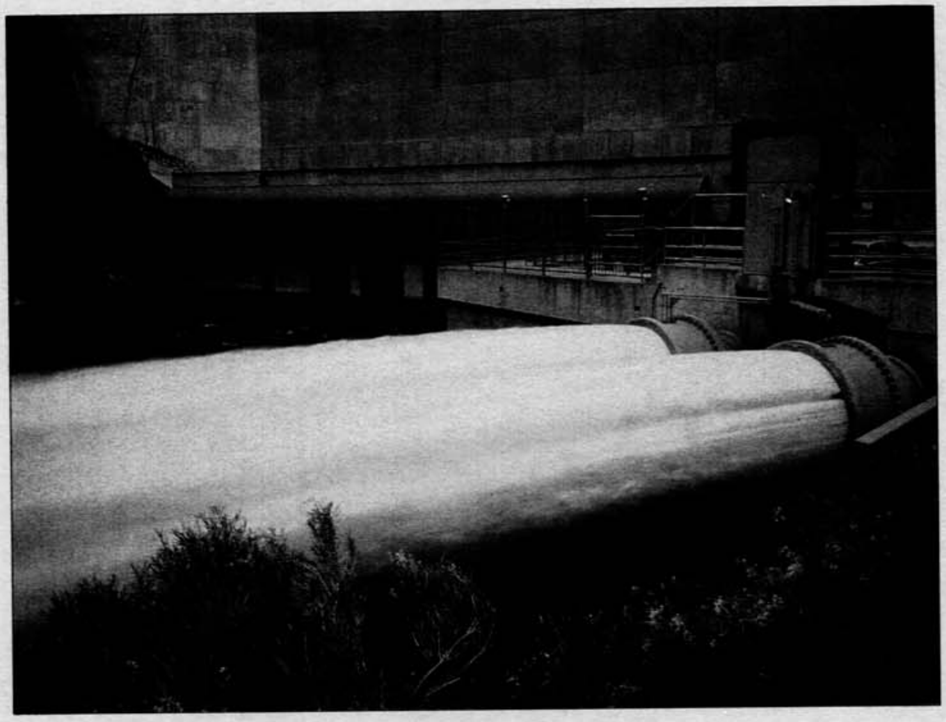
WATER OPERATION AND MAINTENANCE BULLETIN

No. 181

September 1997



IN THIS ISSUE . . .

UNITED STATES DEPARTMENT OF THE INTERIOR

Bureau of Reclamation

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Reclamation personnel and water user groups in operating and maintaining project facilities.

Although every attempt is made to ensure high quality and accurate information, Reclamation cannot warrant nor be responsible for the use or misuse of information that is furnished in this bulletin.

Jerry Fischer, Managing Editor
Bureau of Reclamation
Operation and Structural Safety Group, Code D-8470
PO Box 25007, Denver CO 80225
Telephone: (303) 236-9000, extension 230
FAX: (303) 236-1070

Cover photograph: *Water gushes at 4,000 cubic feet per second from two 72-inch steel outlet tubes running through Flaming Gorge Dam.*

WATER OPERATION AND MAINTENANCE BULLETIN
No. 181—September 1997

CONTENTS

CAN FROST HEAVE ON A DRAINAGE CULVERT CAUSE A CANAL BREAK?

by Chester Jones

In May 1989, a canal washout occurred on a Bureau of Reclamation- (Reclamation) constructed canal that resulted in a train wreck with injuries to many people and much damage to property. The canal washout was on Kennewick Main Canal, built in 1954-55 on the Yakima Project in southeastern Washington State. The lower bank and bottom of the canal washed out at a 36-inch-diameter precast concrete culvert that crossed underneath the canal at a gully. The purpose of the culvert was to carry surface runoff, particularly during localized storms, from a hillside above the canal. It was not possible from investigations after failure to pinpoint the exact cause or causes; the break occurred at night when there were no observers and most of the evidence was washed away.

In this article, the author visualizes how, based on well-known principles, frost action could have been the principal cause of, or at least contributed to, failure. Although canal damage at culverts from frost action has not, to the author's knowledge, been publicized, operations and maintenance personnel in cold areas are well aware of destruction on other structures caused by this natural force.

An Example From Highway Culverts

In cold climates where the water table is near the ground surface, it is not unusual when riding on unpaved country roads in wintertime to feel a slight bump when the car goes over some of the highway culverts under the road; the author experienced this while living in Maine. This bump is caused by cold air in the culvert freezing the soil and water around it and heaving the culvert and roadbed above it higher than the adjacent road surface [1, p. 7]. After the ground has thawed, the bump is no longer noticed because the culvert and soil above it have settled. In the same manner, frost action could take place on canal culverts. However, such action on canal culverts would be difficult to detect without careful observations or measurements.

Requirements for Frost Action

For frost heave to occur, it is necessary to have (1) a type of soil susceptible to frost action, (2) a supply of ground water, and (3) a sufficiently long period of freezing temperatures [2, pp. 2-11].

Soils

Frost action is most likely to take place in soils that have a considerable amount of silt, or lean clay without much plasticity [2, fig. 6]. The culvert at the Kennewick Canal breaksite had a bedding of nonplastic silt, and the foundation contained about 25 percent silt and 35 percent sand, tightly packed among larger particles of gravel and cobbles. Such materials would be highly susceptible to frost action.

Water

The failed Kennewick Canal culvert drained a hillside area of 93 acres. There was some evidence that water would collect naturally in the gully where the culvert was located. In February 1983, before the culvert was replaced, ground water was observed seeping into the canal near the original culvert location. In February 1985, after the culvert had been replaced, there was standing water in a low area adjacent to the canal bank near the culvert which was uphill from the canal.

Temperatures

The normal climate in the Kennewick Main Canal area is relatively mild, with very infrequent cold spells. From temperatures recorded at Prosser and Kennewick, Washington, the nearest National Weather Service stations, the winter of 1978-79 was by far the coldest between 1951 and 1982; this is shown by the plot on figure 1 of accumulative degree-days for the 30-year period. A degree-day is the difference between the average of the maximum and minimum daily air temperatures and the 32 degrees Fahrenheit (°F) freezing temperature. Starting November 1, these differences each day can be accumulated during the winter season to provide a freezing index that is a measure of the intensity of the cold [1, pp. 16-19].

Figure 2 shows that temperatures remained mostly below freezing from about Christmas (1978) into the first week of the following February (42 days). The 1979 Annual Project History for Yakima Project contains references to the very cold winter and to damage to canal structures. On page 11 following mention of the Kennewick Main Canal break is the following: "Sunnyside Valley Irrigation District also suffered a major failure in drop 10 on the main canal when a concrete apron on the bottom of the canal broke up and shifted." On page 169 under the heading of Chandler Canal and Forebay, "very severe cold weather in January with an average of 14 °F compared to 27° normal made it impossible to run water. The extreme temperature also had damaging effects on the canal lining. In May, grouting was required in mile 8. In the fall, parts of three liner panels were replaced in miles 2 and 6." From Roza District, "Frost damage to earth sections of the main canal and laterals were repaired by June. These were mostly high water leaks and easily repaired." Also, the following is from the 1979 Annual Project History of the Columbia Basin Project: "There was an unusual amount of snow and cold weather so that the ground was frozen too deep for usual winter construction work. It is felt that the deep frost moved some pipelines enough to break pipes, resulting in numerous washouts in the spring."

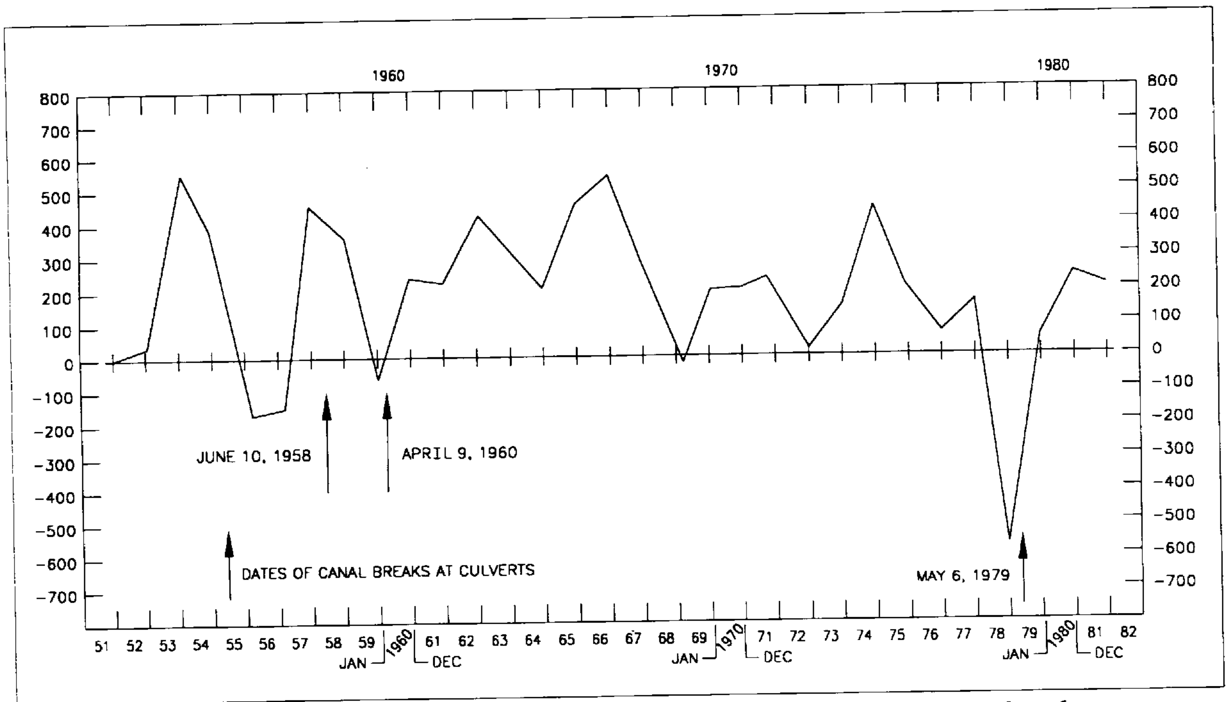


Figure 1.—Average annual cumulative degree-days for winters of 1951-82 based on air temperatures at Kennewick and Prosser, Washington, and dates of canal breaks at 36-inch-diameter culverts.

A canal break at a culvert occurred on the Kennewick Main Canal in June 1958 after two unusually cold winters in 1955-56 and 1956-57 during which there were canal breaks not at culverts. Also, there was a canal break at a culvert in April 1960, after one of the colder winters of the 30-year period.

Mechanics of Frost Heave

Since cold air is heavier than warm air, it would settle in the drainage area and flow down the gully into the culvert (figure 3A). This would provide a continual supply of cold air flowing through the culvert conducting heat from soil embankment and foundation. From a chart of frost penetration for different soil types [1, figure 16], it is estimated that for the winter of 1978-79, when the air freezing index was about 712, the soil under bare-ground conditions in a level area would freeze to a depth of about 2.5 feet in silt, and the presence of any gravel particles would cause it to freeze deeper than that. With a supply of water in the foundation, ice lenses would build up around the pipe (figure 3B), and this could cause very high pressures. Tests have shown (figure 4) that, for a silt, such pressures can build up to over 50 lbf/in^2. This is over three times the pressures that would result from the weight of culvert and 16 feet of embankment over it. Thus, forces from frost action could lift the culvert even under the embankment where collars are located. After thawing in the spring, the culvert

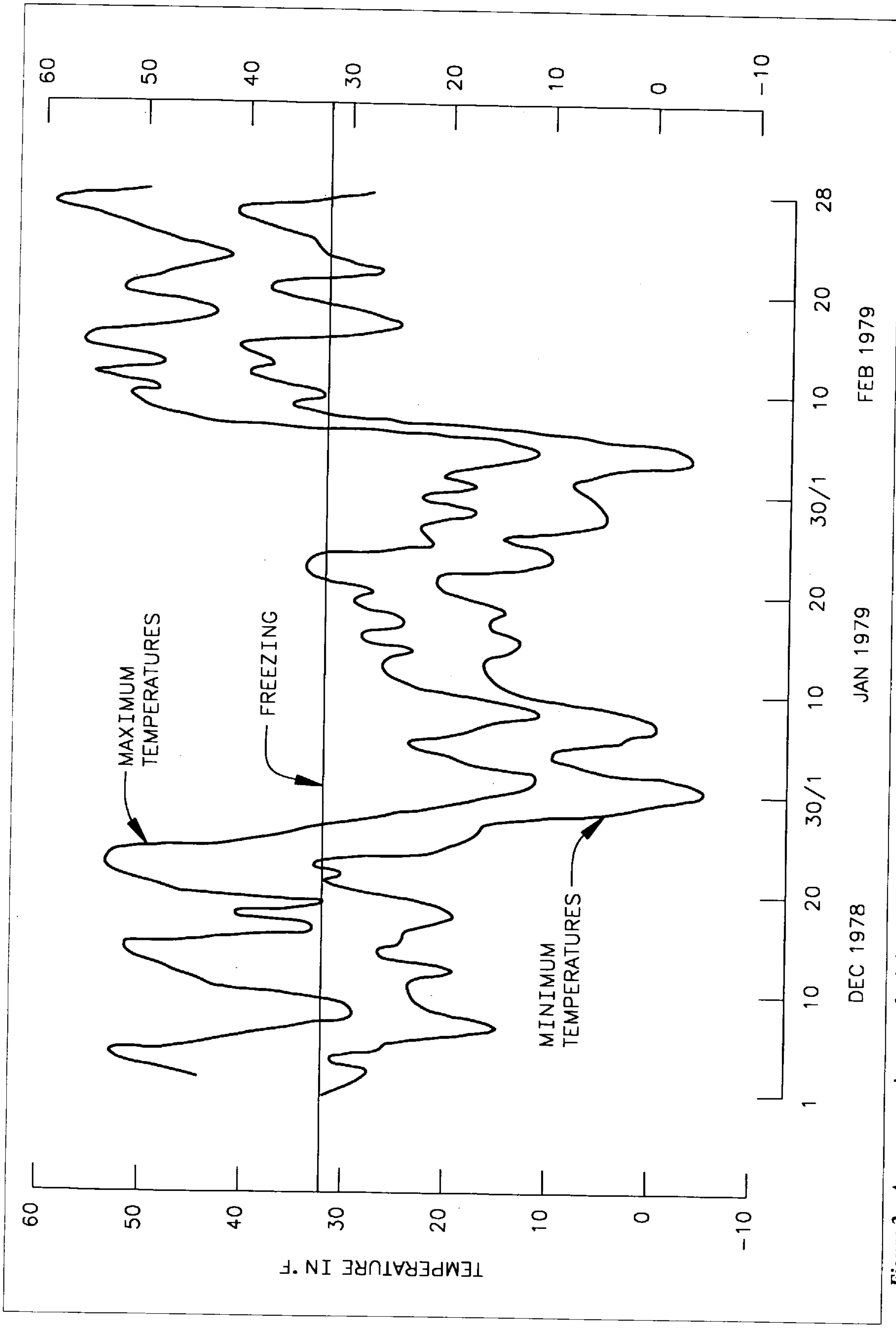


Figure 2.—Average maximum and minimum air temperatures for winter of 1978-79, based on records from Kennewick and Prosser, Washington.

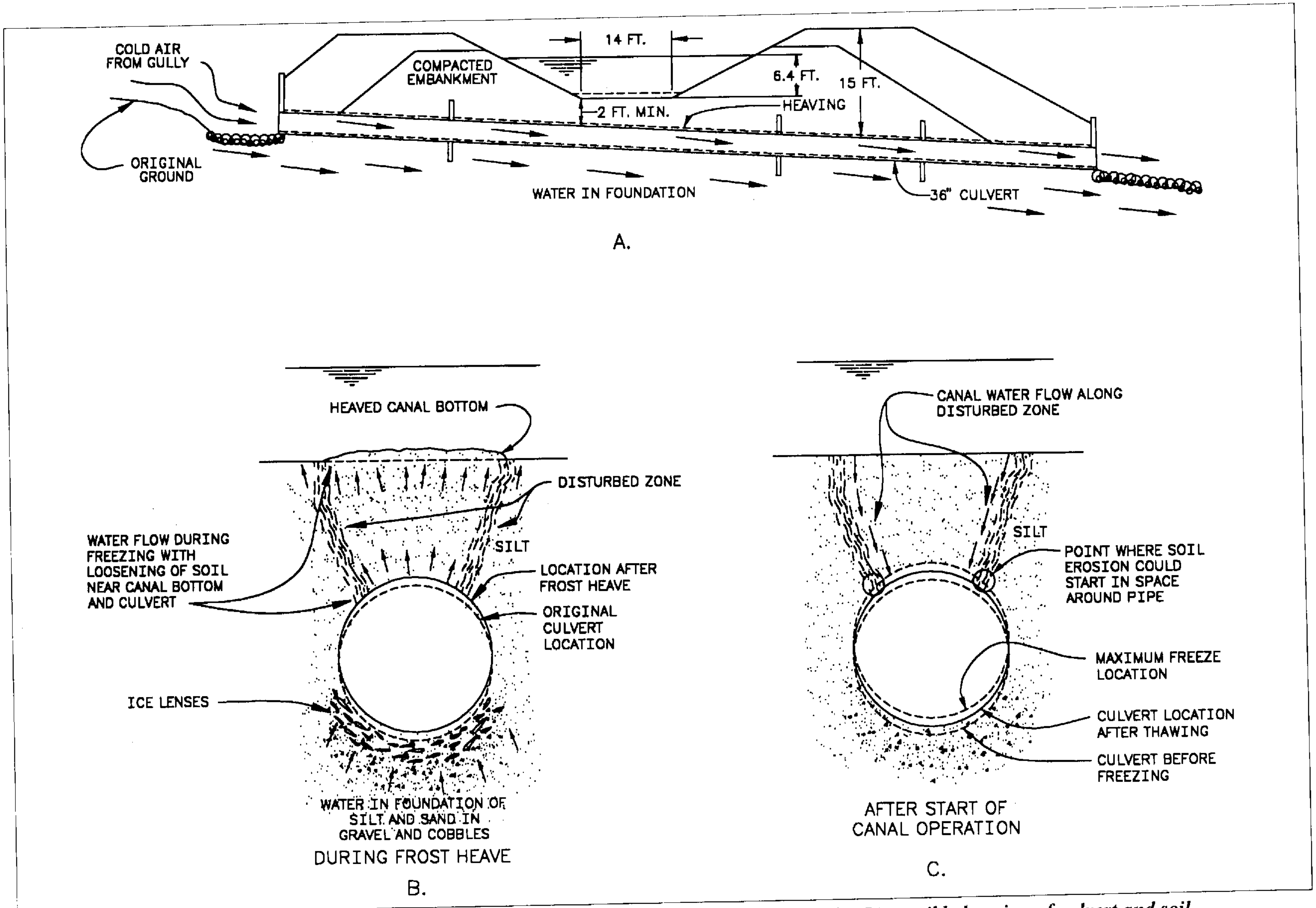


Figure 3.—(A) Canal and culvert cross sections at site of May 6, 1979, canal break; (B) possible heaving of culvert and soil by frost action; (C) possible mode of erosion after start of canal operation.

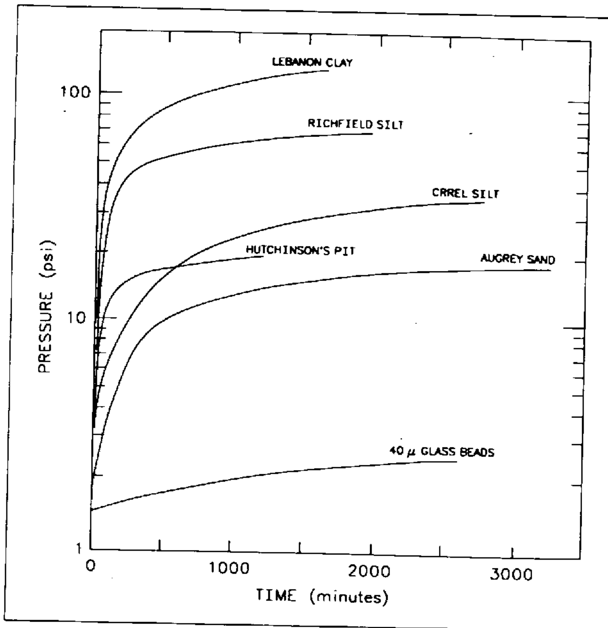


Figure 4.—Results of laboratory tests on different materials showing pressures developed with time (figure 6 in reference 3).

would settle, but the chances are that soil disturbance at the sides of the culvert and around the collars would not allow the culvert to fall back completely to its original position, leaving a space under the culvert. Bridging action of the soil over the culvert would form a space at the top of the culvert. These spaces would provide flow channels for any canal water reaching the culvert, and the channels would only need to be a small fraction of an inch in size for water erosion to start and enlarge them in the highly erosive silt around the culvert. Also, pressures causing a pipe to heave could crack the pipe or open joints enough that fine soil could wash directly into the pipe.

With only 2 to 3 feet of soil over the culvert under the canal bottom, the culvert could heave the soil enough to form cracks to the soil surface. This could provide disturbed shear planes where water, after the canal was placed in operation, could flow through the soil and start a piping action into voids around the pipe (figure 3C).

Even if there is not a supply of ground water available for ice lenses to build up, which is called "open-system freezing," freezing can also change the unit weight and moisture content of soil. This is called "closed-system freezing" [4]. In this case, any water in the soil voids is drawn toward the freezing front and, as water is drawn away from a soil mass, soil consolidation and shrinkage takes place. Operations and maintenance personnel in cold areas have reported seeing spaces up to about 1/4-inch wide between a concrete structure and the adjacent soil. After thawing, the soil unit weight and moisture content may not go back to their original condition and close the spaces.

How Can We Tell If Frost May Damage Culverts

Although the amount of frost heave would be difficult to predict, the tendency for culvert damage from frost heave can be judged in a general way from a determination of soil, water, and air temperature conditions in the vicinity of the culvert. The heave could amount to a matter of several inches, and a careful examination of the canal invert over a culvert in the winter might show a slight hump with or without cracks at the ground surface. Any appreciable shrinkage of soil away from visible portions of structures would be noticeable. Inspection of the inside of the culvert might show dislocations at the joints; otherwise, changes in the culvert location could be monitored by elevation surveys in the culvert from an established benchmark. If frost heave is suspected, excavation could be made in the canal invert around the culvert to look for voids.

After water is placed in the canal, culverts and areas below them should be closely watched to detect any seepage, particularly any water-carrying soil particles; this seepage would indicate that soil erosion was taking place.

Possible Preventive Measures

Closing one end of a culvert pipe would stop the flow of cold air. Heat from the soil surrounding the culvert would then reduce freezing in the soil/culvert contact area. Where extremely cold spells are rare, as in the Kennewick Canal area, selected culverts could be temporarily closed by snow, plastic sheeting, or other measures; this would allow an increase in the flow of water to break through the temporary culvert barrier. This preventive measure would be especially important in areas where a canal washout would cause significant damage.

A properly designed and maintained flexible canal lining placed over a culvert would prevent piping of canal water through any fracture zones down to the pipe. Some short lengths of lining were added over selected culverts on the Kennewick Canal. However, such a lining would not prevent a possible culvert washout during a heavy rainfall if there were spaces around the pipe. If exploration showed voids, soil could be removed and recompacted. A slurry grout of soil might also be effective in filling voids formed by the frost heave action.

Present Reclamation practice for construction of culverts under canals specifies that (1) the pipe be bedded in a soil-cement slurry, (2) a sand filter be placed at the outlet (also at the inlet, under certain conditions), and (3) seepage collars be eliminated. This type of construction would help prevent soil erosion around the pipe, but deep frost action might still heave the pipe and fracture the soil-cement, causing cracks through which water could flow. The trench for the pipe could be over-excavated and backfilled with a soil less susceptible to frost action, or some type of insulation could be added adjacent to the pipe.

Conclusion

For the scenario described above, one can only draw from experience with frost action on structures other than canal culverts. A research program is needed to obtain frost data on culverts, and the author has submitted a research proposal. The research would involve (1) selection of culverts on Reclamation projects where frost heave would most likely occur, (2) records of climatic conditions, (3) investigation of soil and water conditions at culverts, (4) measurements of frost heave, and (5) effects of frost action on soil around the culvert. In the meantime, irrigation personnel should be aware that frost action could damage culverts enough to cause washouts, and they should take necessary precautions.

References

1. Johnson, T.C., et al., "Roadway Design in Seasonal Frost Areas," Technical Report 259, a Joint Project of the Transportation Research Board and the Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, March 1975.

2. Jones, C.W., D.G. Miedema, and J.S. Watkins, "Frost Action in Soil Foundations and Control of Surface Structure Heaving," Bureau of Reclamation Report REC-ERC-82-17, Denver, Colorado, June 1982.

   [This report, which includes summaries of other reports on frost action, was written primarily for Reclamation designers and operation and maintenance personnel to describe (1) the nature and extent of damage to Reclamation structures from frost heave, (2) the general principles involving frost heave, and (3) procedures for controlling frost heave. Reclamation employees may obtain copies of report REC-82-17 by writing to the Reclamation warehouse, mail code D-7913, PO Box 25007, Denver CO 80225-0007, or by calling (303) 236-5275, extension 225].

3. Hoekstra, J., E. Chamberlain, and A. Frate, "Frost Heaving Pressures," U.S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, October 1965.

4. Jones, C.W., "Closed-System Freezing of Soils in Linings and Earth Embankment Dams," Bureau of Reclamation report REC-ERC-81-1, March 1981.

ENSURING THE SAFETY OF SPILLWAY RADIAL GATES

by Gurmukh S. Sarkaria[1]

How can you ensure the safety and reliability of the radial gates on a dam's spillway? In this article, a well-known hydro expert outlines factors to consider in both the operation of existing gates and the design of new ones.

Spillway radial gates—whether located on top or inside the body of a dam or on a structure separate from the dam—can be viewed as "mobile dams." (In other words, they are a civil structure that holds back water, but also can be moved vertically.) These gates play a critical role at water resources projects. Their safety and operational reliability is crucial for attenuating flood peaks, regulating outflows, and abating downstream flooding, as well as for storing water for use during dry periods and, in many cases, for generation of hydropower.

Radial gates are highly reliable when compared to vertical lift-type gates. However, several incidents in which radial gates have malfunctioned have occurred. One of the better known incidents, the failure of a radial gate at the Folsom Dam in California in 1995, resulted in a loss of about 500 million cubic meters of water. The value of that lost water was estimated to be as much as $40 million.

The Folsom Dam incident, plus mishaps at other projects, highlight the importance and significance of the safety of spillway gates. How can you ensure the safety, reliability, and low maintenance cost of a spillway radial gate?

First, the gates must be designed appropriately. Then, existing gates need to be regularly appraised for safety and operational reliability.

---

[1] *Gurmukh Sarkaria is a consulting engineer with 48 years of experience in the design, construction, and operation of dams and hydropower projects throughout the world. He is well-known for his expertise in the area of spillway gate design and operation.*

☑ **Peer Reviewed**

This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.

Determining the Proper Size of a Radial Gate

Economic analyses generally indicate that the fewer number and the larger the size of gates, the lower the total cost of the spillway. In addition, operation, maintenance, and replacement costs generally increase with the number of gates. However, the number and size of spillway gates also are influenced by the space available for locating the spillway and the required flexibility of operation for downstream use.

Another factor influencing the size of the gate is its structural flexibility. There is a tendency when designing radial gates to use high strength steels in order to reduce the gates weight. However, this practice can result in relatively slender structural members that are susceptible to buckling. As a result of this susceptibility, the gate can distort and jam if the gate hoists are not perfectly synchronized or the hoist pull is uneven. Therefore, it is prudent for designers to analyze the deflections of gate members and specify slenderness limits for structural members.

Identifying the 'Weak Link' in a Radial Gate

When conducting a comprehensive safety evaluation of a dam, including the spillway radial gates, it is essential to check for the weakest link in the project. One potential weak link is the trunnion anchorages.

Trunnion anchorages are critical with respect to safety. Reservoir pressure and seismically induced dynamic loads against the gate are transmitted to the piers and walls via the trunnion anchorages. For many large radial gates, the anchorages are comprised of concrete embedded with post-tensioned rods or cables. In some cases, the downstream ends with the anchor plate, the grippers, and the tensioning nuts are exposed. In other designs, these elements are encased in second-stage reinforced concrete.

There have been some failures of these post-tensioned rods, especially in those designs where the downstream ends and tensioning nuts are exposed. For example, two rods failed at the California Department of Water Resources Oroville Dam in 1992 and 1994, and another failed at Pyramid Dam, also located in California, in 1987. At both of these projects, the downstream ends and the nuts of the rods were exposed. The rod failures were attributed to stress corrosion. The gates had been in service for about 15 to 20 years. It appears that embedment of the anchored ends in concrete protects the metal from corrosion and thus reduces the likelihood of failure.

For some large gates, post-tensioned trunnion anchorages are stressed from both the upstream and downstream ends of the piers. The upstream anchorages are always embedded in second-stage concrete. With these gates, and in situations where the reservoir is maintained above the spillway crest for several years, it is necessary to waterproof both the upstream end of the anchorages and the concrete so that water will not corrode the steel.

How Seismic Activity Affects Gate Safety

When designing a radial gate and its trunnion anchorages for a water resources project in a seismically active area, special factors need to be considered. Specifically, hydrodynamic forces and the inertia component of the gates weight due to horizontal and vertical seismic acceleration need to be accounted for.

As a result of studying seismic monitoring dam instrumentation data following the 1994 earthquake in Northridge, California, (an event measuring 6.8 on the Richter scale), designers know more than ever before about seismic forces.

Data collected from instruments at the 111-meter-high Pacoima Dam, a concrete arch structure, indicate that:

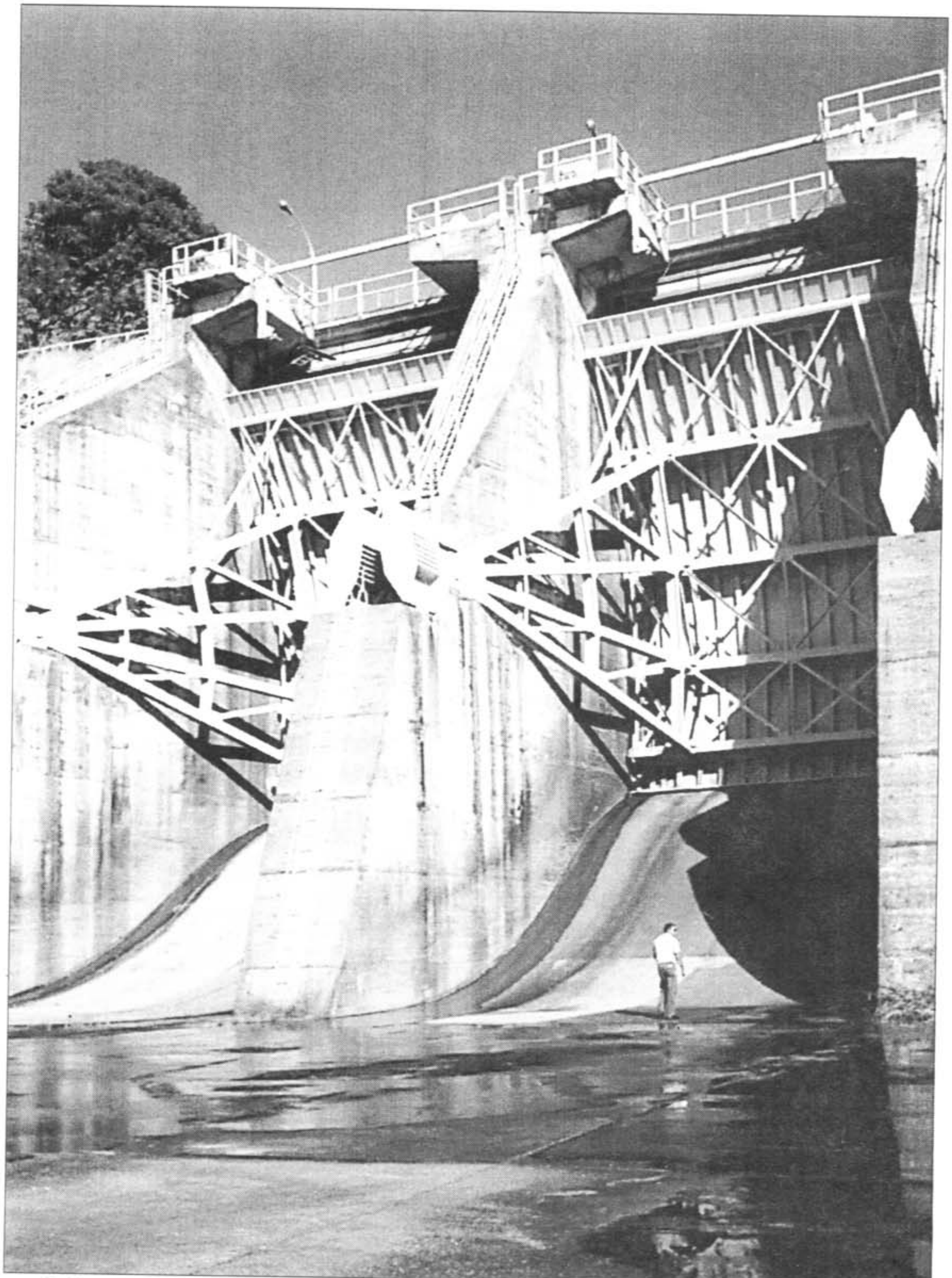
— Earthquake-induced accelerations in both horizontal directions and in the vertical direction can be equal to the horizontal peak ground acceleration (known as the PGA) or base rock acceleration;

— Magnification factors of seismic acceleration from the base to the top of a concrete dam can be as high as 1.5 to 2.5 for a 100-meter-high dam, or 2.5 to 3.5 for a 200-meter-high dam; and

— Magnification of 1.5 to 2.0 from the horizontal peak ground acceleration can occur at spillway structures and gates on an abutment separate from the dam.

The implication of these findings for the safety of spillway gates is that the seismic loads on the gates and trunnion anchorages most likely will be much larger than those indicated by the horizontal peak ground acceleration assumed at the base of the dam. Also, the "cross-canyon" component of seismic acceleration (in which the seismic acceleration occurs along the axis of the spillway structure) could contribute to buckling of structural members or jamming of a gate.

When conducting dam safety inspections or when designing new or replacement gates for a project, these new findings regarding seismic activity should be taken into account.



Spillway radial gates are one of the most critical appurtenances of a water resources project. Their safety and reliability are crucial. There are several factors for gate designers and project operators to consider in both operation of existing gates and design of new ones to ensure safety.

Selecting, Maintaining Gate Hoists

To ensure the safety of spillway radial gates, it is vital that gate hoists—whether cables or chains on the upstream side or hydraulically operated servomotors on the downstream side—operate correctly and in sync each time the gate is raised or lowered.

Unbalanced hoist pulls can warp and jam a gate. In older gates, corrosion can weaken structural members and increase trunnion friction. High and uneven trunnion friction can result in unbalanced hoisting force, which, in turn, may distort the gate frame and even cause failure of some members.

Cable or wire rope hoists are preferable to chain hoists. That's because the chains are prone to getting tangled, particularly when the hoist pull is unbalanced.

Diligent preventive maintenance and periodic test operation under dry and low-flow wet conditions are mandatory to prevent a gate failure under high reservoir or flood conditions. Where the gates are operated frequently and/or the loss of stored water is costly, stoplogs or closure pontoons should be provided to handle gate failure emergencies. For spillways with several gates where downstream servomotor hoists are employed, a spare set of a complete hoist should be kept at the project site so that a damaged hoist can be replaced quickly and the gate can become operational again.

Conducting Regular Gate Inspections

Periodic systematic inspection of spillway gates is necessary for ensuring their continued safety. The Electric Power Research Institute's publication, *Inspection and Performance Evaluation of Dams*, provides practical guidelines for such an inspection. The checklist in the box on page 14, adapted from this publication, is a good tool for use during an inspection.

The publication also is useful when evaluating a defect, deficiency, or problem such as a jammed gate or excessive friction. It provides a list of possible causes of the problem, potential effects on the safety of the gate, and practical remedial measures.

Six Guidelines Toward Ensuring the Safety of Spillway Radial Gates

Developers and owners of water resource projects can work toward ensuring the safety of radial gates on a spillway by following prudent design and operational practices. The following are six important guidelines to follow:

1) Design spillway radial gates with conservative factors of safety in order to ensure margins of safety comparable to that of the dam;

Spillway Radial Gate Inspection Checklist

This checklist can be a helpful tool for conducting gate inspections

Gates and Stoplogs
For closed gates or stoplogs, check for:
— Water leakage, difficulty of closure
For gates in motion, check for:
— Movement: jerky, swaying, or smooth travel
— Position: skewed, normal, tilted, wedged
— Disturbances: noise, vibrations
— Excessive force
For open gates, check for:
— Gate drift; vibrations
For gates under maintenance, check for:
— Deterioration of finish; corrosion
— Status of cathodic protection system components
— Condition of welded and bolted connections
— Status of gate-to-hoist connections
— Status of seals and retaining members
— Geometric check of gate frame
— Condition of trunnion bearings; lubrication

Gate Hoists—Wire Rope and Chain Types
Check:
— Status of gate-to-hoist load block connection
— Wire rope. Review age and diameter, external condition, signs of kinks, abrasion, uneven drum winding, corrosion, lack of lubrication, broken wires
— Status of lifting chain. Look at condition of pin connections, retaining rings, worn bushings, damaged chain links
— Brakes. Check for worn-out brake lining, need for cleaning adjustment, loose parts, deterioration of finish, corrosion. Ensure proper operation with no jarring or vibration and that the brake wheel presents a smooth uniform surface
— Rope drum. Check the diameter of the groove, signs of wire rope scores, rugged and worn groove surfaces, corrosion
— Rope sheaves. Look for broken, distorted, or cracked flanges; an increase in diameter; a scored groove; decrease in the diameter of the groove; corrosion. Check status of bearings

Gears, Pinions, Speed Reducers, Chain Sprockets
— Check status of lubrication and lubricant; bearings
— Look for excessive or uneven wear of gear and sprocket teeth; noise; vibration

Electrical Equipment and Controls
Check:
— Status of electric motor; noise from bearings; indications of overheating; cleanliness; condition of insulation resistance
— Status of control panels; loose or burned connections; damaged insulation, burned or pitted controls; proper operation of switches; push buttons; indicating lights; cleanliness; deterioration of finish

Gate Position Indicator
Check:
—Status of each dial; look for damaged pointer or protective cover; deterioration of finish
— Driving mechanism: check for damaged or worn chain drive; worn gearing; loose parts; corrosion. Check condition of bearings and lubricant

Adapted from the Electric Power Research Institute publication, Inspection and Performance Evaluation of Dams.

2) Design and fabricate gate frames and structural members so that the gate is not excessively flexible and susceptible to distortion and buckling of members;

3) In seismically active areas, ensure that the gate and its trunnion anchorages are strong enough to resist forces due to magnified horizontal and vertical earthquake accelerations. Gates also should be strong enough to withstand horizontal cross-canyon seismic acceleration;

4) Conservatively design post-tensioned rods or cables for trunnion anchorages, assuming that 10 percent of the rods may fail or become ineffective. Do not stress anchors to more than 70 percent of yield strength. Protect exposed parts of the rods with an inhibitive, nonhardening waterproof compound;

5) Provide either stoplo　gs or a floating pontoon to close a spillway bay in case an operating gate is damaged or becomes inoperable. This is especially important when a large volume of water is stored behind the spillway gates; and

6) Conduct thorough and systematic periodic inspections of the gates, hoists, and all other auxiliary systems. Check all components for deficiencies. Conduct inspections and test operations under both dry and wet conditions, and also after several days of gate operation under high flows.

Mr. Sarkaria may be contacted at P.O. Box 856, Vista, CA 92085; (619) 940-8182.

References

The Guide to Hydropower Mechanical Design, "Chapter 7: Gates," HCI Publications, Kansas City, Missouri, 1996.

Inspection and Performance Evaluation of Dams, EPRI AP-4714, Electric Power Research Institute, Palo Alto, California, 1986.

Rudolph, Richard M., and James A. Gundry, "Planning a Cost-Effective Gate Rehab," *Hydro Review*, Volume 15, Number 2, April 1996, pages 10-14.

Sagar, B.T.A., "How Safe Are Your Gates?" *Hydro Review*, Volume 10, Number 5, August 1991, pages 56-63.

Reprinted from Hydro Review, February 1997, HCI Publications, Kansas City, MO 64111. Used with permission.

Water Measurement Manual Hits Best Seller List

The Bureau of Reclamation's (Reclamation) third edition of the *Water Measurement Manual* is now available. This revised and updated edition supersedes the 1967 edition and includes several new chapters. Since 1953, Reclamation's *Water Measurement Manual* has been used by designers, system operators, and water users as the primary source for the latest information needed in accurate and reliable flow measurement of irrigation, municipal, and industrial waters.

The staff of Reclamation's Water Resources Research Laboratory collaborated with the staff of the U.S. Water Conservation Laboratory, Agricultural Research Service, to provide state-of-the-art information on flow measurement technology in this third edition. New chapters and sections were added to make the third edition current and more useful to other government organizations. With this edition, the *Water Measurement Manual* has also become the official manual for flow measurement in the Department of Agriculture.

Copies can be ordered by contacting the Property Operations Team (Warehouse) in Denver, mail code D-7913, with attention to Todd Marvel. Other agencies and the public can order copies from the Superintendent of Documents, U.S. Government Printing Office, PO Box 371954, Pittsburgh, Pennsylvania 15250-7954, or by calling 202-512-1800 (fax: 202-512-2250).

The *Water Measurement Manual,* as well as other information related to flow measurement technologies, is also available on the Water Resources Research Laboratory website at: http://ogee.do.usbr.gov/fmt

Development of a Geomembrane System for Underwater Repair of Concrete Structures

by James E. McDonald, U.S. Army Engineer Waterways Experiment Station

The U.S. Army Corps of Engineers operates and maintains a wide variety of hydraulic structures, including mass-concrete gravity dams, rock-fill dams with concrete facings, and roller-compacted concrete dams. Concrete appurtenances associated with such dams include intake towers, outlet works, and stilling basins. Located at over 600 project sites throughout the United States, these structures are subjected to a wide spectrum of environmental conditions. Also, the advanced ages of these structures, more than 40 percent of which are over 50 years old, increase the potential for concrete deterioration.

Many of these structures exhibit concrete cracking, which allows water intrusion into or through the structure. Water leakage through hydraulic structures can also result from poor concrete consolidation during construction, improperly prepared lift or construction joints, and water-stop failures. When leakage rates through cracked or deteriorated concrete and defective joints become unacceptable, repairs are made. Conventional repair methods generally consist of localized sealing of cracks and defective joints by cementitious and chemical grouting, epoxy injection, or surface treatments. Even though localized sealing of leaking cracks and defective joints with conventional methods has been successful in some applications, in many cases some type of overall repair is still required after a few years. Consequently, the potential for geomembranes in such repairs was evaluated as part of the Corps' Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

Various configurations of geomembranes have been used as impervious synthetic barriers in dams for more than 30 years. Generally, membranes are placed either within an embankment or rock-fill dam as part of the impervious core or at the upstream face of embankment, rock-fill, and concrete gravity dams. In recent years, geomembranes have been increasingly used for seepage control in a variety of civil engineering structures, including canals, reservoirs, storage basins, dams, and tunnels. Geomembranes have also been used successfully to resurface the upstream face of a number of old concrete and masonry dams, particularly in Europe.

A review of geomembrane applications (McDonald 1993) indicated that the success of these systems in arresting concrete deterioration and controlling leakage in dams, canals, reservoirs, and tunnels and the demonstrated durability of these materials are such that these systems are considered competitive with other repair alternatives. With a few exceptions, geomembrane installations to date have been accomplished in a dry environment by dewatering the structure on which the geomembrane is to be installed. Dewatering, however, can be extremely expensive and in many cases may not be possible because of project constraints. A durable geomembrane system that could be installed underwater to minimize or eliminate water intrusion and leakage would be an economical alternative for repair of a variety of hydraulic structures. Consequently, research was initiated to develop a procedure for underwater installation of geomembrane repair systems.

A two-phase contract to develop the system was awarded to Oceaneering International, Upper Marlboro, MD, and CARPI/USA, McMurray, PA, based on their respective expertise in underwater construction and geomembrane systems for dam rehabilitation. In Phase I, a conceptual design for the underwater repair system was developed based on research, material testing, and detailed evaluation of individual components and procedures. The constructibility of the design was demonstrated in Phase II through successful underwater installation of the system on a simulated concrete structure.

Conceptual Design

The objective of this phase of the study was to perform research, material testing, and evaluation of individual components and techniques required to facilitate successful underwater installation of membranes and to develop a procedure for underwater installation on the upstream face of a dam. Work in this phase included developing design criteria, surveying available materials, conducting material testing, and evaluating materials and assembly techniques. Material testing was conducted, when applicable, in accordance with standardized tests. However, other even more valuable information was collected with nonstandardized tests, namely with multiaxial, large-scale tests or tests that were intended to simulate conditions likely to be encountered during actual installation. Testing was conducted on drainage materials, membrane materials, anchorage profiles, gaskets, anchor bolts, and surface repair compounds.

Various types and thicknesses of geomembranes were tested to determine their conformability, burst resistance, and puncture resistance in the presence of a very rough substrate (figure 1). Samples of membrane were placed in a pressure vessel that was sealed and pressurized to a maximum pressure of approximately 150 psi (1 MPa). Samples of membrane that did not rupture during pressurization were subjected to the maximum pressure for 24 hr. The specimens were then removed from the pressure chamber and inspected. A sample of reinforced polyvinyl chloride (PVC) after testing is shown in figure 2. Obviously, the membrane conformed to the very irregular substrate without puncturing.

Figure 1.—Simulated substrate in the puncture test.

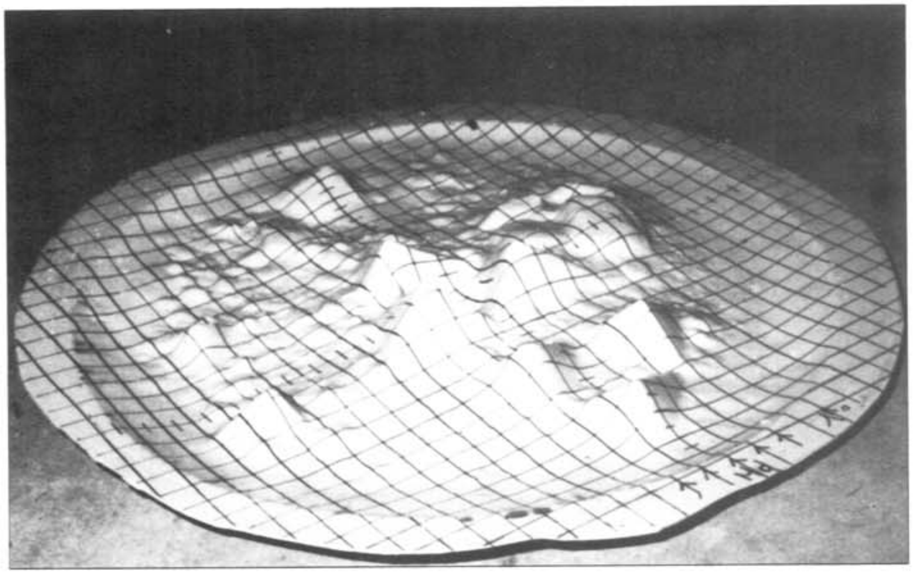


Figure 2.—Condition of the reinforced PVC after a sustained load of 150 psi (1MPa) for 24 hr.

The mechanical fastening system that secures and seals the membrane system to the surface of the structure also received considerable attention in the design phase. The stainless steel profiles must be flexible enough to conform to the substrate, yet stiff enough to ensure continuous compression of the gasket without an excessive number of anchor bolts. The performance of both chemically grouted and mechanical anchors installed under submerged conditions was evaluated. A profile and gasket conformability test is shown in figure 3. In this test, a 1-in. (25-mm) -thick, open-cell neoprene gasket is being compressed by a 1/4-in. (6-mm) -thick stainless-steel profile with anchor bolts on 12-in. (305-mm) centers.

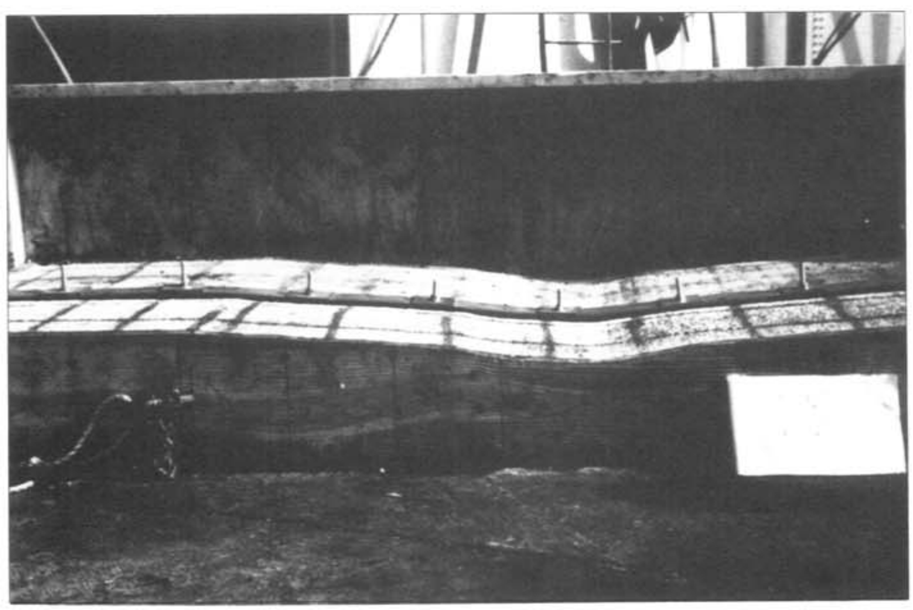


Figure 3.—Profile and gasket conformability test.

The geomembrane system designed for underwater installation on the upstream face of a dam consists of a high-density polyethylene (HDPE) geonet drainage layer, and a PVC geomembrane backed with geotextile reinforcement, anchored and sealed around the perimeter and along vertical splices (figures 4 and 5). Development of the system is described in detail by Christensen et al. (1995).

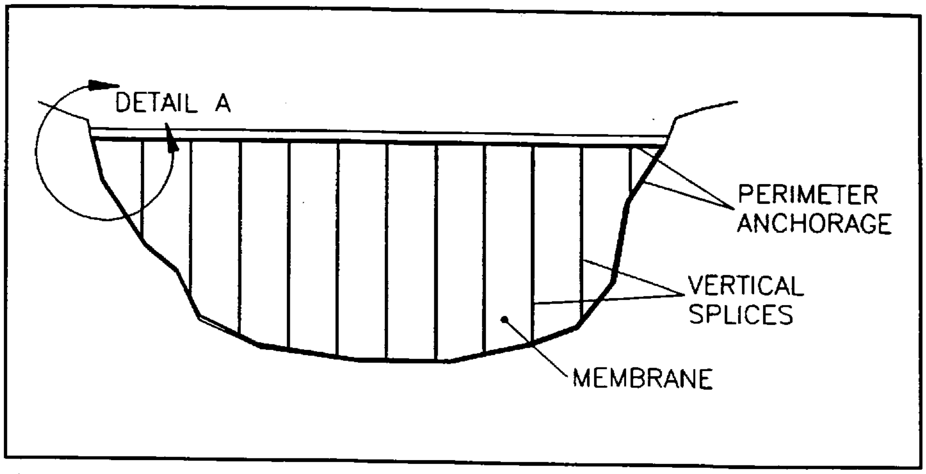


Figure 4.—System general scheme.

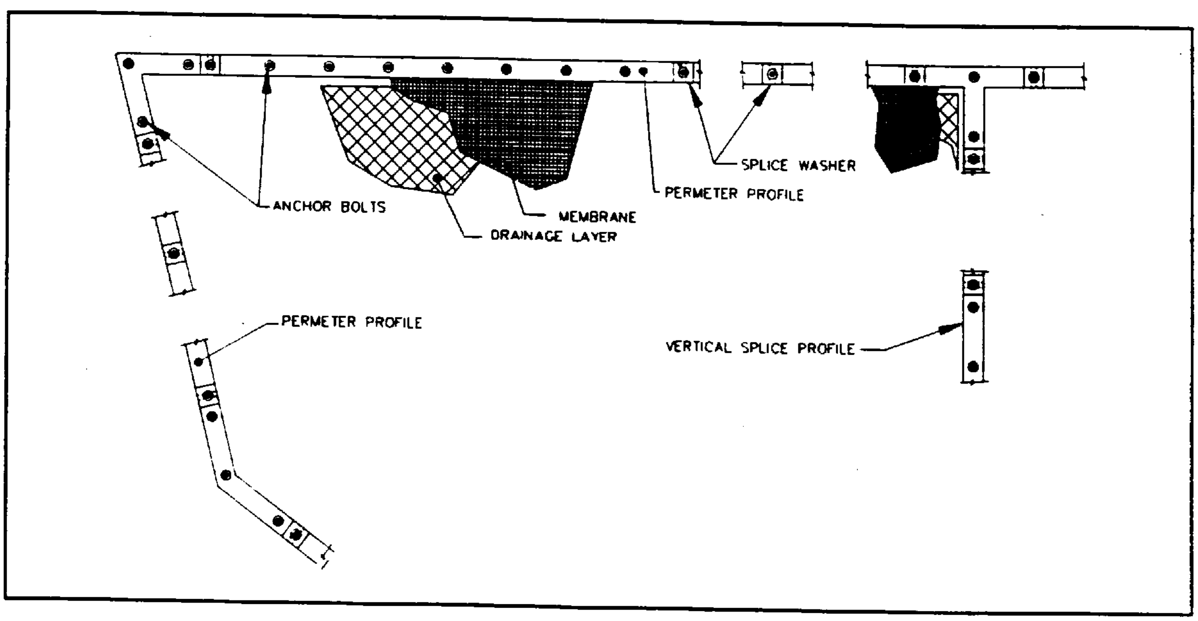


Figure 5.—Assembly detail A from general scheme (Figure 4).

A PVC geocomposite consisting of a geomembrane backed with nonwoven geotextile reinforcement was selected over the other available membrane materials because of its superior qualities with respect to constructibility, mechanical performance, durability, and prior use. HDPE geonet with preferential flow is a suitable drainage medium behind the membrane should a drained system be installed. The drained water can be discharged downstream through the structure or directly into the reservoir. Stainless-steel anchor bolts were selected to secure the perimeter profiles and vertical splice profiles to the concrete structure. Stainless-steel flat-bar profile sections with a minimum thickness of 1/4 in. (6 mm) were selected. Unless site-specific conditions dictate otherwise, the gasket should be open-cell neoprene, medium hardness, with a channel-shaped cross section.

Constructibility Demonstration

The objective of this phase of the study was to demonstrate that the conceptual design could be practically installed underwater and that it provides a reliable barrier to moisture intrusion. The constructibility demonstration is described in detail by Marcy, Scuero, and Vaschetti (1996) and summarized in the following. The conceptual design and the constructibility demonstration are also summarized in a 9-min video report (REMR-CS-5).

The demonstration required a test structure that simulated a concrete hydraulic structure in need of repair. In an effort to make the constructibility demonstration comprehensive, the test structure was designed and built with features that replicate possible situations which could complicate the underwater installation of the geomembrane system. These features included rough surfaces, complex corners, depressions and protrusions, a V-shaped notch representing a construction joint, and various holes simulating discrete leakage points. The concrete structure was designed and constructed in the configuration of an L-shaped wall as shown in figure 6.

A vacuum manifold was incorporated into the wall. The manifold creates a suction behind the membrane to simulate different hydrostatic heads and to test the efficiency of the system. The manifold is connected to 1-1/2 in. (38-mm) holes in the concrete which simulate points of discrete leakage through the structure.

After a successful installation in the dry (figure 7), the wall was lifted with a 60-ton crane and lowered into the test tank to a depth of 20 ft (6.1 m). Multiple installations were performed underwater. The profiles were used as templates for the anchor-bolt holes. Holes were drilled with a hydraulic hammer drill, and the bolt holes were cleaned with water and a plastic brush. Three types of anchor bolts were installed: torque-set wedge bolts, chemical anchors which use a two-part epoxy, and chemical anchors which use two-part epoxy and a glass encapsulated resin cartridge. Underwater epoxy was applied to smooth the rough concrete at the perimeter. The geonet drainage layer was positioned and secured to the wall with small expansion anchors. The gasket was placed over the anchor bolts along the perimeter, and the membrane sections were rolled down the face of the wall. Bolt holes were punched in the membrane by tapping the membrane over the bolts with a hammer. A second gasket layer

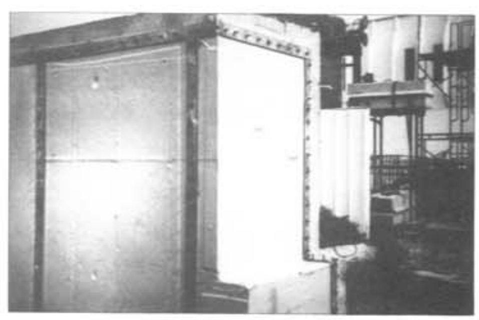


Figure 7.—Completed dry installation.

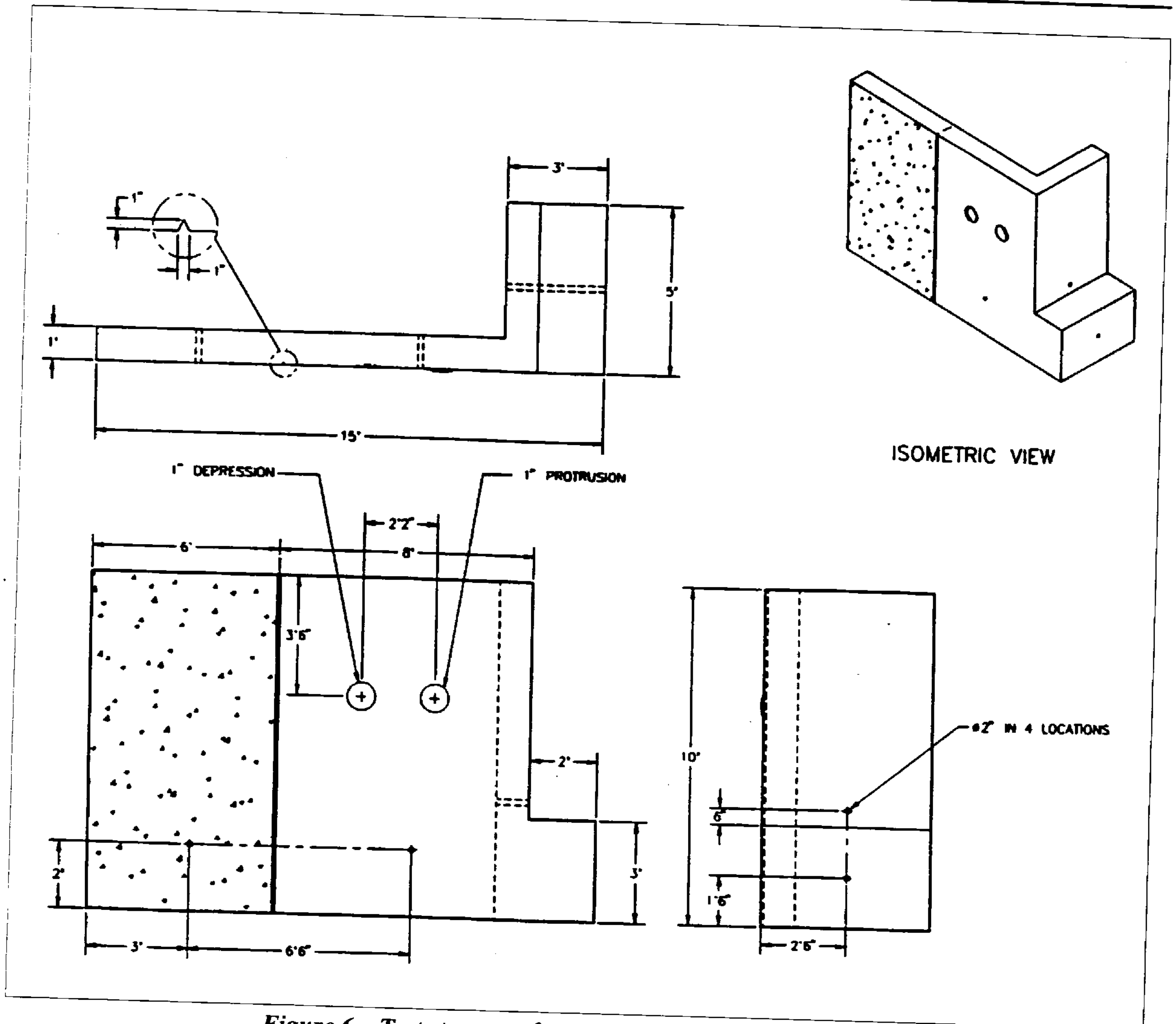


Figure 6.—Test structure for constructibility demonstration.

was placed between overlapping membrane sheets at the vertical splices and perimeter seal. The profiles were placed on the wall and the anchor bolts were torqued to 35 foot-pounds (1.4 joules).

After all of the bolts were tightened, water was evacuated from behind the membrane using a hydraulic ejector. The combined effort of the pressure depression behind the membrane and the water depth resulted in a hydrostatic head of approximately 40 ft (12.2 m) of water. Two weeks after the vacuum was shut off, the membrane remained tightly conformed to the wall (figure 8), indicating that seepage through the repair system was extremely slow. During one of the underwater installations, five anchor bolts that used a combination of two-part epoxy and a glass-encapsulated resin cartridge were used. These five bolts loosened as the nuts were tightened. Failure was later attributed to the installation technique.

Figure 8.—Membrane tightly conformed to the substrate.

The system was tested to determine the effect of the defective bolts. As the ejector evacuated water behind the membrane, the membrane conformed tightly against the wall. With the ejector shut off, the membrane remained tightly conformed for approximately 2 hr. With the suction reapplied, divers were able to locate a small leak near the defective bolts by injecting dye into the water near the bolts. The defective bolts were removed and replacement bolts were installed underwater. When the nuts were tightened, an efficient seal was achieved. This installation demonstrated that the system is repairable as well as constructible.

Results of the underwater installation dealt with two basic issues:

- Installation constructibility.
- Sealing efficiency of the system.

From the standpoint of installation feasibility, the underwater test demonstrated that ease of installation depended on the roughness of the substrate and the geometry of the structure. In rough areas, detailed procedures were required to ensure good perimeter sealing, while on fairly smooth surfaces, installation of all components was easily accomplished. Experience in the dry had already shown this, but environmental conditions underwater amplified the problems associated with difficult features. This test mirrored experience in dry installations and showed that additional care is required to ensure good perimeter sealing when installations are performed in the more challenging underwater environment.

The research team believed that particular geometries of the structures, such as the complex corners, should be treated with a prefabricated sheet. Such scenarios will have to be addressed for each installation. Structures with complex shapes, such as intake towers, may require prefabricated membrane pieces to reduce installation time. Protrusions and depressions may constitute a design issue if they are very sharp. Experience in the dry, however, has proved that such irregularities can be adequately addressed with additional transition layers of nonwoven, needle-punched geotextiles.

Testing the system revealed that seepage through the repaired area was very slow. Even where five adjacent anchor bolts failed, leakage was slow enough to make detection of the leak difficult to notice even when dye was injected at the point of leakage. Although the leakage rate was not measured, the research team believed that it was slow enough to be negligible with respect to the requirements of most concrete hydraulic structures. The use of a drained system helped to locate and rectify the leak.

Conclusions

The successful underwater installation of the membrane repair system demonstrated the feasibility of the system. Although results of the demonstration were more qualitative than quantitative, it is evident that the system is constructible and will perform acceptably when designed and installed correctly.

Compared to dewatering of a structure for repair, a geomembrane system that can be installed underwater minimizes the impact of the repair on project operations such as hydropower generation, and recreation. Also, the underwater repair system eliminates the potentially adverse environmental impacts associated with dewatering of many structures.

Future Work

Pending availability of funding, current plans are to demonstrate the constructibility of the underwater repair system on a prototype structure. Candidate structures or appurtenances are being solicited. Anyone with a potential application for a repair of this type should contact Jim McDonald at (601) 634-3230.

References

Christensen, J. Chris, Marcy, Matthew M., Scuero, Alberto M., and Vaschetti, Gabriella L. (1995). "A Conceptual Design for Underwater Installation of Geomembrane Systems on Concrete Hydraulic Structures," Technical Report REMR-CS-50, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Marcy, Matthew M., Scuero, Alberto M., and Vaschetti, Gabriella L. (1996). "A Constructibility Demonstration of Geomembrane Systems Installed Underwater on Concrete Hydraulic Structures," Technical Report REMR-CS-51, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McDonald, James E. (1993). "Geomembranes for Repair of Concrete Hydraulic Structures," *The REMR Bulletin*, 10(4), 1-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

***James E. McDonald** is a research civil engineer in the Concrete and Materials Division, Structures Laboratory, WES. He is the Problem Area Leader for the Concrete and Steel Structures portion of the REMR Research Program and is also the Principal Investigator for three REMR work units, including 32636, "New Concepts in Maintenance and Repair of Concrete Structures." McDonald has been involved with various aspects of concrete research for 35 years and has authored more than 100 technical reports and articles relating to concrete and other construction materials. He received his bachelors and master's degrees in civil engineering from Mississippi State University. He is a registered Professional Engineer in the State of Mississippi.*

Reprinted from The REMR Bulletin, Volume 14, Number 1, February 1997, with permission.

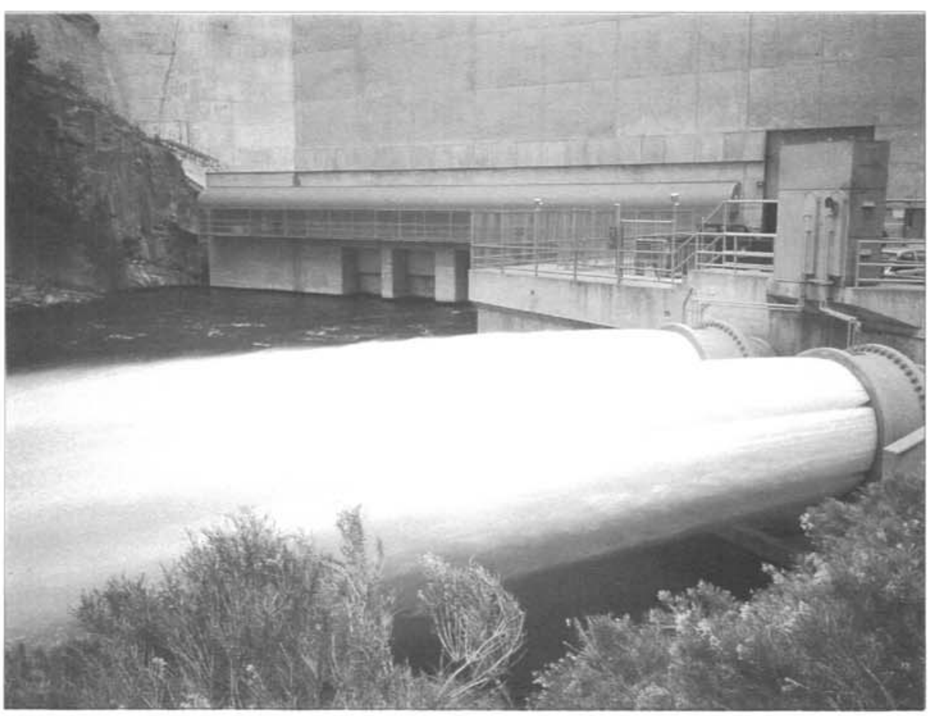
Flows and Woes at Flaming Gorge Dam

by Lisa Iams, Public Affairs Specialist, Salt Lake City, Utah

So far, 1997 has proven to be an unusual hydrologic year throughout much of the West. Case in point, the recent history of Flaming Gorge Dam on the Green River in northeastern Utah. May and June have been interesting to say the least. It all began with the mid-May river flow forecast which projected high inflows to Flaming Gorge Reservoir. With the reservoir level already fairly high, the Bureau of Reclamation initiated bypass releases from the dam's two outlet tubes beginning May 28, 1997. The goal was to evacuate approximately 50,000 acre-feet of water from the reservoir to accommodate the inflows. The bypass tubes were releasing a combined total of 2,000 cubic feet per second (cfs) in addition to the full powerplant capacity releases of 4,600 cfs.

After only two-and-a-half days, Reclamation had to suspend the bypass releases due to unexpected increased river flows in the Yampa River, caused by significant precipitation in the river's headwaters, and a sudden increase in high-elevation temperatures. The Yampa River joins the Green River 68 miles below the dam. The combination of the Yampa's increased flows and the releases from Flaming Gorge Dam would have caused flooding in Jensen, Utah.

For the next two weeks, Reclamation closely monitored and evaluated the hydrologic data to determine when and if the bypass flows from the dam would resume. While the projected inflows to the reservoir dropped lightly during that time, there was still concern that the reservoir would become too full in the summer to release the required low flows for endangered fish.



Water gushes at 4,000 cubic feet per second from two 72-inch steel outlet tubes running through Flaming Gorge Dam. Photograph by Tom Ryan (regional office in Salt Lake City, Utah).

Chronological Highlights of the Flaming Gorge Event

Wednesday, May 28, 1997

- *First bypass releases begin. Both outlet tubes operated at a combined total of 2,000 cfs in addition to powerplant capacity releases of 4,600 cfs.*

Friday, May 30, 1997

- *Bypass flows temporarily suspended due to high Yampa River flows.*

Monday, June 16, 1997

- *Bypass releases reinitiated at higher level—both outlet tubes operated at a combined total of 4,000 cfs in addition to powerplant capacity releases of 4,600 cfs.*

Saturday, June 21, 1997

- *Approximately 6:05 p.m. a hole in #2 bypass outlet tube occurs, triggering alarms and flooding powerplant—powerplant shuts down.*
- *Crews arrive immediately, manually lower ring follower gates to one-half closed, determine problem is in #2 bypass tube.*
- *Crews close #2 bypass tube completely, reopen #1 tube to restore full 2,000 cfs releases, open spillway to release 2,000 cfs.*

Sunday, June 22, 1997

- *Bulkhead gate is placed over upstream opening to #2 outlet tube.*
- *Two- by three-foot hole discovered in #2 outlet tube.*
- *Press conference held in Salt Lake City, Utah.*

Monday, June 23, 1997

- *Assessment on #1 outlet tube detects no significant vibration.*
- *Assessment of powerplant conditions conducted—spare parts brought in for repairs.*
- *Physical inspection of dam begins.*

Tuesday, June 24, 1997

- *Continued powerplant assessment; crews begin examining, removing, and replacing damaged components.*
- *Dam inspection completed—no problems discovered.*
- *Examination of failed bypass tube begins.*

Wednesday, June 25, 1997

- *Reclamation Commissioner Eluid Martinez arrives on site to observe damaged tube and discuss plans for bringing the powerplant back on line.*
- *Technical experts from Reclamation Denver Technical Service Center arrive to inspect damage.*
- *Continued inspection of #2 bypass outlet tube.*
- *Work continues to restore powerplant generating units.*

Thursday, June 26, 1997

- *Start-up procedures for first of three generating units begin; unit is operated on a "spin-no-load" basis.*
- *First generating unit unsuccessful at sustaining power generation load after successfully completing "spin-no-load" start up.*

Friday, June 27, 1997

- *Crews are successful at restoring first generation unit after isolating and correcting problems encountered on Thursday.*

Saturday, June 28, 1997

- *Crews restore second generation unit.*

Sunday, June 29, 1997

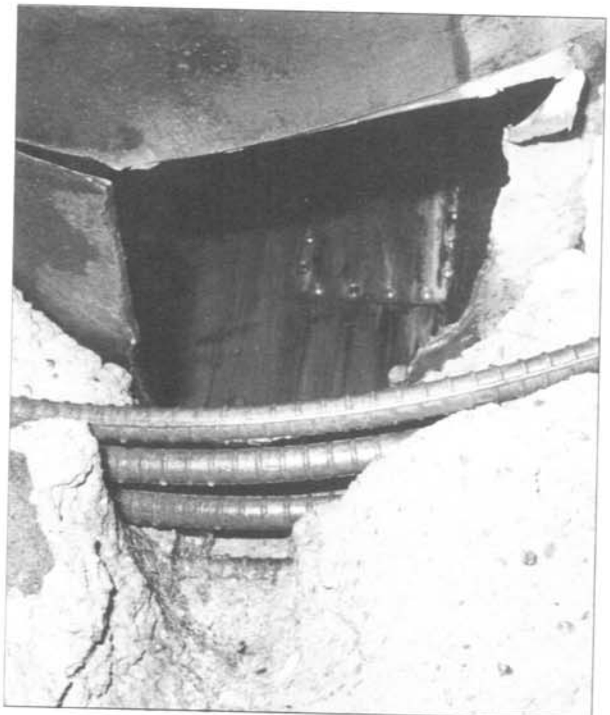
- *Crews restore third generation unit.*
- *All three units were capable of operating at full capacity, but run at less than capacity through mid-week, June 30, 1997, to ensure that all problems had been solved.*
- *Combined releases through the powerplant are 2,000 cfs at 53 degrees.*

Monday, June 30, 1997

- *All three generating units continue to be up and in operation. The units have been tested under a variety of conditions and loads.*
- *Crews prepare to close outlet tube #1 for a complete inspection.*

Tuesday, July 1, 1997

- *Starting at 8:00 a.m., flows from the spillway and #1 outlet tube are reduced.*
- *The #1 outlet tube is shut down so that a thorough inspection can be completed. The spillway is also shut down.*
- *Combined releases through powerplant are consistent at about 4,600 cfs (full capacity) and 53 degrees.*
- *Inspection of #1 outlet tube completed. The tube is determined to be in excellent working condition and available for use if needed.*



Upward view of the hole in the #2 hollow jet bypass tube.

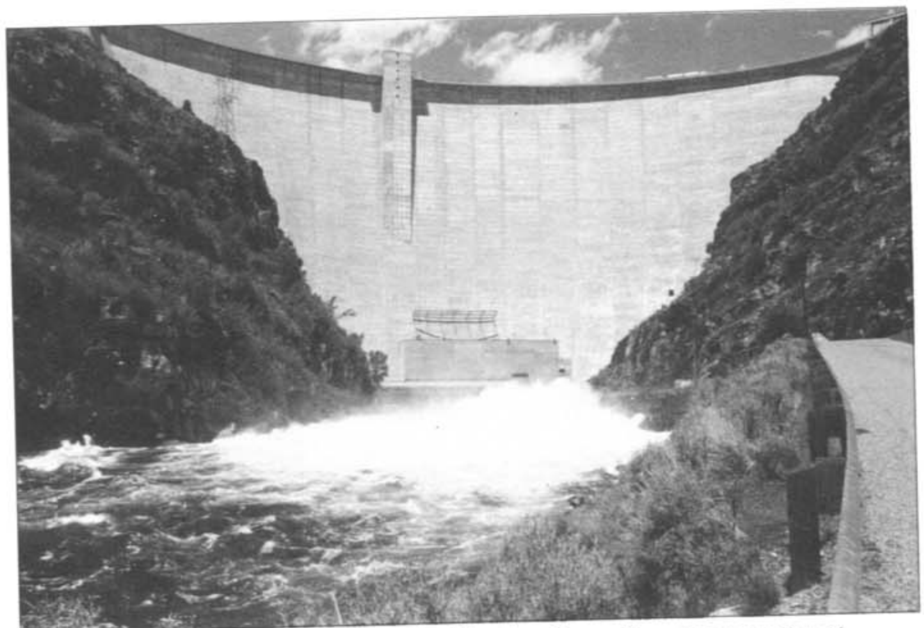
Photographs taken by
Eddy Lennon, Flaming Gorge
Field Division, Dutch John, Utah

Heavy file cabinets, refrigerator, and other office furniture and equipment "rearranged" in an office area damaged by water.

Bay door damaged by water pouring through the hole in the outlet tube.

By mid-June, the Yampa's flow rate had finally decreased, but the forecasted inflows to Flaming Gorge Reservoir had increased again. That's because inflows into Fontenelle Reservoir, upstream from Flaming Gorge Dam in southwestern Wyoming, were at their third highest level since the dam was completed in 1964. High releases from Fontenelle became necessary to avoid an uncontrolled spill.

On June 16, 1997, Reclamation again initiated bypass releases from Flaming Gorge Dam, but this time at the outlet tubes' full capacity of 4,000 cfs, again in conjunction with the full powerplant capacity releases. After receiving the mid-June forecast from the National Weather Service, Reclamation determined that the bypass releases would need to continue through June 23 in order to evacuate enough water to accommodate inflows.



Rising 502 feet above bedrock, Flaming Gorge Dam spews water at 4,000 cubic feet per second from the spillway and the remaining outlet tube.

Before that target was reached, an alarm sounded at approximately 6:00 p.m. on Saturday, June 21, 1997. Flooding within the powerplant was taking place, resulting in a powerplant shutdown and a rapid drop in flows from 8,600 cfs to about 4,000 cfs.

When crews arrived at the dam, there were six inches of water on the main floor of the powerplant, and an additional three to four feet of water on the level below. The releases from the bypass tubes were decreased by half as crews worked to determine which tube was leaking.

When the #2 outlet tube was identified as the source of the problem, crews closed that tube completely, and reopened the #1 tube to full outlet capacity. However, this process took over two hours, since workers had to dry out the electrical control panel which contains the circuit breakers that supply power to the ring-follower gates that close off the tubes. The spillway then had to be opened to release the 2,000 cfs of water no longer being released by the second outlet tube.

Once the situation was stabilized, further inspection of the #2 tube revealed a 2- by 3-foot hole located adjacent to the expansion joint that was initially believed to be the source of the problem. On Wednesday, June 25, 1997, Reclamation Commissioner Eluid Martinez visited the site to discuss the damage and review the plan to bring the powerplant back on line. Crews worked around the clock to restore powerplant operations and clean up the mess created by the water in the powerplant.

In addition to the damage caused by the flood inside the powerplant and the loss of power generation capability, the powerplant shutdown presented some interesting operational challenges. Water must be released from the reservoir to maintain flow levels in the river for the fish. The temperature of this water is an important concern for the trout fishery immediately downstream, because the fish are accustomed to the cool water released through the powerplant, which is drawn from low in the reservoir. The water released through the spillway is much warmer since it is drawn from closer to the reservoir surface. Reclamation has been in close contact with the Utah Division of Wildlife Resources since the first alarm sounded to gather data and discuss the impacts of different operational scenarios. The fish adapted to the temperature changes in the water, and no significant problems emerged.

By Sunday morning, June 29, 1997, crews had restored the operation of all three generating units. However, they were operated at less than full capacity throughout the weekend to ensure that all problems had been solved. Together, these units passed 2,000 cfs flows to the river through Tuesday, July 1, 1997, at a temperature of 53 degrees, the same temperature as the mixed water temperature from the remaining bypass tube and the spillway releases.

Because restarting the generating units was accomplished faster than anticipated, the #1 outlet tube was ready for shutdown on July 1, 1997, so that a thorough inspection of the tube could be conducted. Sound sensing and vibration equipment had been installed on the #1 outlet tube immediately after the #2 tube failure, and readings taken every two hours indicated that there were no problems with the #1 tube. Preparations for an inspection had been underway for several days, concurrent with completing repairs on the water-damaged generating units, and now that Reclamation was satisfied that the powerplant was operational, it was prudent to get the review doneas soon as possible.

Starting at 8:00 a.m. on July 1, flows from both the #1 outlet tube and the spillway were reduced. An operational clearance was then placed on the gate mechanism of the outlet works to ensure it would not start up while workers were inside the pipe. Downstream from the ring-follower valve, the pipe was drained and an access cover removed. The inspectors, which included a metallurgist and several engineers, looked for any signs of damage to the pipe welds or indications of cavitation or corrosion that may signal a potential weakness. After a complete inspection, it was determined that the pipe was in excellent condition. The #1 outlet tube is now available for use if needed.

Flows in the river will remain consistent at about 4,600 cfs and 53 degrees. This is to prevent impacting the trout fishery below the dam and the endangered fish located further downstream with a significant temperature or flow variation. The overall direct impacts to the trout and the endangered fish appear to be minimal.

Reclamation will have a repair plan for the failed outlet works in place within the next month. The outlet tube will be repaired by the end of the year and will be operational in time for the spring 1998 runoff season.

The failure event and loss of the powerplant did not cause any interruption to the power system in the Southwest.

Reclamation staff at Flaming Gorge Dam, and from other sites, that have been at the dam working to stabilize and rectify the problems caused by the outlet tube failure are to be commended for their expertise, quick response, and hard work. Reclamation would like to thank these hard working employees for bringing the situation under control and working to restore normal operations as quickly as possible.

Gantry crane on top of Flaming Gorge Dam used to place the bulkhead gate in front of the opening to the damaged bypass tube.

Reprinted from The Spillway, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, July 1997.

Printed on Recycled Paper

☆U.S. GOVERNMENT PRINTING OFFICE 1997–843-435

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

The purpose of this bulletin is to serve as a medium of exchanging operation and maintenance information. Its success depends upon your help in obtaining and submitting new and useful operation and maintenance ideas.

Advertise your district's or project's resourcefulness by having an article published in the bulletin—let us hear from you soon!

Prospective articles should be submitted to one of the Bureau of Reclamation contacts listed below:

Jerry Fischer, Technical Service Center, ATTN: D-8470, PO Box 25007, Denver, Colorado 80225-0007; (303) 236-9000 ext. 230, FAX (303) 236-1070

Vicki Hoffman, Pacific Northwest Region, ATTN: PN-3234, 1150 North Curtis Road, Boise, Idaho 83706-1234; (208) 378-5335, FAX (208) 378-5305

Dena Uding, Mid-Pacific Region, ATTN: MP-430, 2800 Cottage Way, Sacramento, California 95825-1898; (916) 979-2422, FAX (916) 979-2505

Bob Sabouri, Lower Colorado Region, ATTN: LC-4844, PO Box 61470, Boulder City, Nevada 89006-1470; (702) 293-8116, FAX (702) 293-8042

Don Wintch, Upper Colorado Region, ATTN: UC-258, PO Box 11568, Salt Lake City, Utah 84147-0568; (801) 524-3307, FAX (801) 524-3034

Tim Flanagan, Great Plains Region, ATTN: GP-2400, PO Box 36900, Billings, Montana 59107-6900; (406) 247-7780, FAX (406) 247-7793