may be appropriate. The need for internal movement instrumentation on lower dams should be evaluated on a case-by-case basis.

All proposed concrete structures on soft or deformable foundations should have instrumentation to measure horizontal and vertical movements of the dam with respect to the foundation and deformation of the foundation. The appropriate number and location of instruments depends on the specific foundation conditions.

Arch dams may impose higher stresses on foundations and abutments than other types of dams. Proposed arch dams on foundations or abutments that are expected to have significant deformation should have instrumentation to measure the deformation of those foundation and abutments. The appropriate number and location of instruments depends on the specific foundation conditions.

9-4.3.2.3 Temperature

No temperature measurements are recommended for embankment dams. Proposed concrete gravity and arch dams should have an array of instruments to measure internal and surface temperatures along a transverse plane through the maximum section. In addition, concrete arch dams should have a string of instruments to measure reservoir temperature along the height of the maximum section. The data should be collected until the dam has been in satisfactory service for several years and the temperatures stabilize and fluctuate between predictable values.

9-4.3.2.4 Seismic Loads

Seismic strong motion instrumentation should be considered on a case-by-case basis for dams in seismic zones 3 and 4 shown on the seismic zone maps in Chapters III and IV of these guidelines. Dam design, foundation materials, and methods of construction, and any site-specific seismotectonic studies should be reviewed and any potential benefits should be weighed against the life-cycle costs before seismic strong motion instrumentation is required.

9-4.3.2.5 Loads in Post-Tensioned Anchors

Loads should be monitored in post-tensioned anchors that are required to meet stability criteria. The number of anchors to be monitored should be evaluated on a case-by-case basis, but should typically be between 5 and 10 percent of the total number of anchors.

9-4.4 Additional Instrumentation

Instrumentation, in addition to the minimum recommended, should be required wherever there is a concern regarding a condition that may affect dam safety or other critical water retaining structures. Typical reasons to require additional instrumentation are to check design assumptions; to provide data to evaluate specific problems such as continuing movement, excessive cracking, or increased seepage; to provide data to support design of remedial modifications; and to provide data to evaluate effectiveness of remedial work.

Table 9-4c lists typical types of instrumentation that should be considered to evaluate common problems and concerns. The table is not exhaustive, but it provides examples of instrumentation and monitoring that can be used for general types of problems and concerns. The instrumentation listed may not be appropriate for all cases. Instrumentation and frequency of monitoring for specific problems and concerns should be selected based on the specific circumstances. Once the problem or concern has been resolved, the usefulness of the instrumentation should be re-evaluated. If it no longer provides useful information, it should be abandoned as discussed in Section 9-7.4.

Appropriate remedial measures should be taken for all problems and concerns. Possible remedial measures for a wide variety of problems and concerns are discussed in EPRI (1985), National Research Council (1983), ASCE (1975 and 1988), USACE (1986a), and Chapter V of these guidelines.

9-5 Instrumentation System Design

Instrumentation system design should receive the same level of effort as other features of a dam. It should follow a logical step-by-step process beginning with establishing the objectives and ending with pre-determined action based on the data obtained. General considerations for design of instrumentation systems are discussed by ICOLD (1969), USACE (1989a), and USCOLD (1986). Basic steps involved in the process are described below. The process is discussed in more detail by Dunnicliff (1982, 1988, 1990) and USCOLD (1986). Dunnicliff (1988, Appendix A) gives a checklist of steps for planning an instrumentation system.

9-5.1 Project Conditions

The initial step in any instrument system design is to establish the site conditions. At existing dams, all information available about the design, construction, and performance of the dam should be reviewed. At proposed dams, groundwater levels, foundation stratigraphy, dam design, and construction methods should be reviewed. Areas of potential weakness and their potential effects on the stability of the dam should be identified. Often some type of instrumentation, such as piezometers, will be used to help identify site conditions.

9-5.2 Purpose of Instrumentation

The next step is to define the purpose of all existing and proposed instrumentation. All instrumentation should have a specific purpose. The designer should understand what data will be generated by the instrumentation and how the data will be used. If there is not a valid purpose for the instrumentation, it should be abandoned or should not be installed.

There are a variety of valid purposes for using instruments to monitor dams. Minimum instrumentation provides the basic engineering measurements required to adequately assess dam stability and to monitor indications of developing problems. Additional instruments might be required to confirm design assumptions and to evaluate performance by comparing measured to predicted behavior during construction, first filling, rapid drawdown, and long-term operation. Instruments can be installed to support operations, to evaluate specific conditions at a site, or to obtain data for design or evaluation of remedial repairs.

Dams with complex foundations, known geologic anomalies, unique designs, marginal design criteria, or unconservative assumptions usually require more instrumentation to demonstrate satisfactory performance than dams without those features.

9-5.3 Types of Measurements

The types of measurements that are commonly monitored at a dam site are discussed in Section 9-3. They include headwater level, tailwater level, pore pressure, uplift pressure, seepage, leakage, surface movement, internal movement, crack or joint movement, stress, strain, temperature, and seismic loads. The magnitude and expected ranges of the parameters should be estimated to allow selection of the proper instruments. Levels that indicate the development of potentially hazardous conditions should be established during instrumentation system design.

9-5.4 Types of Instruments

Usually there are several commercially available instruments for each type of measurement required. When selecting instrumentation, the major consideration should be reliability and not cost. Reliability encompasses a variety of factors including simplicity, durability, longevity, precision, accuracy, and a length of satisfactory performance history. The relative importance of each of the factors depends on the purpose of the instrument. Instruments appropriate for use during construction may be different than those for long-term operation. For example, piezometers that have very short time-lag, but limited life, may be appropriate for control of construction operations, whereas longevity may be more important for long-term monitoring.

The type of data acquisition — manual or automated — should be considered when choosing instruments. However, automated data acquisition systems should not be used to justify the use of inaccessible electrical transducers. Transducers that are accessible for calibration or replacement should be used wherever possible. For example, vibrating wire piezometers should not be used in preference to open standpipe piezometers just because the data will be acquired automatically. Open standpipe piezometers can be automated with accessible electrical transducers. For conditions for which access could be difficult (e.g. uplift pressures during floods), consideration should be given to using remotely read instruments.

The total cost should be considered when comparing alternative instruments or instrument systems. The total cost includes the instruments, installation, maintenance, longevity, monitoring, and data processing. The least expensive instrument does not necessarily provide the lowest life-cycle cost, especially if replacement instruments will have to be installed. Allocation of sufficient funds to cover the total cost of instrumentation during design phase can help avoid inadequate collection and evaluation of data due to lack of funds.

9-5.5 Location and Number of Instruments

Minimum instrumentation should be installed where behavior is expected to be representative of the dam as a whole. The number of instruments should be sufficient to provide a complete picture of the parameter being measured. Usually, minimum instrumentation should be installed along longitudinal or transverse sections of the dam.

Often, depending on access and equipment costs, it may be more cost-effective to install redundant instruments to account for the possibility of malfunction, than to replace inoperable instruments at a later date. For example, vibrating-wire piezometer transducers are relatively inexpensive and are often installed in pairs to provide continuity of data if one of the transducers should fail. If a sensor will be inaccessible for calibration or replacement, multiple sensors should be considered to provide redundancy.

Redundant measurements are also useful for verifying and evaluating unusual readings.

Redundancy can be provided by using additional lines of instruments, more closely spaced instruments, or different instruments to measure the same feature.

Instrumentation to monitor a particular area of concern should be placed along cross sections where the suspected behavior will most likely manifest itself. The results of structural analyses may indicate appropriate locations and numbers of instruments. Often additional cross-sections should be monitored adjacent to areas of concern to provide data for comparison and to aid in the evaluation of the extent and magnitude of the concern.

For new dams, the need to install instrumentation should be established early in the design phase and before the preparation of final construction drawings to avoid interference. For existing structures, as-built drawings and the location of equipment should be reviewed. Potential interferences with rebars, pipes, and gates should be identified prior to finalizing instrument drawings.

9-5.6 Procurement and Installation

Typically, once the type and quantity of instruments have been selected, a specification is prepared for their procurement and installation. Because many organizations are required by policy to select the lowest bid, it is important that the evaluation criteria are included in the technical specifications so that the best equipment can be obtained at the lowest cost. Consideration should be given to instruments that have been proven in the field in similar applications and have a record of reliability (as defined in Section 9-5.4), ease of testing and maintenance, suitable response time, and ease of installation in the specific locations chosen. In some cases, delivery times, repair policies, and the number of vendors providing the type of instrument, can be important. "Or equal" provisions in the specifications should be avoided since there is often a considerable difference between similar instruments made by different manufacturers. Proposed substitutions for specified instruments should be carefully evaluated and compared to the selection criteria.

Installation specifications should include detailed step-by-step procedures for installing and testing instruments. The installation should include an installation log to document "as-built" conditions. Where appropriate, calibration measurement, performance testing, and initial readings should be obtained during installation. Consideration should be given to the level of the contractor's experience with installing similar instruments in similar conditions that the contractor should have. A quality assurance program should be included in the specification.

Drilling to install instruments can potentially damage existing structures. Hydrofracturing of embankments can be caused by drilling and can lead to piping and loss of the reservoir. Drilling can intercept and destroy filter or transition zones in embankments, or damage drains, underground utilities, or other structures. Installation specifications should be carefully written and enforced to prevent damage to existing dams and appurtenances.

Instrumentation is often damaged by maintenance equipment or vandals. All instrumentation should be enclosed in lockable covers or should be otherwise protected. For example, the tops of embankment piezometers should be installed inside metal guard pipes with locking covers. Embankment survey measuring points should be sturdy enough so that they will not be damaged by mowing equipment or should be protected with guard poles.

9-5.7 Monitoring Program

A monitoring program that includes responsibility assignments and procedures for data collection, reduction, processing, and presentation should be developed and documented. Responsibility for collecting, reducing, and evaluating the instrumentation data should be assigned to specific groups or individuals. Specific step-by step procedures for setting up equipment, taking measurements, recording data, and field screening data should be included. This information may be provided by the supplier. The monitoring program should include steps for reporting the monitoring results through responsible management personnel and a system to ensure timely response to problems disclosed in the surveillance and evaluation of data.

Personnel who perform visual observations, and collect, reduce, and evaluate data, should be given basic dam safety training. The training should include as a minimum, common causes of dam failures and incidents, identification of signs of potential distress by visual observation, and actions to be taken when unusual conditions, signs of potential distress, or emergency conditions occur. A series of videotapes and workbooks known as Training Aids for Dam Safety (TADS) are available from the USBR.

For manual data acquisition, data sheets should be developed to use for recording instrument data. All data sheets should show the project name, instrument type, and instrument location. They should have places to record the date, time, operator, data, and comments. The sheets should also have places to record complementary data such as headwater and tailwater levels, weather, rainfall, snowfall, temperature, and any unusual conditions. Examples of data sheets are included in USBR (1987a and 1987b) and USACE (1987b).

Threshold limits and the criteria used to develop them should be documented in the monitoring program. Threshold limits should be established based on the specific circumstances. In some cases, they 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 measured behavior (e.g. seepage from an embankment dam). Sometimes they may be used to identify unusual readings, readings outside the limits of the instruments, or readings which, in the judgement of the responsible engineer, demand evaluation. Both magnitude and rate of change limits should be established.

Threshold limits are intended to provide checks and balances in a monitoring program. Readings that exceed threshold limits do not necessarily mean that drastic action must be taken, only that some action must be taken. The monitoring program should include action to be taken if an instrument reaches its threshold limit. However, predetermined actions are no substitute for situation specific responses and should only be used as a guideline. Actions to be taken upon exceeding a threshold limit depend on the particular circumstances, but might include a combination of the following.

- Notify the responsible engineer.

- Confirm the reading by retaking it, and where possible, confirm the instrument calibration by the use of redundant readings.

- Inspect the dam.

- Evaluate the situation and revise the threshold limit.

- Increase the frequency of readings to monitor and provide data to further evaluate the situation.

- Implement investigative measures such as the installation of additional instruments.

- Implement remedial measures such as cleaning foundation drains, repairing damage, or modifying the dam.

- Implement emergency measures such as drawing down the reservoir.

The monitoring program should include requirements for establishing initial or baseline measurements. Since most data are compared against these measurements, it is important that they are correct. A minimum of three and preferably more measurements should be taken. The readings should meet expected values and accuracy. If they do not, the equipment should be checked and additional readings should be taken until readings meet expected values and accuracy or the measured values can be justified.

Some instruments such as piezometers, and some types of strain gages, take a significant amount of time to stabilize after installation due to drilling effects, lag time, or temperature. For these instruments, daily or more frequent readings should be taken until the readings have stabilized.

9-5.8 Documentation

An instrumentation document should be developed that includes a discussion of the purpose of each instrument, expected ranges of data, threshold limits, manufacturers' literature, procurement and installation specifications, installation logs, calibration data and initial readings. Plan and section drawings showing the number, location and details of each instrument should be included in the document. Appropriate subsurface stratigraphy should be shown on the drawings.

Details of subsurface conditions and construction should be documented for all proposed dams and remedial work at existing dams.

9-5.9 Maintenance and Calibration

A routine of regular maintenance of instruments, readout devices, and field terminals should be established. For many instruments, manufacturers will suggest maintenance procedures and schedules that should be followed unless there is adequate justification to alter them.

Periodic calibration of all instruments is necessary to provide accurate data. Detailed measurements and careful evaluation of data has little value, and may be misleading, if the data are inaccurate. The nature and frequency of calibration depends on the specifics of the instrumentation and should be developed on a case-by-case basis.

Instruments that are suspected to be malfunctioning should be tested to evaluate whether or not they are functioning properly, as discussed in section 9-7.4.

If the responsible engineer determines that an instrument no longer provides useful or meaningful information, it should be abandoned as discussed in 9-7.4.

9-6 Monitoring Schedules

Typical monitoring schedules are discussed in this section. The schedules are considered to be generally applicable for all significant and high-hazard dams; however, since each dam is unique, the schedules should be applied using engineering judgement and common sense. For example, more frequent readings of reservoir level should be taken at pumped storage projects. Table 9-6 summarizes typical frequencies of measurements for various stages in the life of a dam. Specific monitoring schedules should be developed on a case-by-case basis.

The types of measurements listed in Table 9-6 are the same as used for minimum instrumentation. Visual observation is listed as a type of measurement to emphasize its importance. Frequent visual observation by trained personnel will often detect unusual conditions, such as increased seepage, or cloudy seepage, or large movements, before instrumentation readings taken at widely spaced points and at long intervals would reveal such conditions or where no instrumentation exists.

During construction, the dam and foundation are adjusting to such factors as self-weight, thermal loads, seepage, and any unusual conditions. Measurements should be taken frequently to allow construction operations to be adjusted to changing conditions. Less frequent measurements may be appropriate during construction shutdowns.

During first filling, the dam and foundation are adjusting to the reservoir load. Monitoring frequencies should depend, in part, on the rate of filling. In the first few years of operation following first filling most dams have not reached equilibrium with respect to self-weight, concrete thermal load, reservoir load, seepage forces, and pore pressure/uplift. Measurements should be taken frequently because most dam failures and incidents occur during these periods.

Even though existing dams have generally reached equilibrium with imposed loads, baseline data must be obtained to compare with subsequent measurements. Therefore, the frequency of measurements shown for first, second, and third years apply to new instrumentation installed at existing dams.

After a dam has substantially adjusted to imposed loads, the frequency of readings can be reduced to that shown in Table 9-6. Further reduction of frequency may be justified in some cases. For example, after surface settlement of an embankment dam has ceased or become very small, surveys every 2 to 5 years may be adequate. The frequency of measurements shown in the table for long-term operation assumes that the performance of the project is satisfactory.

More frequent measurements than shown in the table should be made whenever an unusual situation develops or whenever they will help to resolve a dam safety concern. For example, when the reservoir is abnormally raised or lowered (whether for a specific reason or because of flood surcharge), frequent readings during the raising or lowering should be made, plotted, and compared to expected behavior in order to identify any potentially unusual behavior. Examples of other situations requiring more frequent measurements include sustained high reservoir levels, earthquakes, unusual movements, abnormal measurements, threshold measurements exceeded, new cracks, new seeps, and new leaks. Following resolution of the problem or concern, measurements should return to the normal schedule.

TABLE 9-6

TYPICAL MONITORING SCHEDULE FOR SIGNIFICANT AND HIGH-HAZARD POTENTIAL DAMS [1]

TYPE OF MEASUREMENT[2]	FREQUENCY OF MEASUREMENTS				
	CONSTRUCTION	FIRST FILLING	FIRST YEAR AFTER FILLING	SECOND AND THIRD YEARS	LONG-TERM OPERATION
VISUAL OBSERVATION	Daily	Daily	Weekly	Monthly	Monthly
RESERVOIR LEVEL	-	Daily to Weekly	Semi-monthly and at same time as any other measurements	Monthly and at same time as any other measurements	Monthly to quarterly and at same time as any other measurements
TAILWATER LEVEL	-	Weekly	Semi-monthly and at same time as any other measurements	Monthly and at same time as any other measurements	Monthly to quarterly and at same time as any other measurements
DRAIN FLOW	-	Daily to Weekly	Weekly to monthly	Monthly	Monthly to quarterly
SEEPAGE/ LEAKAGE FLOW	Monthly	Daily to Weekly	Weekly to monthly	Monthly	Monthly to quarterly
PORE PRESSURE/ UPLIFT	Daily to Weekly	Daily to weekly	Monthly	Monthly	Monthly to quarterly
SURFACE SETTLEMENT	-	Monthly	Quarterly	Semi-annually to annually	Semi-annually to annually
SURFACE ALIGNMENT	-	Daily to monthly	Quarterly	Semi-annually to annually	Semi-annually to annually
INTERNAL MOVEMENT	-	Weekly to Monthly	Monthly to quarterly	Monthly to semi-annually	Monthly to annually
JOINT/CRACK DISPLACEMENT	-	Weekly to Monthly	Monthly to quarterly	Monthly to semi-annually	Monthly to annually

TYPE OF MEASUREMENT[2]	FREQUENCY OF MEASUREMENTS				
	CONSTRUCTION	FIRST FILLING	FIRST YEAR AFTER FILLING	SECOND AND THIRD YEARS	LONG-TERM OPERATION
FOUNDATION MOVEMENT	Weekly	Weekly to Monthly	Quarterly	Semi-annually	Semi-annually to annually
TEMPERATURE	Hourly to weekly	Weekly	Semi-monthly	Monthly	Typically not required
LOADS IN POST-TENSIONED ANCHORS	Typically not required	Typically not required	Annually	Typically not required	Quinquennially

[1] Refer to Section 9-6 for a discussion of monitoring schedules. Readings should be taken following major events such as earthquakes and floods. More frequent readings should be taken as needed to address specific concerns.

[2] Refer to Sections 9-3 and 9-4 for discussion of types of measurements, and minimum instrumentation.

Schedules should be arranged so that all instrumentation data are collected at the same time to facilitate correlation between the measurements. For example, measurements that are taken quarterly should be taken on the same day as measurements that are taken monthly.

Infrequent measurements should be scheduled to coincide with maximum and minimum reservoir, thermal, or other significant loads on the dam. For example, semi-annual measurements might be taken to coincide with low and high reservoir levels or minimum and maximum temperatures, and annual measurements might be taken to coincide with high reservoir levels.

Data should be collected from instrumentation immediately after installation. This is especially true of movement measurement devices, because all subsequent measurements will be subtracted from the initial reading to calculate movement.

For concrete dams where thermal loads can be significant, internal movement and crack/joint movement measuring devices should be read early in the morning to reduce the influence of daily temperature changes and solar radiation. Where it can be done safely, precise surveys for surface movements should be done in the early morning, just before sunrise, to avoid visual distortion due to heat waves and wind currents.

9-7 Data Processing and Evaluation

This section is written assuming data are collected manually. Automatic data acquisition is becoming more common and is discussed in Section 9-8. The steps required to process and evaluate data, whether collected manually or automatically, are the same.

Instrument data should be processed and evaluated according to the procedures established by the monitoring program. Accumulation of instrument data by itself does not improve dam safety or protect the public. Data must be conscientiously collected, meticulously reduced, graphically summarized, and interpreted in a timely manner. Data must be evaluated with respect to the safety of the dam. A poorly planned program will produce unnecessary data that the dam owner will waste time and money collecting and interpreting, often resulting in disillusionment and abandonment of the program. A typical monitoring program would include the steps discussed below. Example data collection forms, data tables, and data plots, are provided in Appendix B.

9-7.1 Data Collection

Data collected manually should be recorded on the data sheets prepared as part of the monitoring program. Complementary data, such as air temperature, reservoir level, reservoir temperature, recent precipitation, and other information or observations that may be important in evaluating the instrumentation data should be noted on the data sheets. Data should be compared against previous measurements and threshold limits in the field to identify erroneous measurements. Measurements that are outside of normal scatter or threshold limits should be immediately retaken.

Personnel collecting data should be trained in the operation of the instruments, the importance of the data and the need for proper documentation. They should be trained to identify improperly functioning instruments based on measured data or visual observations. They should be aware of the procedures to follow, should unusual or threshold measurements occur.

Personnel collecting data should visually observe the dam for indications of poor performance such as offsets, misalignment, bulges, depressions, seepage, leakage, change in color of seepage or leakage, and cracking.

All monuments and measuring points should be inspected during data collection for evidence of damage or movement from external sources such as frost heave, impact from maintenance equipment, or vandalism. The assumption is made during data reduction and interpretation that the survey control monuments have not moved and that any movements of the measuring points represent movement of the structure.

9-7.2 Data Reduction

Most instruments require raw data to be converted into useable engineering units. The arithmetic calculations required to convert data are known as data reduction. The data reduction may be done in the field or office. It should be done under the supervision of the responsible engineer and it should be checked by someone other than the preparer to reduce errors. Reduced data should be summarized in tabular form showing the date, time, measurements, and comments. Spreadsheet type software is readily available and can facilitate this step.

Reduced data should be reviewed for measurements that are significantly different from previous measurements and for data exceeding threshold limits. Usually this step should be taken within a few days of collecting the data. Any questionable measurements should be retaken. If any of the data reach threshold limits, pre-planned actions established in the written monitoring program should be taken.

9-7.3 Data Presentation

Plots facilitate screening of data and comparison with expected data. Plots are also useful to summarize data. All reduced data should be summarized in graphical form. All plots should include sufficient previous data to identify any long-term trends. Furthermore, the plots should be self-explanatory. They should show the project name, type of instrument, and what is being measured. If more than one set of data are on one plot, different symbols or line types should be used to distinguish the data and a legend should be provided. Scales should be consistent to allow comparison of data between plots and they should be labeled. Threshold limits, scatter, and magnitude of significant changes should be considered when selecting scales. Plan and section drawings showing the number, location, and details of each instrument should be included with the plots. Where practical, threshold limits should be shown on the plots. Plotting software is available to facilitate this step.

The best type of plot depends on the purpose of the instrument(s) and should be selected on a case-by-case basis. Generally data versus time plots are good for displaying piezometric, seepage, and most movement data. Location versus movement graphs are preferable for surface movement data and some internal movement data. Often more than one type of plot is useful for evaluating data.

Factors that have significant influence on instrument data should be plotted or noted on the data plots. For example, reservoir and tailwater levels should be included on all post-construction piezometer plots, or they should be included as separate plots to the same scale as the piezometer plots. Other factors that might be included on the plots are the height of the dam during construction, daily temperature, rainfall, and seismic events.

9-7.4 Data Interpretation

Data should be reviewed for reasonableness, evidence of incorrectly functioning instruments, and transposed data. Several checks for reasonableness can be made on all 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. 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. Open standpipe readings at the top of the pipe are ambiguous because the phreatic surface could be exactly at the top of the pipe, or it could be well above the pipe. The standpipe must be raised or have a pressure gage added to it to clarify the reading. Whenever the phreatic surface is above the top of a standpipe it may indicate a developing problem and should be investigated.

It is important to distinguish between accuracy and precision when dealing with measurements. Accuracy is the nearness to the true value. Precision is the degree of refinement of 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.

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.

All data will 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. 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 more frequent readings. Erroneous readings should be so noted on the original data sheets and should be removed from summary tables and plots.

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.

Instruments that do not appear to be functioning properly should be further investigated. For example, data should be checked against redundant data 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 expected behavior.

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 or that provide unnecessary redundancy should be abandoned.

Abandonment procedures should be evaluated on a case-by-case basis. They may consist of a variety of actions such as:

- ceasing readings and maintenance;
- ceasing readings, but continuing minimal maintenance to keep the instrumentation in a safe condition;
- plugging and sealing the instrument; and
- removing the instrument and repairing the hole.

If the abandoned instrument remains in place, it should be clearly marked as such to avoid continued collection of data.

9-7.5 Dam Performance Evaluation

The purpose of instrumentation and monitoring is to maintain and improve dam safety. The data should be used to evaluate whether the dam is performing as expected and whether it provides a warning of developing conditions that could endanger the safety of the dam.

The licensee's responsible engineer should evaluate dam performance for each set of data. Additionally, during Part 12 Safety Inspections, the Independent Consultant will evaluate the dam performance using the data.

All data should be compared with threshold levels established in the monitoring program (Section 9-5.7). Trends of measurements toward threshold levels should be identified and evaluated. If threshold levels will be reached within a short time, investigations and remedial action should be implemented.

All data should be compared with expected behavior based on the basic engineering concepts that were discussed in section 9-3. Variations from expected behavior may suggest development of conditions that should be evaluated. For example, at a concrete gravity dam, increasing uplift pressure, or decreasing drain flow may indicate that the foundation drains may 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.

More than one phreatic surface may exist where there are impervious strata in the foundation. Piezometric data should be evaluated with geologic data to identify multiple phreatic surfaces. If the phreatic surface for any strata is above the ground surface, the stability of the dam should be evaluated using the elevated phreatic surface.

If no unusual behavior or evidence of problems is detected, the data should be filed for future reference. If 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:

- 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
- emergency lowering of the reservoir.

9-7.6 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.

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?

The licensee's responsible engineer should evaluate the adequacy of instrumentation and monitoring for each set of data. Staff will evaluate the adequacy of instrumentation during annual Operation Inspections. Additionally, during Part 12 Safety Inspections, the Independent Consultant will evaluate the adequacy of instrumentation and monitoring.

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 it is often useful to perform field investigations and install additional instrumentation to evaluate the 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 the potential impacts with respect to dam safety. A dam safety program is inadequate if the performance of a dam is not understood. Instrumentation provides the means for that understanding.

9-8 Automated Data Acquisition

Automated data acquisition systems (ADAS) have evolved significantly over the last 10 years and are currently installed on over 40 dams in the United States. Most of the dams are owned by federal agencies (USACE, USBR, and TVA). Design of successful ADAS requires considerable effort. ADAS can range from the simple use of a datalogger to collect data from a few instruments to computer based systems that collect, reduce, present, and interpret data from a network of hundreds of different instruments. Most types of water level, water pressure, seepage, leakage, stress, strain, and temperature instrumentation can be readily monitored. Some types of instrumentation such as movement surveys and probe inclinometers cannot be automated.

Advantages of automated data acquisition include: reduced manpower costs for collecting data, remote collection of data, and data collection in electronic format suitable for computer reduction, analysis, and printout. Rapid notification of potentially hazardous performance and increased frequency of measurements can be taken on demand.

Disadvantages include high initial costs and complex equipment. By far the greatest disadvantage is that visual observations normally made during routine manual data collection will not be made.

Basic requirements of successful ADAS, according to USCOLD 1993, are listed below.

- Each instrument or sensor should maintain the ability to be read manually and electrically prior to entering the automated network.

- There should be a redundant system for critical and very important instruments.

- The automated system should have a central network monitor station at the project office to manage the field system and provide an external communications interface. This station must also be able to collect, process, validate, display, and produce hard copy of all data at the project.

- A primary and backup external communications link for data transmission should be provided.

- The system should have multiple, redundant systems of lightning protection that isolate various components of the systems from the inevitable lightning strike-induced power surge. Grounding and shielding of all cables is mandatory.

- A primary and backup power source should be provided for uninterrupted data collection (this is usually in the form of a rechargeable battery, together with some form of reliable charging method such as solar panels).

- The systems should be protected from vandalism by protection inside a structure or by burial in specifically designed units.

USCOLD (1993) discusses whether ADAS is appropriate; the design, installation, and operation of ADAS; case histories; and provides a list of ADAS vendors. Other references include ICOLD (1982) and USACE (1985, 1986b, 1986c, 1986d, 1987b, 1988, 1989b, and 1990).

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9-10 APPENDICES

APPENDIX IX-A

Examples of Minimum Instrumentation

Appendix A
Examples of Minimum Instrumentation

Case histories of instrumentation are provided in Dunnicliff (1981), ICOLD (1989 and 1992), USCOLD (1986) and Wilson (1979). Illustrative examples are provided in Dunnicliff (1988) and USBR (1990). Examples illustrating these instrumentation and monitoring guidelines are given in the following appendices for an existing and proposed embankment dam and an existing and proposed concrete dam.

Example 1. Minimum Instrumentation for an Existing Embankment Dam

Figure A-1 shows a plan and section of an existing 46-foot-high homogeneous embankment dam. A small toe drain had been constructed previously in order to lower the phreatic surface. The foundation is semi-pervious alluvium. There is no grout curtain and no instrumentation was installed in the dam when it was constructed.

Minimum recommended instrumentation is shown on Figure A-1. The headwater and tailwater levels are measured with a staff gage located on the separate spillway on the left abutment (not shown in figure). Seepage from the toe drain is collected by a pipe and is measured with a calibrated container.

Several observation wells had been installed in the embankment during the toe drain construction. Since then, the phreatic surface has remained below the embankment surface. Though installation of the observation wells would not be required by the guidelines, monitoring of them provides useful information. Therefore, the existing observation wells are used to monitor the phreatic surface and the performance of the toe drain.

Well points were added at the toe of the embankment dam to evaluate seepage conditions. Underseepage existed as a result of a more pervious layer in the foundation. Several years after the well points were added, seepage was observed along the toe of the dam. A weighted reverse filter was placed over the seepage area while plans for a new toe drain were being developed.

Survey monuments and measuring points were established for a horizontal and vertical movement survey of the crest of the dam. The survey monuments were established on each abutment. The measurement points were located near the downstream edge of the crest at approximately 250-foot intervals.

No foundation movement instrumentation was installed because the alluvium was judged to be stronger than the embankment material, the factors of safety against sliding were adequate, and there was no evidence of structural distress.

Example 2. Minimum Instrumentation for a Proposed Embankment Dam

Figure A-2 shows a plan and section of a proposed 180-foot-high embankment dam. The dam is a zoned type with a central core, chimney and blanket drains, random fill shells, and a semi-pervious upstream fill. The foundation is a horizontally interbedded sandstone and siltstone with occasional clay seams overlain by alluvium. A single line grout curtain is located beneath the core trench.

Minimum recommended instrumentation is shown on Figure A-2. The headwater and tailwater levels will be measured with staff gages located on the separate spillway on the left abutment (not shown in figure). Seepage from the chimney and blanket drain will be collected by a pipe and measured with a portable flume.

Two transverse lines of instrumentation will be installed because of the length of the dam. The designer anticipates that the core material will consolidate rapidly. An array of pneumatic piezometers will be located in the core to verify this design assumption. These piezometers will be used for construction control and will be abandoned after consolidation of the core is complete.

Pneumatic piezometers will be located in the alluvium beneath the blanket drain to monitor its operation. Several additional pneumatic piezometers will be located beneath clay seams in the sandstone to monitor the pore pressures in the foundation. Two sensors will be located in each piezometer for redundancy.

Survey monuments and measuring points will be established for a horizontal and vertical movement survey of the crest and downstream slope of the dam. The survey monuments will be established on each abutment. The measurement points will be located near the downstream edge of the crest at approximately 250-foot intervals through the major portion of the embankment and 500-foot intervals elsewhere.

The designer is concerned about potential movement of the dam along the clay seams in the foundation, therefore, several inclinometers will be installed to monitor for this type of movement. To avoid drilling through the blanket drain, in-place inclinometers will be used. Shear strips will be installed adjacent to each in-place inclinometer for redundancy.

Example 3. Minimum Instrumentation for an Existing Concrete Gravity Dam

Figure A-3 shows a plan and section of an existing 88-foot-high concrete gravity dam. The dam has a center overflow spillway and a gallery that extends through the tallest sections. The foundation is horizontally interbedded sandstone and shale. A single-line grout curtain and row of foundation drains extend into the foundation from the gallery. No instrumentation was installed in the dam when it was constructed.

Minimum recommended instrumentation is shown on Figure A-3. The headwater and tailwater levels are measured with staff gages located on the left side of the spillway.

Seepage from the internal formed drains and the foundation drains is collected by the gutter along the gallery. Weirs were installed in the gutter adjacent to the gutter drain at the center of the spillway.

Since a reduction in uplift pressure at the line of drains is needed to meet stability criteria, standpipe piezometers were installed to verify the reduction. One piezometer was installed midway between two drains in the maximum section near the center of the spillway. At least one additional piezometer downstream of the line of drains would be desirable. Installation of a downstream piezometer from the gallery would be difficult because of the narrow confines of the gallery. Installation of a piezometer from the surface of the spillway would leave it exposed to possible damage from spillway flows. Therefore, a piezometer was installed from the downstream face in the adjacent non-overflow section. Uplift pressures at the non-overflow section were judged to be representative of the maximum section because the foundation geology of both sections is similar. A second piezometer was installed midway between two drains in the non-overflow section as a check on the assumption of similar uplift pressure between the two sections and to provide some redundancy.

The borings for the piezometers were extended into the foundation to document foundation conditions and obtain samples for laboratory testing. A horizontal shale seam, found about 20 feet below the base of the dam, was judged to be a potential sliding plane. Pressure measurements in the borings showed increased uplift pressures immediately below the seam. Therefore, piezometers were installed immediately below the seam.

Survey monuments and measuring points were established for a horizontal alignment survey of the crest of the dam. The survey monuments were established on each abutment. The measurement points were located on either side of the spillway and at approximately 100-foot intervals.

Crack meters were installed on the ceiling of the gallery to monitor potential movement in the transverse direction. There were no cracks that were judged to be evidence of structural distress so no additional crack meters were installed.

No foundation movement instrumentation was installed because even though the foundation contains a shale seam, the factors of safety against sliding were adequate and there was no evidence of structural distress.

Example 4. Minimum Instrumentation for a Proposed RCC Gravity Dam

Figure A-4 shows a plan and section of a proposed 120-foot-high RCC gravity dam. The dam has a center overflow spillway and a gallery that extends through the tallest sections. The foundation is massive granite. A single-line grout curtain and row of foundation drains extend into the foundation from the gallery.

Minimum recommended instrumentation is shown on Figure A-4. The headwater and tailwater levels will be measured with staff gages located on the left side of the spillway.

Seepage from the internal formed drains and the foundation drains will be collected by the gutter along the gallery. Weirs will be installed in the gutter adjacent to the gutter drain at the center of the spillway.

Since a reduction in uplift pressure at the line of drains is needed to meet stability criteria, standpipe piezometers will be installed to verify the reduction. Two transverse lines of two piezometers each will be located in the spillway. The granite foundation contains several sub-horizontal exfoliation joints that could potentially be a path of seepage. Piezometers will be installed in the foundation at the location of the exfoliation joints to monitor pressure in the joints.

Survey monuments and measuring points will be installed for a horizontal alignment survey and settlement survey of the crest of the dam. Survey monuments will be established on each abutment and measurement points will be located on either side of the spillway and at approximately 150-foot intervals.

Crack meters will be installed on any significant cracks to monitor potential vertical, longitudinal, and transverse movement. No internal or foundation movement instrumentation will be installed because the foundation is strong and competent. An array of thermocouples will be installed to monitor the heat of hydration gradient during construction.

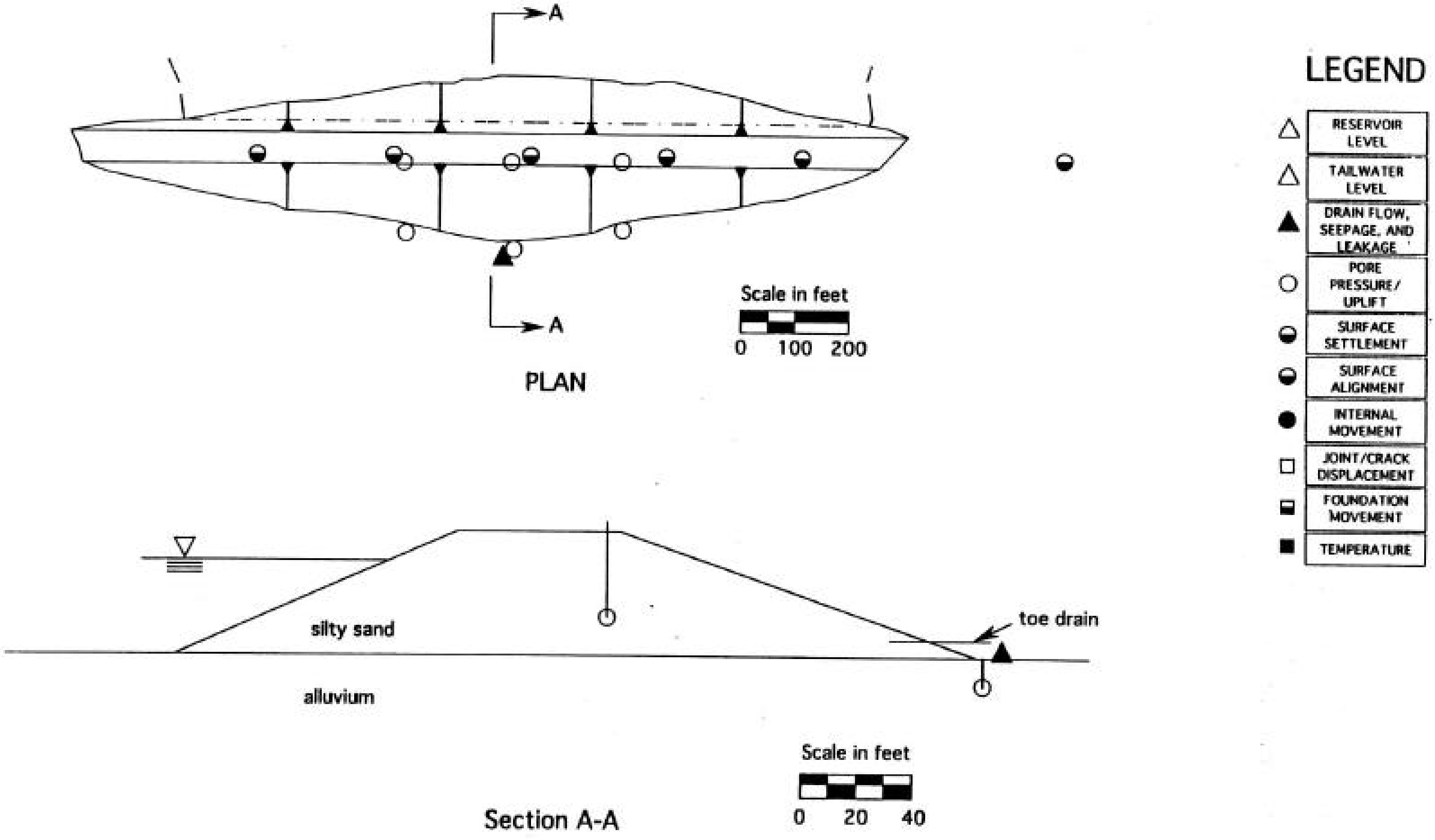


FIGURE A-1. EXAMPLE OF MINIMUM INSTRUMENTATION FOR AN EXISTING EMBANKMENT DAM

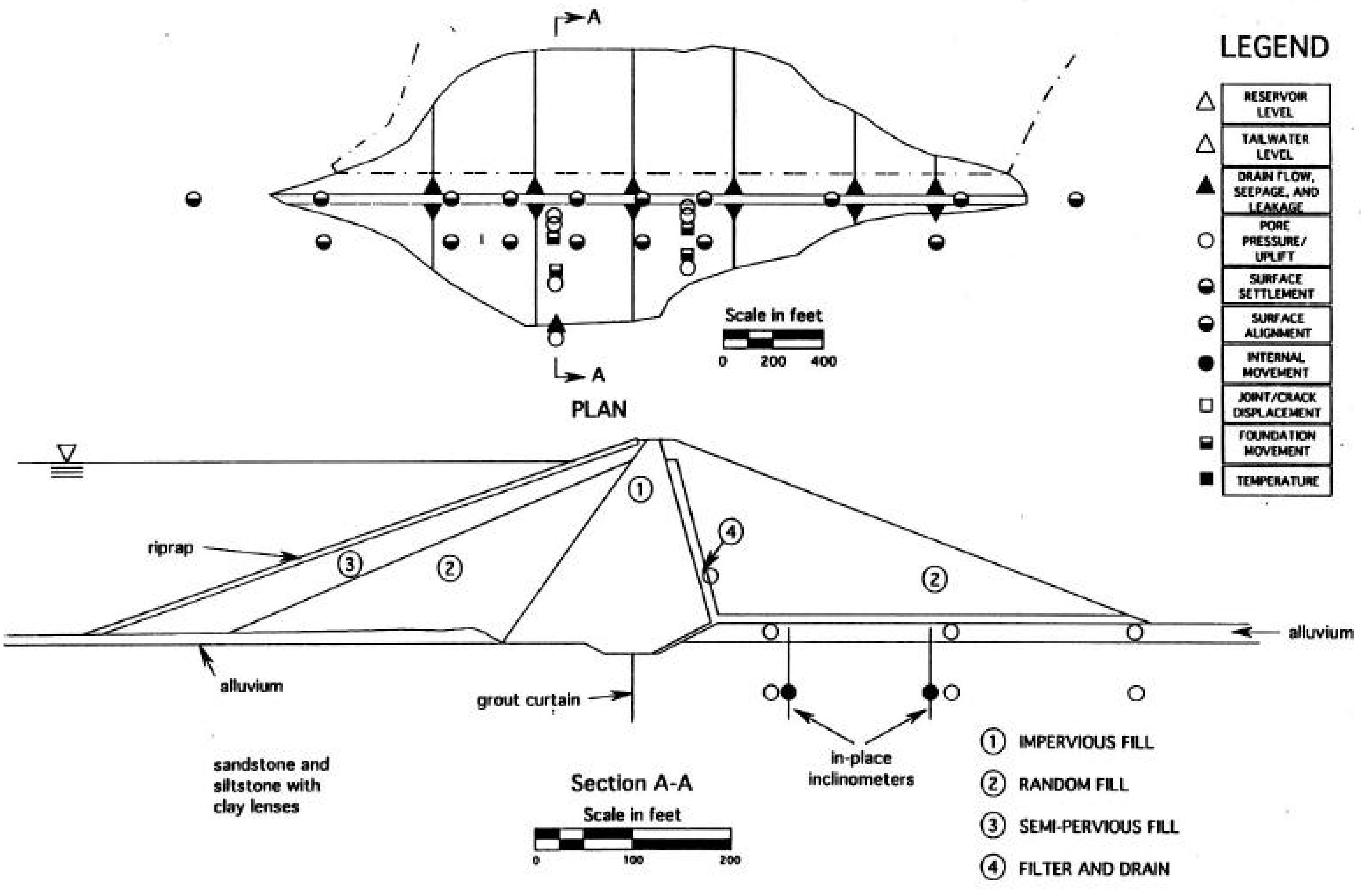
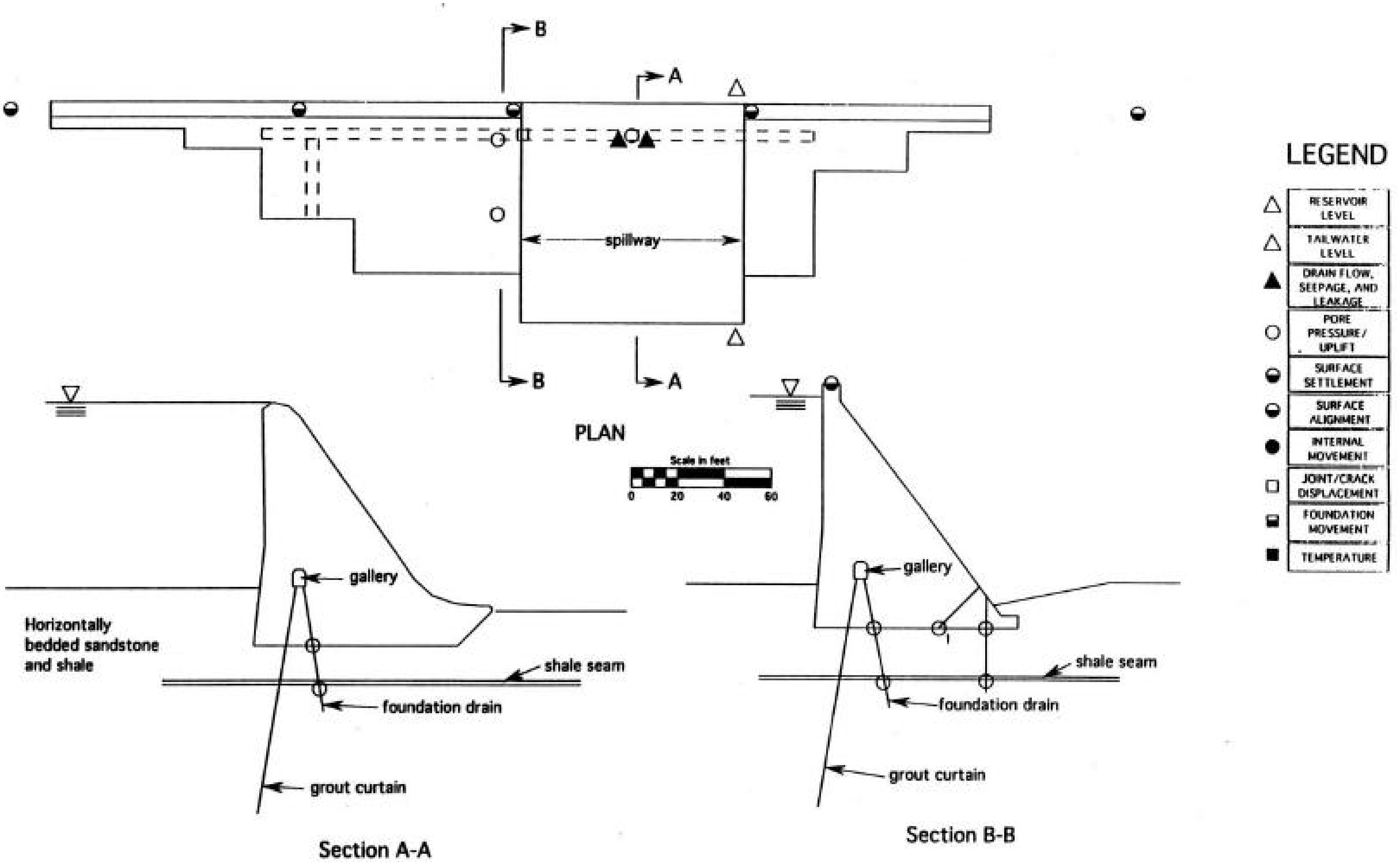
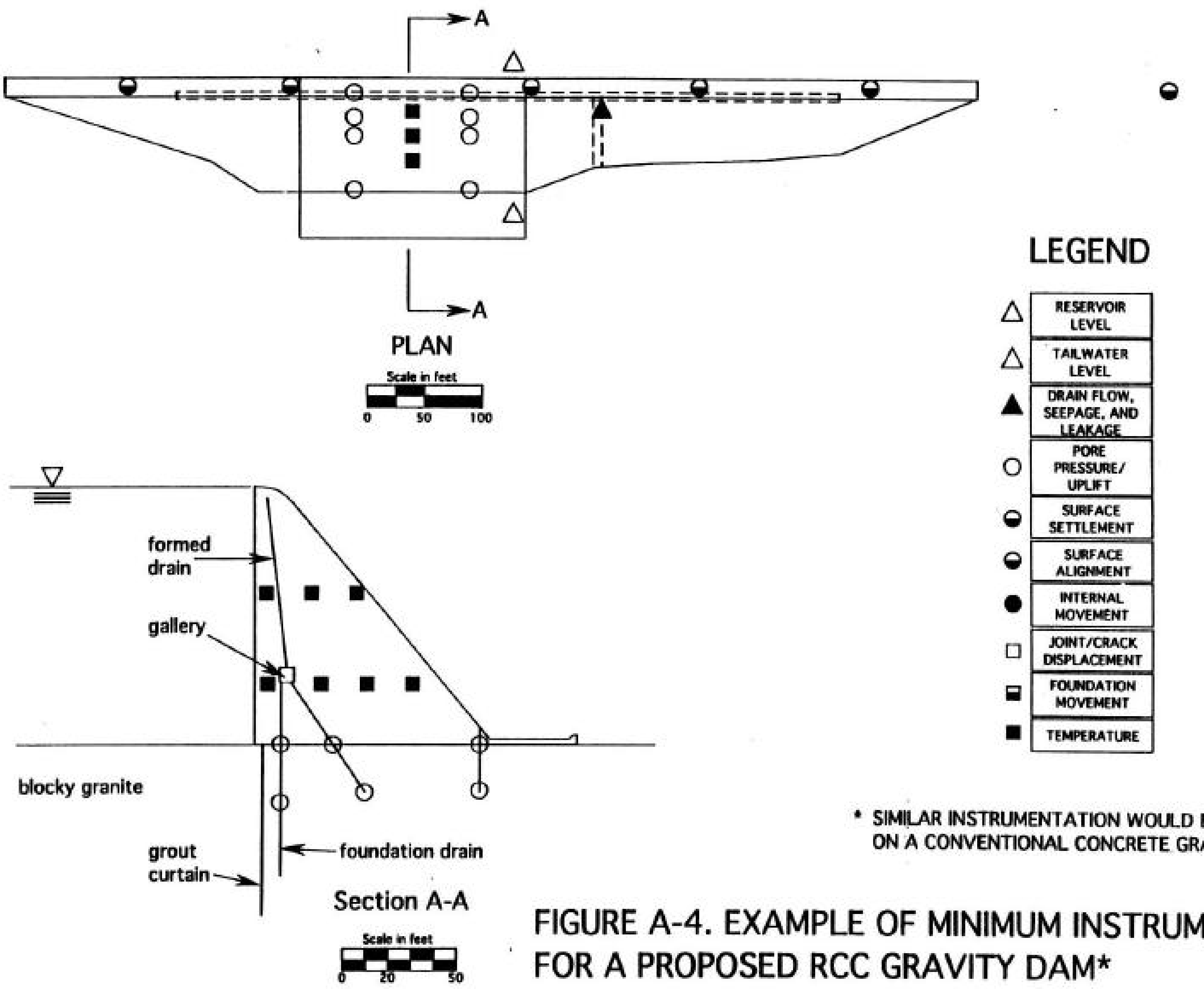


FIGURE A-2. EXAMPLE OF MINIMUM INSTRUMENTATION FOR A PROPOSED EMBANKMENT DAM



GURE A-3. EXAMPLE OF MINIMUM INSTRUM TATION
R AN EXISTING CONCRETE GRAVITY DAM



* SIMILAR INSTRUMENTATION WOULD BE REQUIRED ON A CONVENTIONAL CONCRETE GRAVITY DAM

FIGURE A-4. EXAMPLE OF MINIMUM INSTRUMENTATION FOR A PROPOSED RCC GRAVITY DAM*

APPENDIX IX-B

Sample Data Presentation

Appendix B
Sample Data Presentation

Sample data collection forms, tables, and plots are illustrated in this appendix to show proper data presentation.

Instrument Plan

Figure B-1 is a plan of the dam showing instrument locations. There is a transverse line of piezometers through the maximum section and several observation wells near the abutments. Seepage is measured by a weir located approximately at the downstream toe of the maximum section.

Figure B-2 shows a section through the embankment along the line of piezometers. Pertinent embankment and foundation details are shown on the section.

Sample Data Collection Forms

Figure B-3 is a sample data collection form for the observation wells and piezometers. The upper portion of the form is for pertinent and complementary data. The lower portion is for the actual readings. Figure B-4 is a sample data collection form for the seepage measurements.

Sample Data Reduction Spreadsheet and Summary Tables

Figure B-5 shows a spreadsheet that reduces the observation well and piezometer data, checks the measurements against threshold levels and depth to the top and bottom of the standpipes, and summarizes the data in tabular form. Threshold limits are based on previous minimum and maximum readings.

The seepage weir data are reduced manually. Threshold limits for seepage data are based on the range of the instrument.

Sample Data Plots

Figures B-6 through B-8 are plots of the observation well and piezometer data. The instruments are grouped according to type and location. Embankment and alluvium piezometer data are plotted on Figure B-6. Headwater level is plotted along with the piezometer data. The piezometers respond to changes in headwater and piezometric levels decrease with distance downstream. It was assumed there was no tailwater, so it was not plotted. If there is tailwater, the licensee should plot it.

Embankment observation well data are plotted in Figure B-7. The data has slightly more scatter that the piezometer data. OW-2 responds markedly to the heavy rainfall that occurred in early May. Otherwise, the data are consistent with the piezometer data.

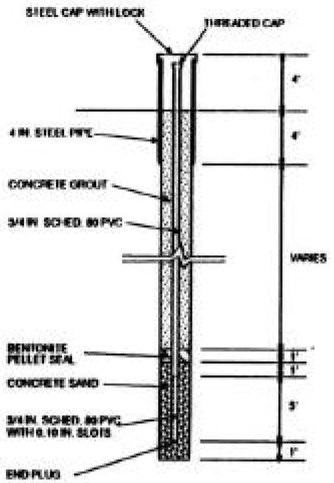
Foundation piezometer data are plotted in Figure B-8. The data respond to changes in reservoir level and piezometric level in the sandstone decreases with distance downstream.

Phreatic surface data for the highest reservoir level are plotted on Figure B-2. The phreatic surface in the embankment and alluvium are essentially the same and are shown by the long-dashed line. There is a distinct drop in the phreatic surface across the concrete core wall. The sandstone is isolated from the embankment by the shale layer, which acts as an aquiclude. The phreatic surface for the sandstone layer is shown by the short-dashed line. It is not affected by the presence of the core wall.

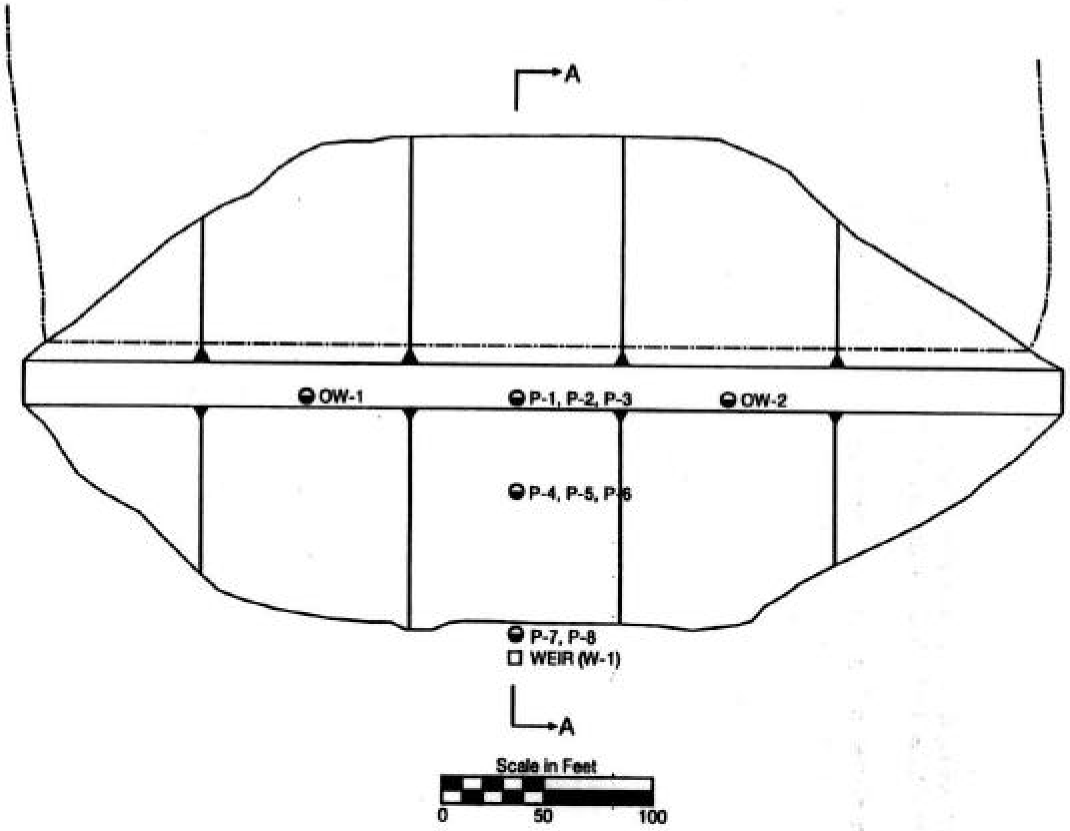
The seepage data are plotted in Figure B-9. Seepage approximately follows headwater, but is influenced by surface runoff from rainfall. Although rainfall was not plotted, it is sometimes helpful to plot that data in order to understand changes in drainflows.

PIEZOMETER AND OBSERVATION WELL DATA

Piezometer/ Oservation well	Top of Pipe elevation, feet	Ground surface elevation, feet	Depth to bottom, feet	Screened length, feet
OW-1	887.2	883.8	55.8	4.5
OW-2	887.5	883.9	55.4	4.5
P-1	887.7	883.7	89.2	5.0
P-2	888.0	883.5	68.3	5.0
P-3	877.5	883.6	56.2	5.0
P-4	868.5	864.5	72.0	5.0
P-5	868.2	864.6	48.1	5.0
P-6	868.9	864.3	35.5	5.0
P-7	839 6	833.9	39.1	5.0
P-8	838.1	834.1	16.8	5.0



Detail of Piezometers
NTS



Sam Adams Dam PLan
FIGURE B-1. INSTRUMENT LOCATION PLAN

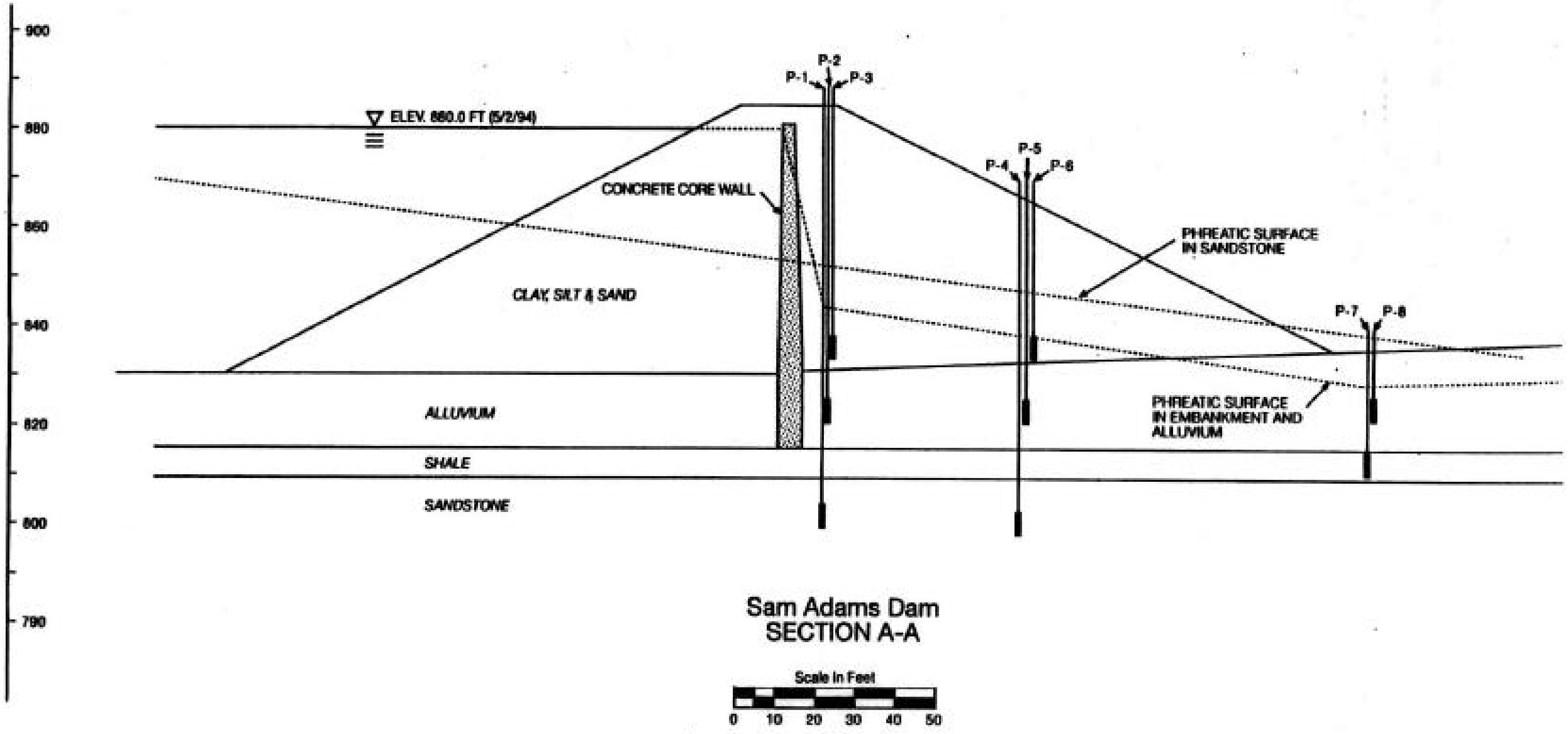


FIGURE B-2. INSTRUMENT LOCATION SECTION

SAM ADAMS DAM

OBSERVATION WELL AND PIEZOMETER DATA COLLECTION FORM

Date: Time: Personnel:

Weather:

Recent rainfall:

Headwater Elevation: __________ feet Tailwater Elevation: __________ feet

Visual Observations (unusual or abnormal conditions):____

____

____

READINGS

INSTRUCTIONS: Measure depth to water from top of standpipe with water level meter. Record depth to nearest 0.1 foot. Note under "COMMENTS" any difficulties in taking the measurements, need for repair, maintenance, etc. Compare readings with threshold limits and previous readings. If readings exceed threshold limits or are more than 3 feet different than previous readings, retake the readings to confirm them.

PIEZOMETER/ OBSERVATION WELL	THRESHOLD READINGS, FEET (MIN/MAX)	DEPTH TO WATER, FEET	COMMENTS
OW-1	41.9/54.8		
OW-2	38.9/53.6		
P-1	34.4/43.4		
P-2	44.1/54.3		
P-3	43.7/55.3		
P-4	20.8/28.0		
P-5	30.0/35.9		
P-6	30.6/36.5		
P-7	0.3/7.4		
P-8	9.3/12.4		

FIGURE B-3. PIEZOMETER DATA COLLECTION FORM

SAM ADAMS DAM

SEEPAGE WEIR DATA COLLECTION FORM

Date:	Time:	Personnel:

Weather:

Recent rainfall:

Headwater Elevation: ___________ feet Tailwater Elevation: ___________ feet

Visual Observations (unusual or abnormal conditions):____
____
____
____

READINGS

INSTRUCTIONS: Measure depth of water upstream of weir from invert of weir notch. Record depth to nearest 1/8 inch. Note under "COMMENTS" and difficulties in taking the measurements, need for repair, maintenance, etc. Compare readings with threshold limits and previous readings. If readings exceed threshold limits or are more than 2 inches different than previous readings, retake the readings to confirm them.

WEIR	THRESHOLD READINGS, INCHES (MIN/MAX)	DEPTH OF WATER, INCHES	COMMENTS
W-1	0/6.0		

FIGURE B-4. SEEPAGE DATA COLLECTION FORM

12/7/94 SAM ADAMS DAM prepared by: EPSMITH 12/7/94
16:45:38 OBSERVATION WELL AND PIEZOMETER DATA checked by: J. JONES 12/7/94
piezdatb.wk1

TABLE 1
PIEZOMETER AND OBSERVATION WELL DATA

INSTRUMENT	OW-1	OW-1	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8
TOP OF PIPE EL., FT.	887.2	887.5	887.7	888.0	887.5	868.5	868.2	868.9	839.6	838.1
BOTTOM DEPTH, FT.	55.8	55.4	89.2	68.3	56.2	72.0	48.1	36.5	39.1	16.8
MIN. THRESHOLD, FT.	41.9	38.9	34.4	44.1	43.7	20.8	30.0	30.6	0.3	9.3
MAX. THRESHOLD, FT.	54.8	53.6	43.4	54.3	55.3	28.0	35.9	36.5	7.4	12.4

TABLE 2
PIEZOMETER AND OBSERVATION WELL READINGS

DATE	HEAD WATER EL. FT.	TAIL WATER EL. FT.	OW-1	OW-2	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8
1/3/94	864.0	N/A	53.5	53.4	43.2	53.7	54.2	27.6	35.3	36.3	6.8	11.4
2/7/94	864.2	N/A	53.8	53.2	43.1	53.9	54.8	27.2	35.5	36.4	6.4	11.8
3/7/94	865.3	N/A	52.2	53.3	42.5	52.5	53.2	27.8	34.5	35.1	5.1	11.7
4/4/94	871.5	N/A	48.1	49.5	39.5	49.5	49.7	24.6	33.5	34.5	3.5	10.5
5/2/94	880.0	N/A	42.7	39.4	35.2	44.9	44.6	21.2	31.3	31.5	1.1	9.8
6/6/94	878.2	N/A	43.8	44.2	36.1	45.9	45.8	21.2	31.5	32.4	1.4	9.8
7/5/94	875.3	N/A	45.2	47.3	37.5	47.5	47.2	23.8	32.5	32.1	2.1	10.7
8/1/94	876.2	N/A	45.8	46.2	37.1	46.9	46.8	22.2	32.5	32.4	2.4	10.2
9/6/94	871.2	N/A	48.8	49.2	39.6	49.4	49.8	24.2	33.5	34.4	4.4	10.8
10/3/94	868.5	N/A	50.9	51.5	40.5	51.5	51.5	25.8	34.5	34.5	4.5	10.5
11/7/94	867.2	N/A	51.8	51.2	41.6	51.4	52.8	26.2	34.5	35.4	5.4	11.8
12/5/94	865.1	N/A	52.4	53.1	42.5	53.5	53.4	27.6	35.5	35.7	6.7	11.9

TABLE 3
PIEZOMETER AND OBSERVATION WELL ELEVATIONS

DATE	HEAD WATER EL. FT.	TAIL WATER EL. FT.	OW-1	OW-2	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8
1/3/94	864.0	N/A	833.7	834.1	844.5	834.3	833.3	840.9	832.9	832.6	832.8	826.7
2/7/94	864.2	N/A	833.4	834.3	844.6	834.1	832.7	841.3	832.7	832.5	833.2	826.3
3/7/94	865.3	N/A	835.0	834.2	845.2	835.5	834.3	840.7	833.7	833.8	834.5	826.4
4/4/94	871.5	N/A	839.1	838.0	848.2	838.5	837.8	843.9	834.7	834.4	836.1	827.6
5/2/94	880.0	N/A	844.5	848.1	852.5	843.1	842.9	847.3	836.9	837.4	838.5	828.3
6/6/94	878.2	N/A	843.4	843.3	851.6	842.1	841.7	847.3	836.7	836.5	838.2	828.3
7/5/94	875.3	N/A	842.0	840.2	850.2	840.5	840.3	844.7	835.7	836.8	837.5	827.4
8/1/94	876.2	N/A	841.4	841.3	850.6	841.1	840.7	846.3	835.7	836.5	837.2	827.9
9/6/94	871.2	N/A	838.4	838.3	848.1	838.6	837.7	844.3	834.7	834.5	835.2	827.3
10/3/94	868.5	N/A	836.3	836.0	847.2	836.5	836.0	842.7	833.7	834.4	835.1	827.6
11/7/94	867.2	N/A	835.4	836.3	846.1	836.6	834.7	842.3	833.7	833.5	834.2	826.3
12/5/94	865.1	N/A	834.8	834.4	845.2	834.5	834.1	840.9	832.7	833.2	832.9	826.2

FIGURE B-5. DATA REDUCTION SPREADSHEET

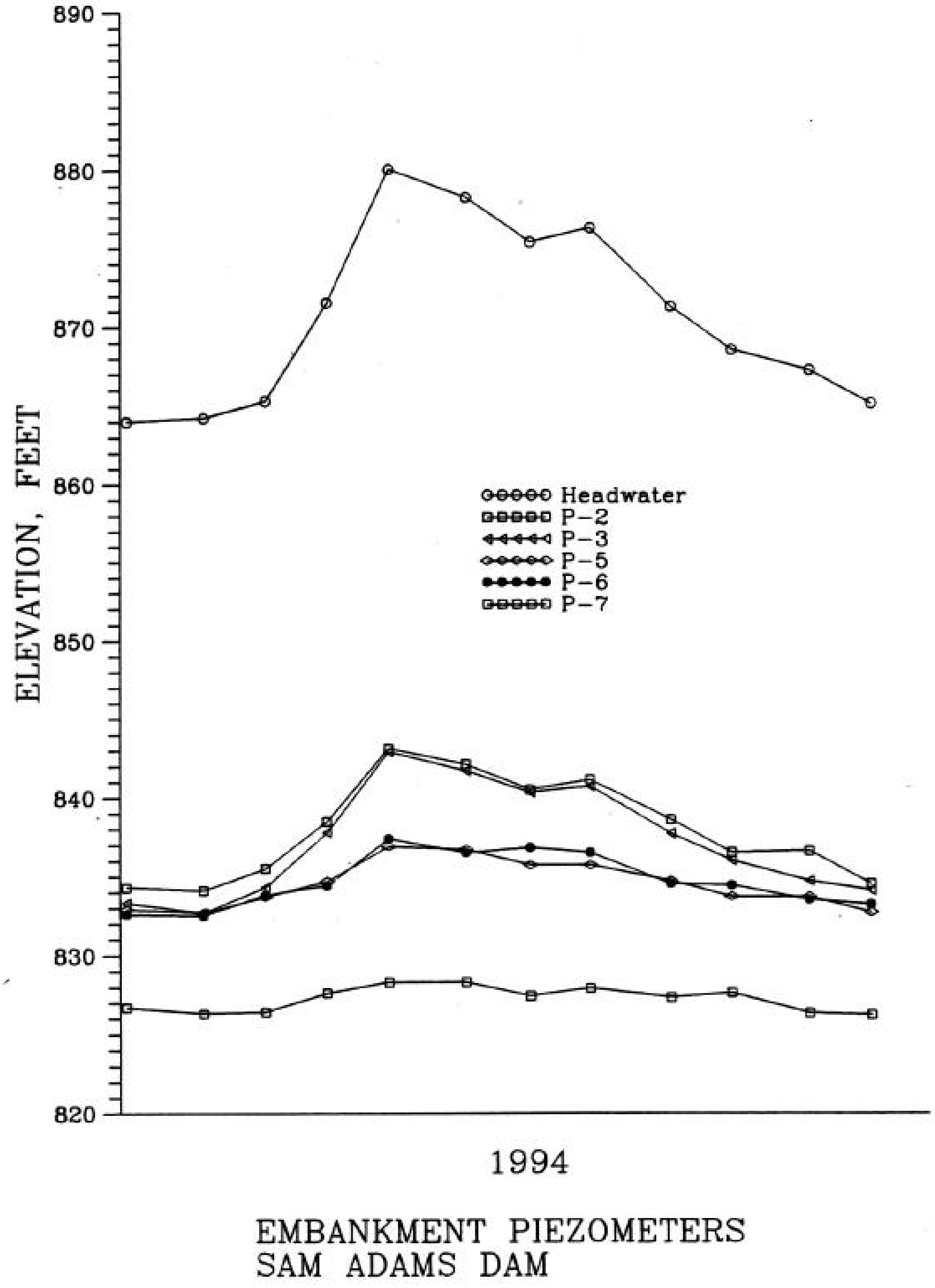


FIGURE B-6. EMBANKMENT PIEZOMETER PLOT

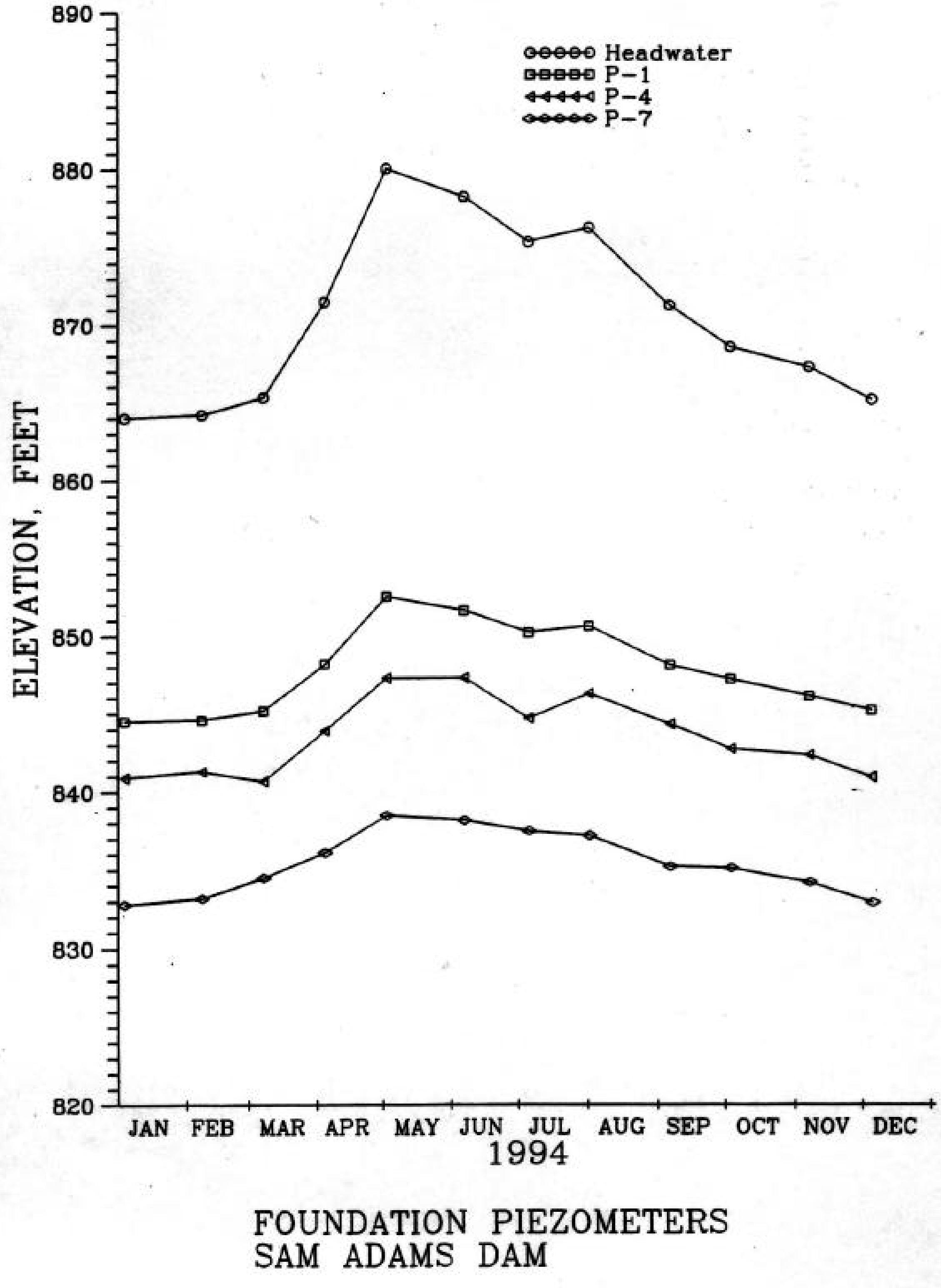


FIGURE B-7. FOUNDATION PIEZOMETER PLOT

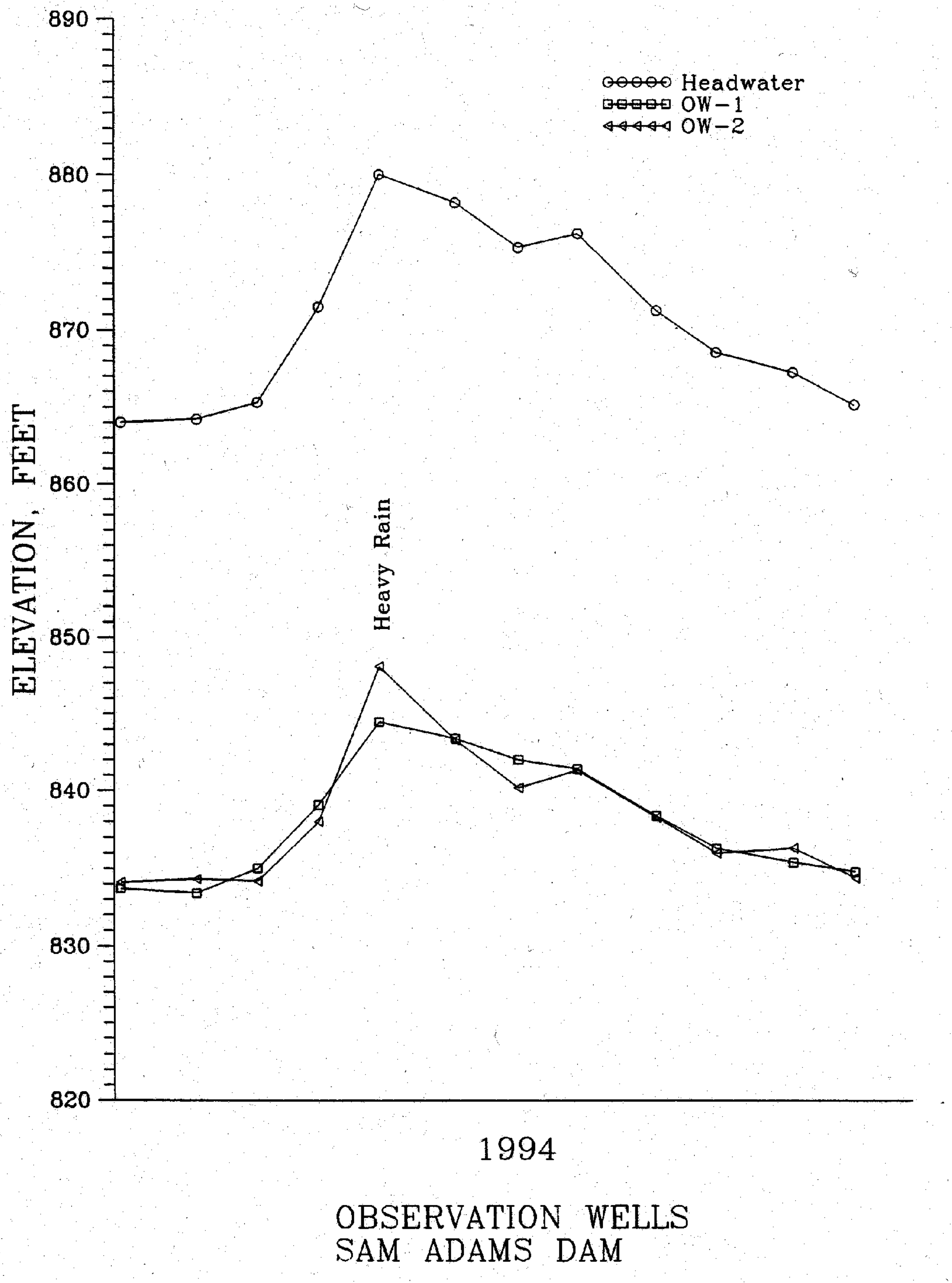


FIGURE B-8. OBSERVATION WELL PLOT

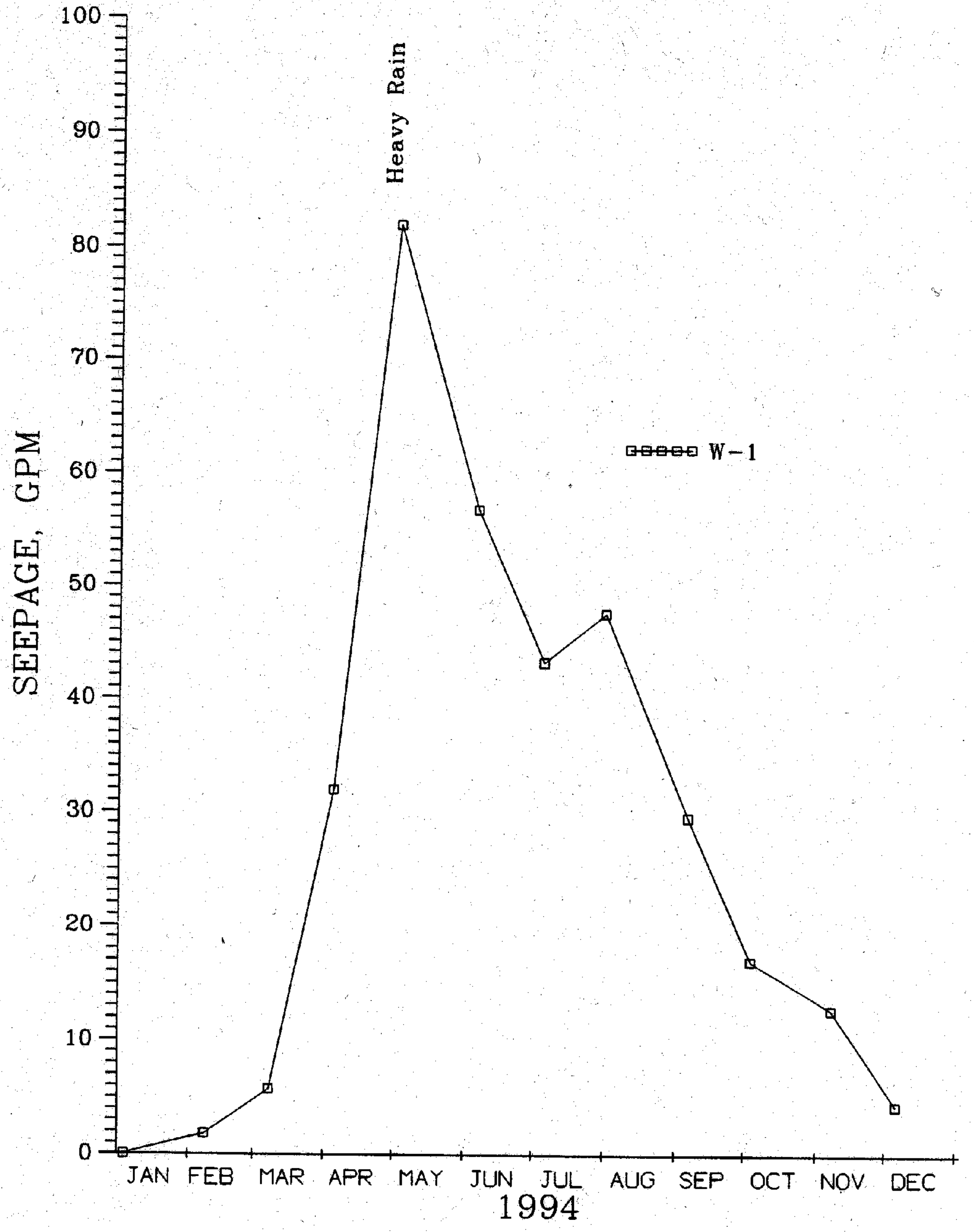


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FIGURE B-9. SEEPAGE PLOT