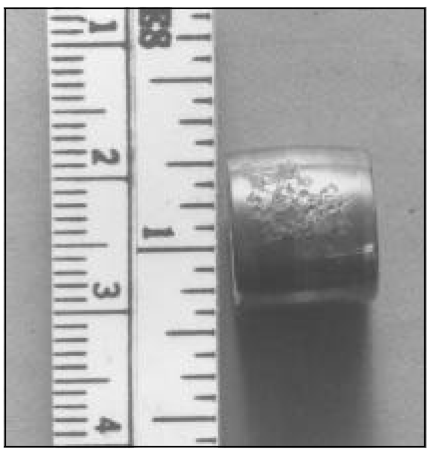
WATER OPERATION AND MAINTENANCE BULLETIN

No. 185 **September 1998**



IN THIS ISSUE. . .

- Inspection of Brake Motors and Speed Reducers for Gate Hoists
- Abrasion/Erosion in Stilling Basins
- Hydraulic Model Studies of Aeration Enhancements at the Folsom Dam Outlet Works: Reducing Cavitation Damage Potential
- Nondestructive Testing of Large Concrete Dams

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.

For further information about the *Water Operation and Maintenance Bulletin* or to receive a copy of the index, contact:

Jerry Fischer, Managing Editor
Bureau of Reclamation
Inspections and Emergency Management Group, Code D-8470
PO Box 25007, Denver CO 80225
Telephone: (303) 445-2748
FAX: (303) 445-6381
Email: jfischer@do.usbr.gov

Cover photograph: *Roller bearing removed from secondary speed reducer after approximately 40 years in service (left). Climbers of Reclamation's Climb Team (right).*

UNITED STATES DEPARTMENT OF THE INTERIOR **Bureau of Reclamation**

WATER OPERATION AND MAINTENANCE BULLETIN
No. 185—September 1998

CONTENTS

Page

INSPECTION OF BRAKE MOTORS AND SPEED REDUCERS FOR GATE HOISTS

by Bill Nixon, Jr.[1]

Introduction

Brake motors and speed reducers require little service and normally receive no service. They are usually quiet and run very slowly. These are not characteristics that attract attention. Running time is extremely low—1 hour or less in a year is not unusual. Brake motors and speed reducers would last forever if kept in a hermetically sealed environment. However, if the machinery has been outside in the hot sun, blowing sand, snow, and rain for approximately 40 years, moisture and dirt may have worked into the various parts.

Description

A brake locks the hoist machinery, engaged by spring pressure and disengaged by an electromagnet. It may also have a manual release. The brake mechanism is normally bolted to one end of the motor.

The motor is normally two direction, three phase, 440 volt, 60 Hertz, totally enclosed fan cooled, and weatherproof. In most applications, the motor is bolted to the primary speed reducer.

A primary speed reducer is bolted to the structure. Many designs include a secondary speed reducer, and some have a tertiary or final reducer.

Inspection of the Brake

Many of the brakes have been specified to include a manual release. The manual release is usually a small lever extending through an opening in the inspection cover. Very little force is required to operate the lever. Experience has proven that the gate will go down when the brake is manually released.

Because of the manual release lever, unauthorized or accidental lowering of a gate may be possible. The Mid-Pacific Region has installed covers over several manual release levers. Covering the levers may be more important when the equipment is open to the public.

[1] Division of Resources Management, Mid-Pacific Region, Sacramento, California.

Remove the inspection cover to examine the brake mechanism, and you will often find sand and rust inside. If the brake mechanism has a manual release, sand may get in through the release lever opening. The machinery is delicate. Use compressed air to blow out the dirt. Use a soft cloth to carefully clean the brake parts. Examine the brake lining and rotors. Study the mechanism to identify the fulcrums and bearings. Wipe the parts with a clean soft cloth that is dampened with light oil (20 weight oil, for example). ***Do not use spray can lubricant. It is imperative that no oil gets on the lining or rotors.*** If the gate is open, you may carefully release the brake just enough to watch the rotor turn one or two revolutions—this will lower the gate less than ten thousands of an inch. Inspect the electrical release solenoid. Inspect wires for cracked insulation. Do not move any wires unless there is a need to do so. Do not make any adjustments unless there is a need to do so. If it is working, do not adjust it. Clean the inspection cover. Apply a thin coat of heavy grease or gasket former to the cover seal. Remember, the cover must be removable—do not cement it on. New parts for the brake are very likely unavailable.

Inspection of the Motor

Check the air cooling system for mud and wasp nests. The motor will be equipped with sealed ball bearings which were greased at the factory. After 30 or 40 years, the grease becomes hard and dry and no longer lubricates. There is no acceptable way to add grease. Look for evidence of motor shaft side play. There should be no measurable play. Sound is a very good test, provided the motor can be run for a few minutes. The motor should be very smooth and quiet. You can use a wood rod or a stethoscope to listen and determine if there are unusual sounds and where they are coming from. New bearings are available for almost any motor, no matter how old it is. And, any motor can be rewound, although the expense may make it impractical.

Inspection of the Primary Speed Reducer

The primary reducer is normally a factory design. The gear ratio is always high. For example, the gear ratio could be 180 to 1, the motor R.P.M. could be 1,800, and the output R.P.M. would be 10. The torque would be multiplied by 180. The primary gear box is always a wet box, meaning it will use liquid oil for lubrication. Determine if the oil is ever changed. If possible, remove a sample of oil from the bottom of the gear box. Any visible water is a hint of more serious problems and reason enough to suggest that the oil be changed. Check the input and output shafts for oil leaks. Some seepage is acceptable; a leak that forms a puddle is not acceptable. When you are listening to the motor, also listen to the speed reducer. New bearings are probably available, but the gears and other parts are almost certain to be orphans.

Inspection of the Secondary Speed Reducer

The secondary speed reducer will be a much larger machine. It will run very slowly. It may have been designed by the Bureau of Reclamation, and any parts, other than bearings and seals, will have to be designed and made to order. There should be inspection covers. Examine the inside parts for rust or discoloration. Some boxes are designed with semi-external bearings that are greased manually from the outside. Examine the oil for water. Check the records regarding oil changes. The oil change schedule is affected by climate and weatherproof quality of the gear box. These large speed reducers should last a very long time, perhaps over 100 years. Leaking seals and bad bearings are parts that must be scheduled for replacement.

Inspection of the Tertiary or Final Drive

The final drive will be similar to the secondary drive, and all comments apply to both of them. Sometimes, the final drive is a dry type. The gears may be exposed or may be inside a dry box. The lubricant is often a tar-like grease. Inspect this grease for sand or other contamination; otherwise, there may be no reason to change it. Some exposed gears run without any lubricant—this is to prevent sand or dust from sticking to the surface.

Conclusion

The following photograph shows a roller bearing removed from a secondary speed reducer. The unit had been in service for approximately 40 years. The oil had never been changed. There was water in the bottom of the gear box, and the bearings had been destroyed by corrosion.

Roller bearing removed from secondary speed reducer after approximately 40 years in service.

ABRASION/EROSION IN STILLING BASINS

by Leslie Hanna and Elisabeth Cohen, Bureau of Reclamation, Denver, Colorado, USA

Introduction

Many stilling basins have experienced damage caused by rock, gravel, and sand brought into the basin by back flow over the stilling basin end sill. Normal operation of a hydraulic jump energy dissipation basin can cause a reverse flow eddy over the basin end sill and lower apron, as shown in figure 1. This counter-rotating eddy is driven by a high-velocity jet rising off the basin floor near the end of the basin. Riprap placed on the apron downstream of the basin end sill is typically designed to be stable under this condition. However, small material can be transported into the basin and trapped where turbulent flow continually moves the material about the surface, eroding the concrete. The cost for these repairs, in terms of time, effort, and money, can be significant. If a means to reduce the reverse flow can be found, large savings can be obtained. One possible solution that is currently being studied at the Bureau of Reclamation's Water Resources Research Laboratory (WRRL) is to install flow deflectors in the basin to improve inter-basin flow conditions and minimize upstream velocities over the basin end sill (figure 2).

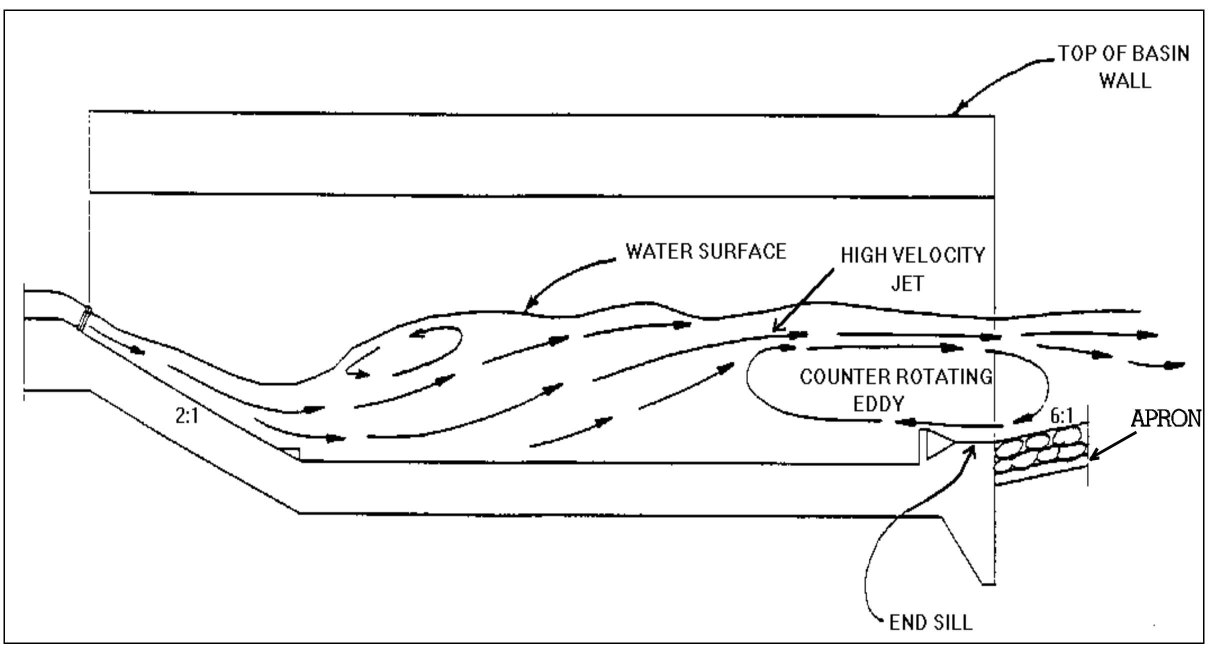


Figure 1.—Counter-rotating flow eddy over basin end sill and lower apron.

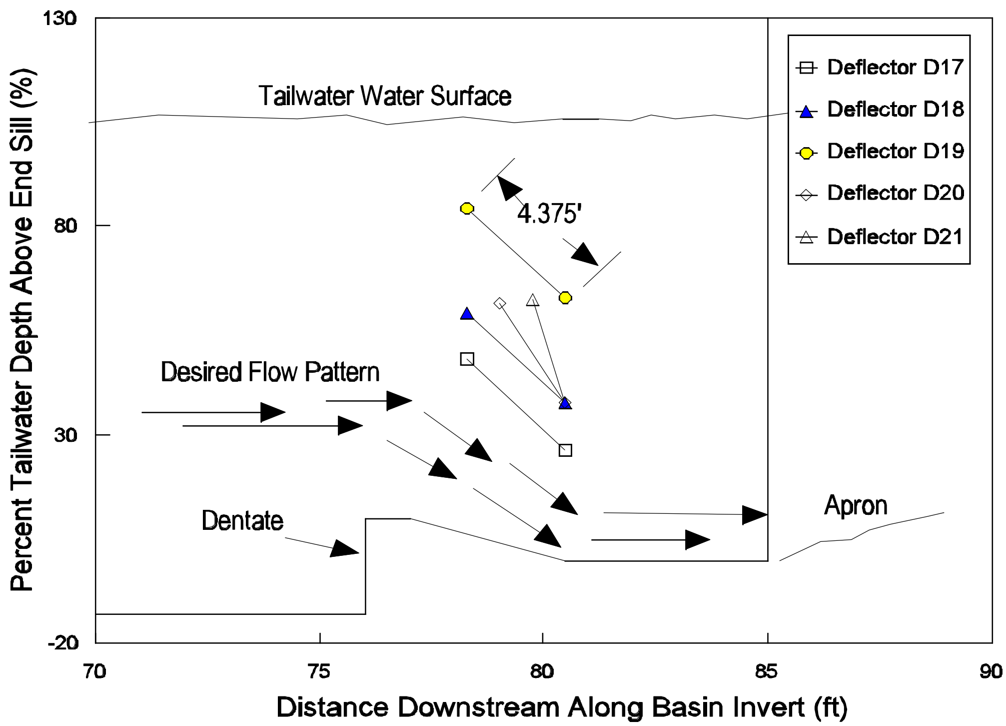


Figure 2.—Deflector locations with respect to tailwater depth above the basin end sill.

Experiences

Many stilling basins have experienced abrasion damage, as exemplified below, at several Bureau of Reclamation dams. Often abrasion has progressed to depths exposing reinforcement and requiring repair of concrete by sawcutting, sandblasting, and concrete replacement with polymer concrete or silica fume concrete.

Vallecito Dam—Vallecito Dam, completed in 1941, experienced abrasion/erosion damage in the outlet works stilling basin in the 1980's. The repairs, completed in 1991, involved a silica fume concrete with high slump and strengths of 9,000 pounds per square inch. The spillway chute has since experienced more erosion, indicating that this is a continuing problem.

Ridgway Dam—An underwater inspection of the Ridgway Dam outlet works stilling basin revealed that the concrete floor was severely eroded, with the reinforcing bars exposed. The region will have this work repaired using a two-phase process. The first phase is to construct bypass capacity to dewater the stilling basin, remove all materials, and determine the extent of repairs needed. The second phase the following year will be to make the repairs. The work scope is not determined, but the total cost may be between $200,000 and $1,000,000.

Taylor Draw Dam—In 1991, about $200,000 was spent to repair abrasion damage to the Taylor Draw Dam outlet works stilling basin. After just one operating season, an inspection revealed that abrasion damage had again occurred. After repairs were completed the second time, a study conducted by WRRL demonstrated that the installation of flow deflectors improved the basin's flow distribution significantly, greatly reducing the potential for movement of material into the basin. The deflectors have been in place for 4 years, with no further repairs to the basin concrete required.

The Model

A physical model is being used to investigate hydraulic conditions in Type II stilling basins and to study the affect of deflector positioning and inclination on flow patterns over the basin end sill. The study will be used to optimize and generalize flow deflector designs based on basin geometry and operating conditions. The Ridgway Dam outlet works and its Type II twin bay stilling basin are being used for the model investigations. The model includes the 42-inch high-pressure slide gates discharging into 2:1 sloping chutes and 12-foot-wide bays. The basin is 85 feet long. Froude scaling was used to model the outlet works at a 1:10.5 scale. The downstream riprap apron topography was modeled on a 6:1 slope with moveable bed material to simulate the abrasion source. Unit discharges (q) (corresponding to 40-, 60-, 80-, and 100-percent gate openings for the Ridgway Dam outlet works) and percent of tailwater depth were used to describe flow conditions. Velocity measurements were determined using a sontek acoustic flow meter and were measured at the downstream end of the basin end sill in the center of the bay. Bottom velocities were measured 5.25 inches above the basin end sill. All velocities are described in terms of average velocities. Tailwater was set according to the tailwater curve generated for the Ridgway Dam outlet works operations.

Investigations

Flow conditions over the basin end sill were characterized with profiles representing average velocities (negative values represent velocities in the upstream direction) mapped along the vertical axis in the center of the bay for unit discharges of 29 cubic feet per second per foot ($ft^3/s/ft$) (40-percent gate), 41 $ft^3/s/ft$ (60-percent gate), 52 $ft^3/s/ft$ (80-percent gate), and 60 $ft^3/s/ft$ (100-percent gate), as shown in figure 3. The vertical axis shows the relative depth in percent of total tailwater depth over the basin end sill. Initial investigations determined that the most effective position along the length of the basin was to locate the deflector directly above the downstream slope of the basin dentates. Once this was established, the most effective position along the vertical axis was investigated. Figure 3 shows that as values of unit q increase, the thickness of the high-velocity (downstream) jet increases, thereby

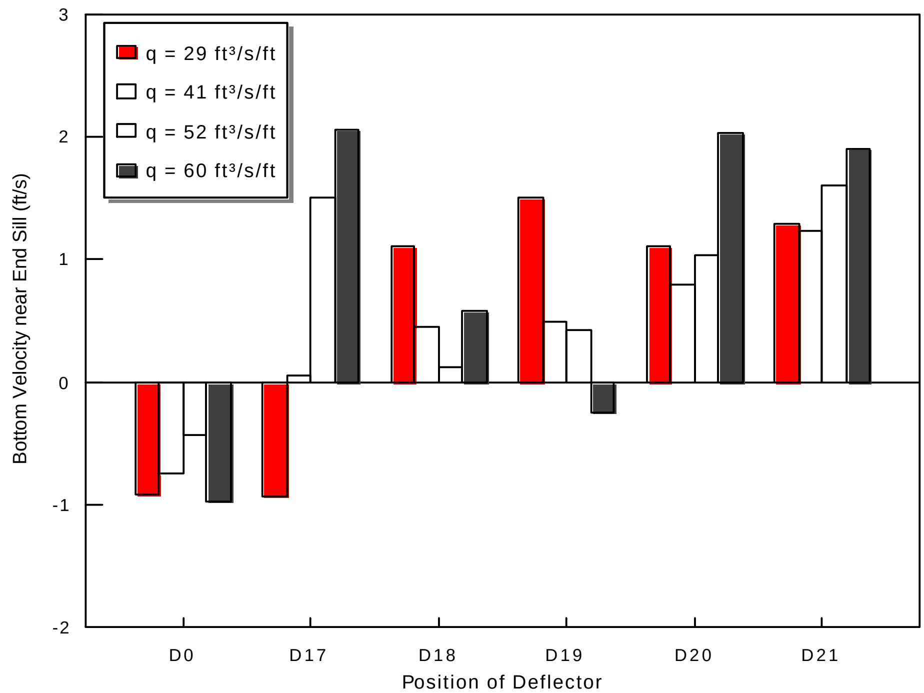


Figure 3.—Bottom velocities (average) measured for each deflector position. (D0 indicates no deflector was installed.)

lowering the transition point between upstream and downstream velocities above the basin end sill. The effectiveness of the flow deflector is dependent on the vertical location of the deflector with respect to this transition point and its ability to trap and redirect a large enough portion of the high-velocity jet (immediately above the transition point) to improve flow conditions. With this in mind, three vertical locations and several deflector angles were investigated.

All the deflectors tested were 4.375 feet deep and were located as shown in figure 2. Deflectors D17 through D19 were positioned at an angle of 60 degrees, and deflectors D20 and D21 were positioned at 70 and 80 degrees, respectively.

Figure 4 shows bottom velocities measured near the basin end sill for deflector positions D17 through D21 for each flow tested. The results of these investigations show that the performance of each deflector varies over the range of flows. When the deflector was positioned low in the basin and just above the transition points of the higher flows (i.e., D17), the deflector performed well at the high flows. However, it became ineffective as the flow was decreased because the transition point moved above the location of the deflector. As a result, at the lower flows, the deflector missed a major portion of the high-velocity jet because it was positioned below it. A similar problem occurred when the deflector was positioned too high (i.e., D19). Although the deflector was in good position (just above the transition point)

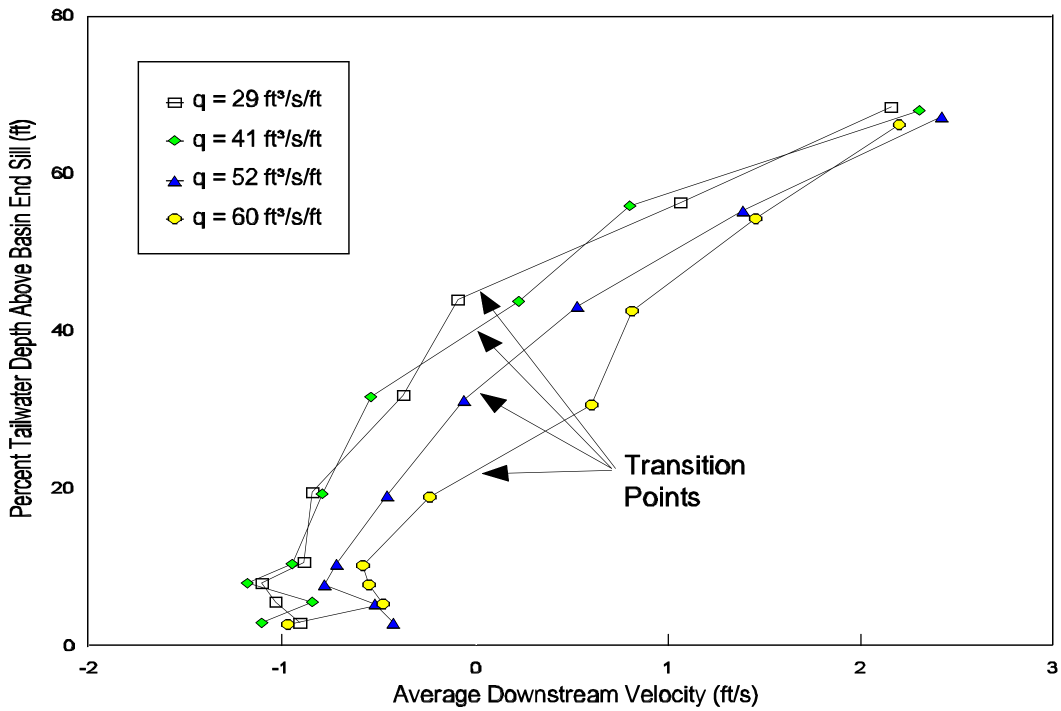


Figure 4.—Velocity profiles measured along the vertical axis above the basin end sill.

to redirect the jet at the lower flows, as the flow was increased, the transition point moved too far below the deflector for it to remain effective. The solution was to position the deflector (D18) between the locations of deflectors D17 and D19 where it would be less sensitive to the movement of the transition point. This produced positive downstream velocities (average) throughout the range of flows.

Next, the angle of the deflector was varied. Deflectors D20 and D21 were installed at the same location as D18 except with the angle increased to 70 and 80 degrees, respectively.

Figure 4 demonstrates that flow conditions were improved as the angle was increased, and the best overall results, throughout the range of flows, occurred with deflector D21 installed.

Table 1 shows the velocity range within one standard deviation (67-percent confidence level) for the bottom velocities measured for deflector D21 and with no deflector (D0) installed. The table demonstrates that, with deflector D21 installed, velocities over the basin end sill act predominately in the positive or downstream direction. Without a deflector, the velocities predominantly act in the upstream direction.

Table 1.—Bottom velocities within one standard deviation

Deflector position	Velocity range within one standard deviation (feet per second)			
	q = 29 $ft^3/s/ft$	q = 41 $ft^3/s/ft$	q = 52 $ft^3/s/ft$	q = 60 $ft^3/s/ft$
D21	-.14 to 2.67	-.08 to 2.56	.05 to 3.13	.14 to 3.62
D0	-2.1 to .239	-2.22 to .02	-1.62 to .43	-1.7 to .51

Each of these investigations was conducted with the tailwater depth set at a specific level according to the tailwater curve for Ridgway Dam outlets works operations. Future investigations will determine the best deflector positioning relative to fluctuations in tailwater depth.

Conclusions

Deflectors have been designed and installed at Taylor Draw Dam with marked improvements in stilling basin flow patterns, and, based on the model study, performance of the deflectors show the potential for significant savings by reducing damage caused by abrasion.

The results of the Ridgway Dam hydraulic model study indicate that the effectiveness of the deflector depends on the basin discharge and on the deflector's relative position and sensitivity to the movement of the transition point throughout the range of operations. The study showed the deflector was most effective when it was located between 38 percent and 69 percent of the average tailwater depth over the full operating range and positioned at an angle of 80 degrees.

Further investigations will determine if the deflector location can be generalized over large ranges of tailwater depth. If the variation of the tailwater (i.e., the operating range) is greater than 200 percent, a single deflector may not be effective. The structural design of the deflectors will depend on the material used, the overall width of the stilling basin, and the angle of the deflector. Future work may also involve determining the maximum basin width at which the deflector design will be effective.

Further work at WRRL will include generalizing flow deflector designs for Type III stilling basins.

References

[1] Dodge, Russ, "Hydraulic Study of Taylor Draw Dam Outlet Works," U.S. Department of the Interior, Bureau of Reclamation Report R-92-10, March 1992.

HYDRAULIC MODEL STUDIES OF AERATION ENHANCEMENTS AT THE FOLSOM DAM OUTLET WORKS: REDUCING CAVITATION DAMAGE POTENTIAL

by K. Warren Frizell[1]

Introduction

Folsom Dam is on the American River about 20 miles northeast of Sacramento, California. The dam was built by the Corps of Engineers (Corps) and transferred to the Bureau of Reclamation (Reclamation) for operation and maintenance in 1956. The dam is a concrete gravity structure 340 feet high and impounds a reservoir of a little over 1 million acre-feet.

The dam features two tiers of four outlets each (figure 1), controlled by 5- by 9-foot slide gates. The outlets consist of rectangular conduits of formed concrete passing through the dam and exiting on the face of the service spillway. Historically, the outlets have not been operated much. Flood releases in 1955, 1963, and 1964 resulted in cavitation damage initiating at the constriction on the crown of the outlets just upstream from the junction with the spillway face. The 1955 flood conditions were studied by the Corps using the model for Red Rock Dam which had a similar outlet configuration (Corps, 1965). These tests revealed scaled vapor pressure readings at several piezometer locations near where the damage had occurred. Reclamation studied the problem using a 1:16.7 scale sectional model of one of the upper tier outlets (Isbester, 1971). An eyebrow-type flow deflector was tested and later installed at Folsom over each outlet exit (figure 2). Besides the eyebrow, a gate operating restriction of 60-percent maximum was set when combining outlet works flows with spillway flows. These modifi-cations to the structure and operating criteria have performed well over the years, and no additional damage has occurred at the outlet/spillway junction.

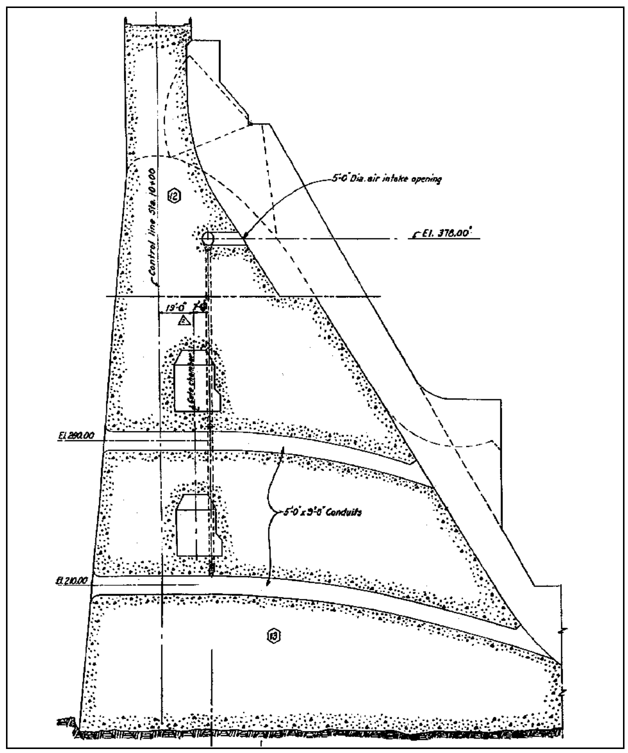


Figure 1.—Section through the dam showing outlet works.

[1] Research Hydraulic Engineer, Water Resources Research Laboratory.

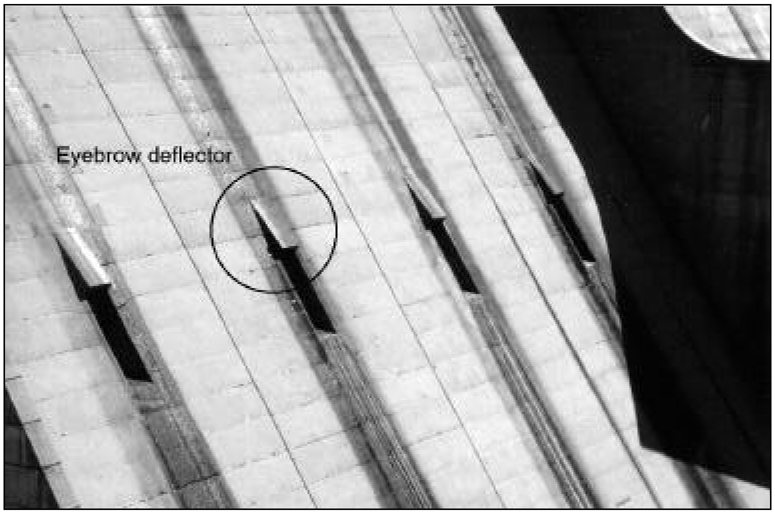


Figure 2.—Eyebrow deflector installed above an outlet exit on the Folsom spillway.

Additional repairs to the outlet conduits (Nos. 1-4) were completed in March 1988. These repairs followed discovery of damage to the invert and lower sidewalls of the low-level outlets at locations from 15 to 60 feet downstream from the end of the gate frame (figure 3).

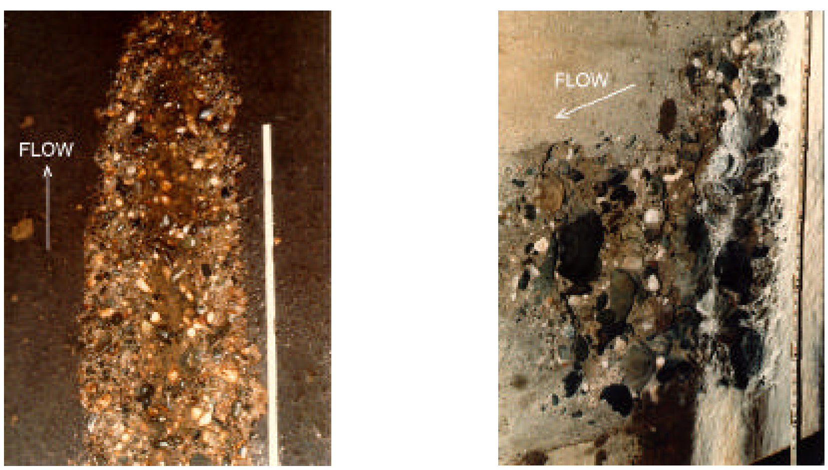


Figure 3.—Damage to invert (left) and the sidewall (right) which occurred in 1987. This damage was 30 to 40 feet downstream from the end of the metal liner.

Operational records from 1988 to the present show increased operation of the low-level outlets at large gate openings since 1993. Between 40 and 45 percent of the total operation of the low-level outlets since that time has been at gate openings of 6 feet or greater (>67 percent open). This change in operations was due to revisions of the operation plan calling for more frequent use of the outlets in order to reduce the chance of exceeding levee capacity downstream and also to supplement flows during repair of the spillway gates.

During major releases in the winter of 1996-97, observers noted that the trajectories of the discharge from outlet Nos. 3 and 4 were falling short of those from outlet Nos. 1 and 2. Inspections in May 1997 revealed major damage due to cavitation in outlet Nos. 3 and 4 (figure 4), minor damage in outlet No. 2 (figure 5), and little or no damage in numbers 1, 5, 6, 7, and 8.

Figure 4.—Damage to conduits 3 and 4, low-level outlets, May 1997.

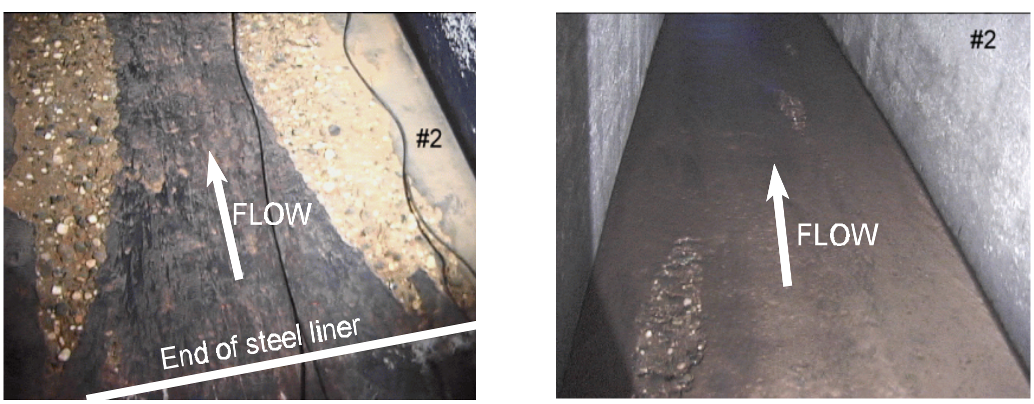


Figure 5.—Damage to invert of conduit 2. Left photo is at the end of the steel liner. Note the pattern of damage on the right photo.

This damage was initiated by cavitation and accelerated by a combination of both cavitation and abrasion. Abrasion damage is probably primarily responsible for the deep lateral extent of the damage in outlet Nos. 3 and 4, especially along the construction joints. There was a widely varying degree of damage between outlets 1, 2, 3, and 4. Cavitation intensity is largely a function of pressure and velocity, so the variation in damage is attributable to very low, localized pressures downstream from the gates due to air starvation. Previous studies have shown the manifold system to be undersized for the expected air demand. Outlets 3 and 4 are at the end of the air manifold that brings air to the conduits.

Model Studies

A 1:12 scale Froude-based hydraulic model of a single low-level outlet gate and conduit was constructed in Reclamation's Water Resources Research Lab. This model was used to verify present operating conditions as well as test modifications aimed at preventing future cavitation damage. The sectional model included the 5- by 9-foot slide gate and the rectangular conduit downstream from the gate. The junction between the outlet and the spillway was also modeled to allow observations of combined spillway and outlet works operations with any proposed modification to the structure (figure 6).

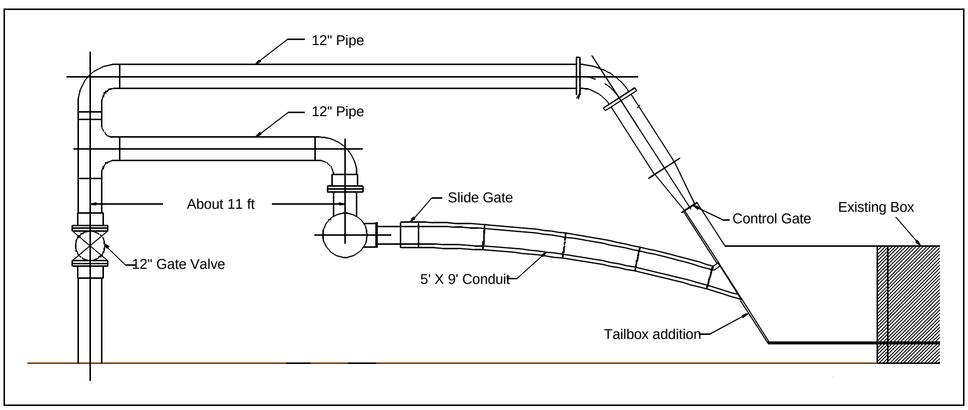


Figure 6.—Elevation of the 1:12 scale hydraulic sectional model.

The model similitude was based on equating the Froude numbers of the model and the prototype:

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \qquad (1)$$

where:

V = velocity
L = length
g = gravitational acceleration
m = model
p = prototype

This lead to the following scale relationships when a common fluid (water) is used in both model and prototype: $L_p=12L_m$, $V_p=3.464V_m$, *and* $Q_p=498.83Q_m$. The scale was chosen due to the desire to measure air demand characteristics. Model Reynolds Numbers ranged from 1.5 x 10^5 to 2 x 10^5. Prior research has shown that to model free surface flows with air entrainment, the flows in the model need to be fully turbulent, $\boldsymbol{Re}_m \geq 10^5$ (Wood, 1991). Much of the prior defining work was done on spillway aerators—a similar concept to the modifications which were tested in this gate model.

Data were collected for a range of reservoir elevations and gate openings. At each point, water discharge was measured using venturi meters. The venturi meters were calibrated against a weigh tank and provide discharge accuracy to within 0.1 percent. Pressures along the conduit invert downstream from the regulating gate were measured using piezometers with water manometers. Piezometer taps were located along the centerline of the invert of the 5- by 9-foot conduit at 9.25, 11.5, 12.5, 16.5, and 22.5 feet downstream from the regulating gate. The amount of air flowing into the conduit downstream from the regulating gate was measured using an orifice plate with three different sized orifices. Multiple orifice plates were used in order to simulate various loss coefficients in the vent/manifold system, including K=1.55, K=6.91, and K=28.85.

Calculations based on Isbester's study showed the air vent system to be well undersized. The 5-foot-diameter air intake header would not be able to carry the full capacity with all gates operating. In addition to increasing the air vent capacity, a more effective method to distribute the air to the sidewalls and invert downstream from the gates was needed. Previous studies on aeration slots and ramps (Beichley, 1975; Beichley and King, 1975; Pinto et al., 1984; Volkart and Rutschmann, 1986) have shown them to be effective in reducing the potential for cavitation damage in outlet works and on spillways. The addition of even small quantities of air into the flow along boundaries has proven effective in eliminating cavitation damage (Peterka, 1953).

The model was first used to verify data for the as-built condition. Once this was completed, an insert resembling the constriction in a jet-flow gate was installed and tested. The 6-inch-high ramp angled at 45 degrees yielded a large reduction in discharge capacity (20 to 25 percent) and was abandoned in favor of reduced slope, smaller offset ramps. Three different aeration ramp configurations were tested. These ramps were placed just downstream from the regulating gate. All ramps had a 15-inch horizontal length, yielding offsets of 3 inches and 1.5 inches for the 1:5 and 1:10 ramps, respectively. The modifications which were tested are shown on figure 7. These ramps were designed to allow air from the present vent system to be distributed down the sidewalls and along the conduit floor.

Results

Model experiments began with measurements of the original as-built conditions. Discharge characteristics, along with air demand and pressures downstream from the gate, were

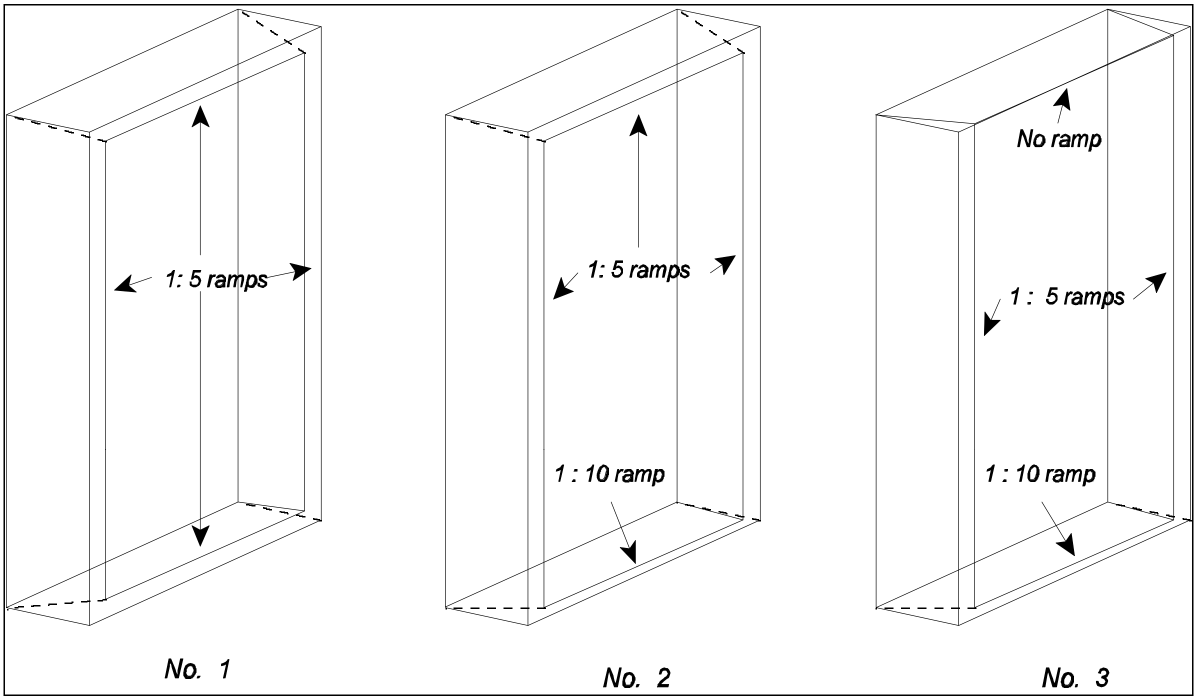


Figure 7.—Ramp configurations tested in the hydraulic scale model.

measured. Figure 8 shows the as-built discharge for one lower-level outlet conduit. Results from three reservoir elevations ranging from 400 feet to 450 feet are reported. The air demand is shown on figure 9, and results are reported for a vent/manifold loss factor, K=6.91. Piezometric pressures downstream from the gate are reported on figure 10.

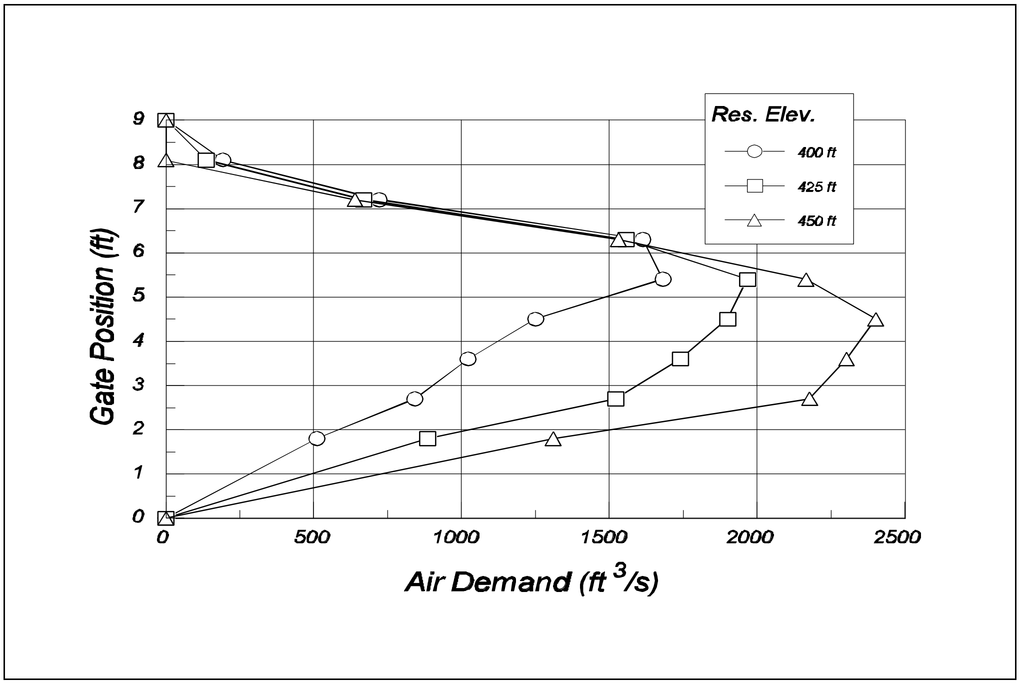


Figure 9.—Air demand for a low-level outlet conduit, as-built conditions.

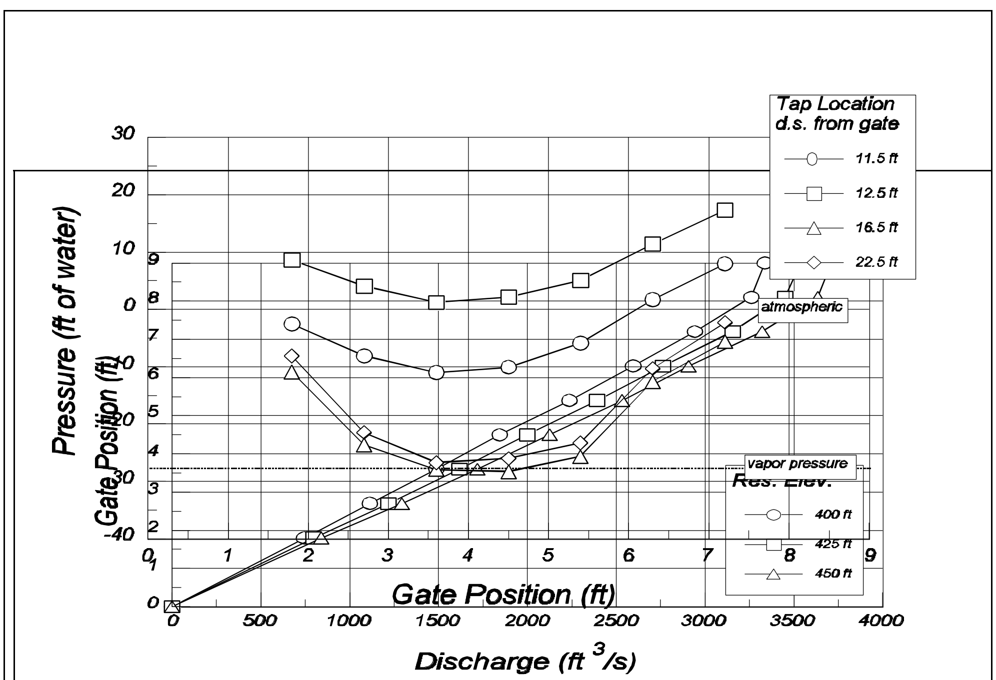


Figure 10.—Pressures on the conduit invert, downstream from the regulating gate. Reservoir elevation 450 feet.

Figure 8.—Discharge for one, low-level outlet conduit, as-built conditions.

The third and final insert that was tested featured no upper ramp. The side ramps remained at a 1:5 slope, and the bottom ramp was at 1:10 (figure 7). The data reported for this insert were taken at range of reservoir elevations from 400 to 450 feet and an air vent loss coefficient of K=6.91. The discharge with insert No. 3 in place appears on figure 11. The air demand and piezometric pressures downstream from the gate are shown on figures 12 and 13, respectively.

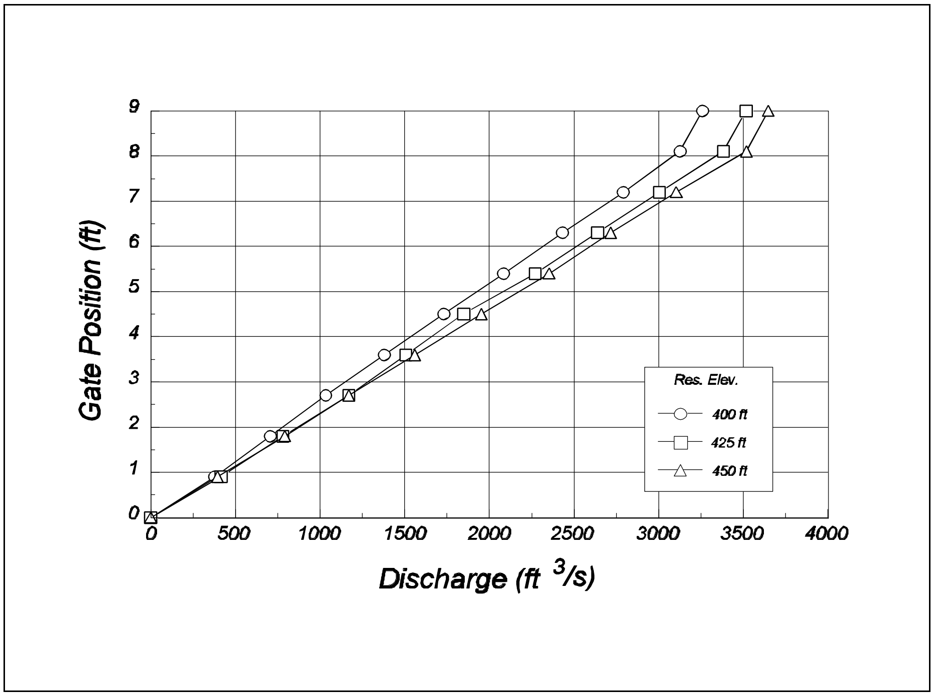


Figure 11.—Discharge for one low-level outlet conduit with insert No. 3 installed.

Discussion

Historically, the outlet works at Folsom Dam have operated infrequently. Modified operations, construction activities, and large storm events are primarily responsible for the flows that resulted in cavitation damage to the outlet conduits in 1997. In addition, an undersized air manifold that distributes air just downstream from each of the eight regulating gates appears to be responsible for air starvation of specific conduits, resulting in variable amounts of damage.

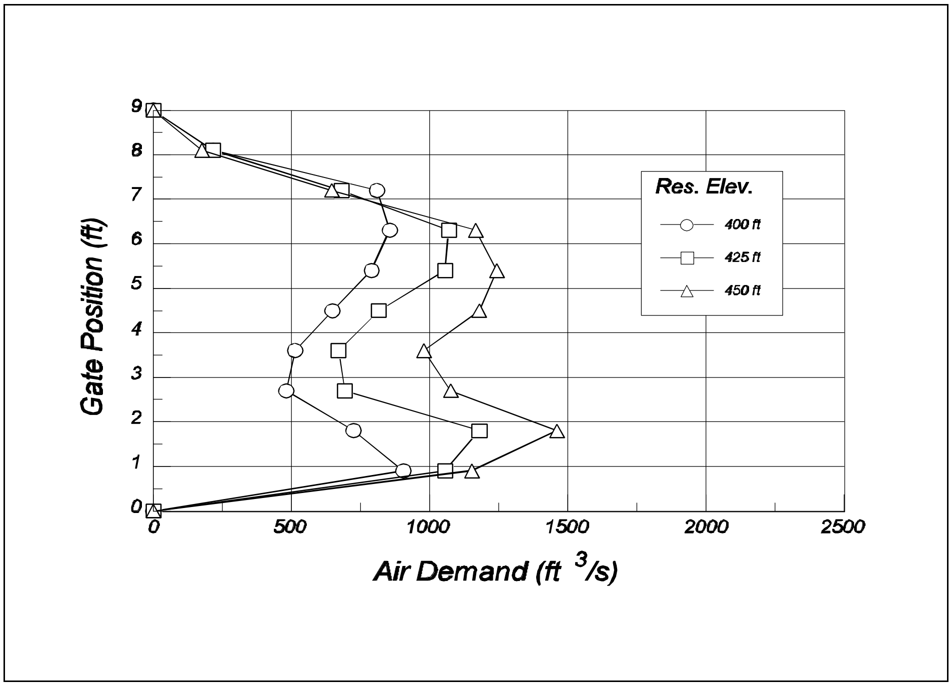


Figure 12.—Air demand for one low-level outlet conduit with insert No. 3 installed.

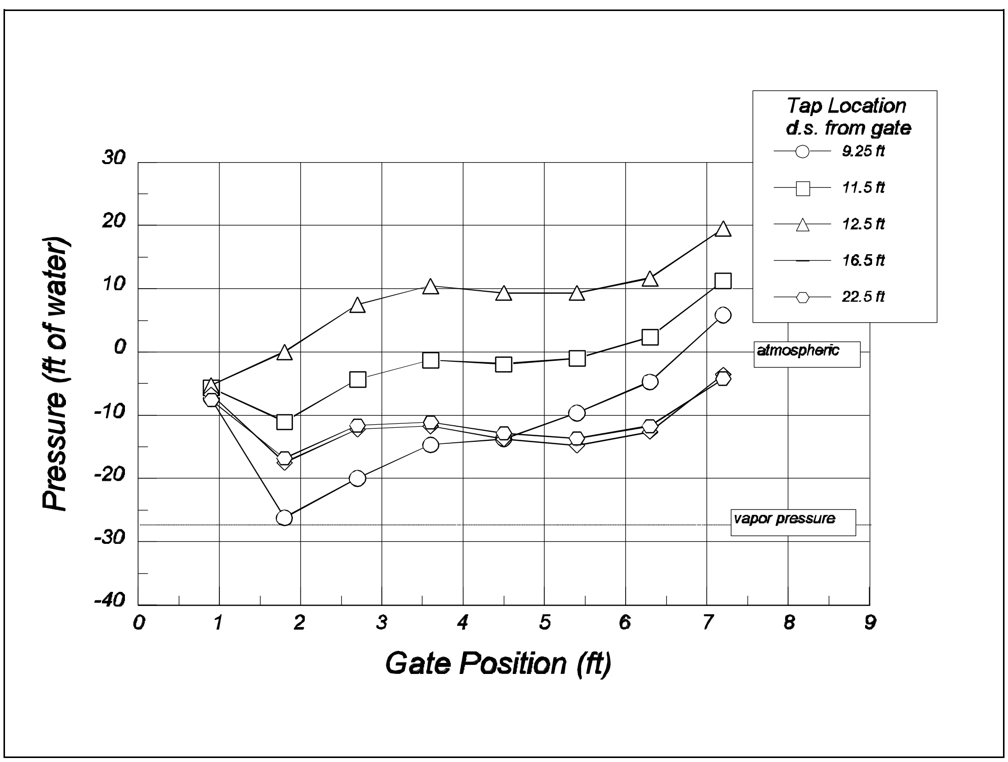


Figure 13.—Piezometric pressures downstream of the regulating gate with insert No. 3 in place.

Analysis of the cavitation potential for the mean flow shows a cavitation index greater than 0.2, where the cavitation index is given by:

$$\sigma = \frac{P_o - P_v}{\rho V_o^2/2} \qquad (2)$$

where:

P_o = reference pressure and P_v = vapor pressure
V_o = reference velocity
ρ = density of water

Usually, no damage occurs at $\sigma \geq 0.2$ (Falvey, 1990). However, localized flow features, such as vortices, can still carry a vapor core and cause damage during collapse and implosion of the vortex core. The damage patterns which have occurred in the Folsom outlets show characteristics of damage resulting from shear layers or vortices emanating from the gates or gate slots.

Air demands measured for the as-built condition (no ramps) showed a substantial air flow into the conduit behind the gate. At a reservoir elevation of 450 feet, a maximum demand of 2,400 cubic feet per second (ft^3/s) was measured for a single low-level outlet. The corresponding demand for an upper-level outlet would be about 1,600 ft^3/s. Using these data, a total air flow requirement, if all eight gates were operating at a reservoir elevation of 450 feet, would be about 16,000 ft^3/s of air. With the present 5-foot-diameter air header, velocities would easily exceed the design limitations of maintaining subsonic flow.

Solving the damage problem appears to be two-fold; an increase in the capacity of the air manifold that supplies air to the regulating gates is needed, as well as a method to better distribute the air to the locations which need it (i.e., the invert and sidewalls just downstream from the gates).

Previous and present model studies reinforced the fact that the current air header (5-foot-diameter) is well undersized, restricting the quantities of air which are distributed to each of the eight outlet gates. A new air intake was designed and constructed at Folsom Dam. This intake was sized based on trying to limit air velocities in the vent to 100 feet per second. In addition, the size was increased slightly to facilitate construction. The new vent was drilled and blasted from the left abutment and joined with the existing 5-foot-diameter air header. The system was then split by installation of a bulkhead, allowing four outlet gates to be supplied by the existing system and four gates to be supplied by the new air intake.

The introduction of air into an area where cavitation damage potential exists can be an effective way to lessen or eliminate possible damage which might result. A standard method developed over the years is to separate the flow from the boundary and allow air to be pulled to the area naturally by the low pressures created by the separation. This method has been used on many spillway applications, and, while it has not seen wide application on outlet works, it has also been effective.

The effectiveness of an aeration ramp is not strictly evaluated on the amount of air which is pulled into the vent. Of more concern is how well the air is distributed along the sidewalls and invert areas of the structure in question. Even though the as-built condition has a large air demand, most of the air just passes down the conduit along the top of the water flow without mixing effectively. This is due to the very rough water surface and large amounts of spray generated by the gate operation. A properly designed aeration ramp or slot can effectively distribute air to regions of the conduit which need protection. Figures 14 and 15 show model photos comparing the as-built with insert No. 3.

Insert No. 3 performed well throughout the testing and was chosen as the final design to be installed in the prototype. This insert can be welded to the existing steel liner, allowing for easy installation. The insert reduces the flow area by 11.25 percent at the point of the largest constriction; however, a discharge reduction of only 2 to 3 percent was measured.

With the combination of the new aeration ramp and construction of an additional air intake manifold (over doubling the capacity), operation of the outlet works should be possible without any additional cavitation damage.

References

Beichley, G.L. and D.L. King. 1975. "Cavitation Control by Aeration of High-Velocity Jets," *Journal of the Hydraulics Division, ASCE,* vol. 101, No. HY7, pp. 829-846.

Falvey, Henry T. 1990. *Cavitation in Chutes and Spillways,* Engineering Monograph No. 42, Bureau of Reclamation, Denver, CO.

Isbester, T.J. 1971. Hydraulic Model Studies of the Folsom Spillway-Outlet Junction, REC-ERC-71-12, Bureau of Reclamation, Denver, CO.

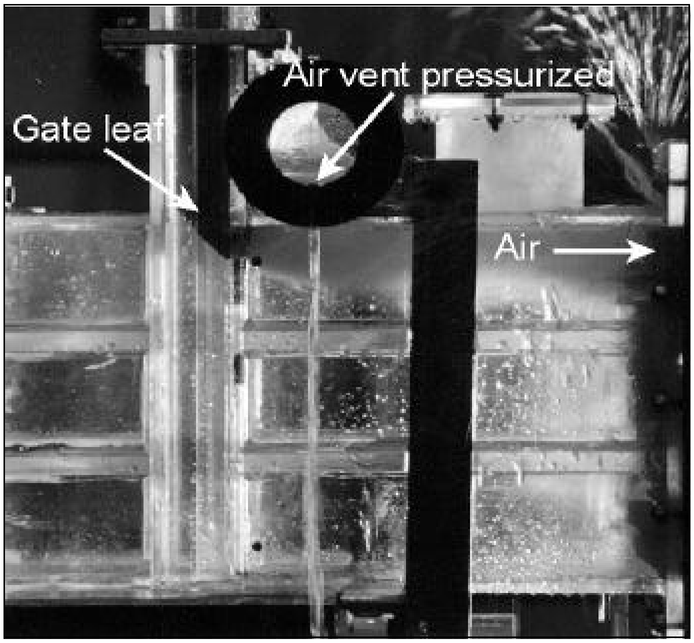
Peterka, A.J. 1953. "The Effect of Entrained Air on Cavitation Pitting," Proceedings of the Joint Meeting of the International Association for Hydraulic Research and the American Society of Civil Engineers, Minneapolis, MN.

Pinto, N.L. de S., S.H. Neidert, and J.J. Ota. 1982. "Prototype and Laboratory Experiments on Aeration at High Velocity Flows," *Report No. 36*, Centro de Hydraulica e Hidrologia Prof. Parigot de Souza, Universidade Federal do Parana, Curitiba, Brazil.

U.S. Army Corps of Engineers. 1965. "Spillway and Sluices, Red Rock Dam, Des Moines River, Iowa," Technical Report No. 2-673, Waterways Experiment Station, Vicksburg, MS.

Volkart, P. and P. Rutschmann. 1986. "Aerators on Spillway Chutes: Fundamentals and Application," *Proceedings of the ASCE Specialty Conference on Advancements in Aerodynamics, Fluid Mechanics, and Hydraulics,* Minneapolis, MN.

Wood, I.R. (editor). 1991. *Air Entrainment in Free-Surface Flows,* International Association for Hydraulic Research, Hydraulic Structures Design Manual 4, A.A. Balkema, Rotterdam, Netherlands.



a) Gate position is 90 percent, head is 450 feet, as-built. Air vent is pressurized (note stream of water pouring out of air vent).

b) Gate position is 90 percent, head is 450 feet, final design aeration ramp installed just downstream from the gate slot. Note air vent is not pressurized, and air is being carried all the way to the floor.

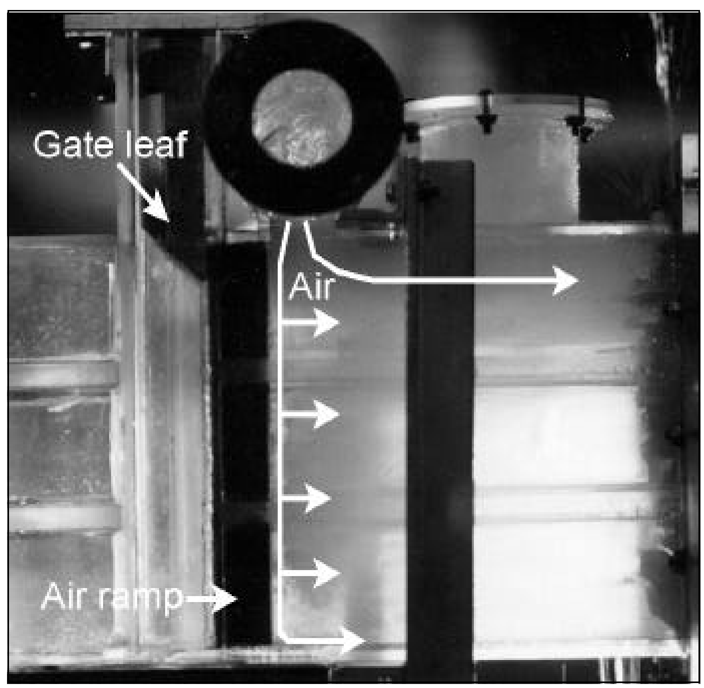
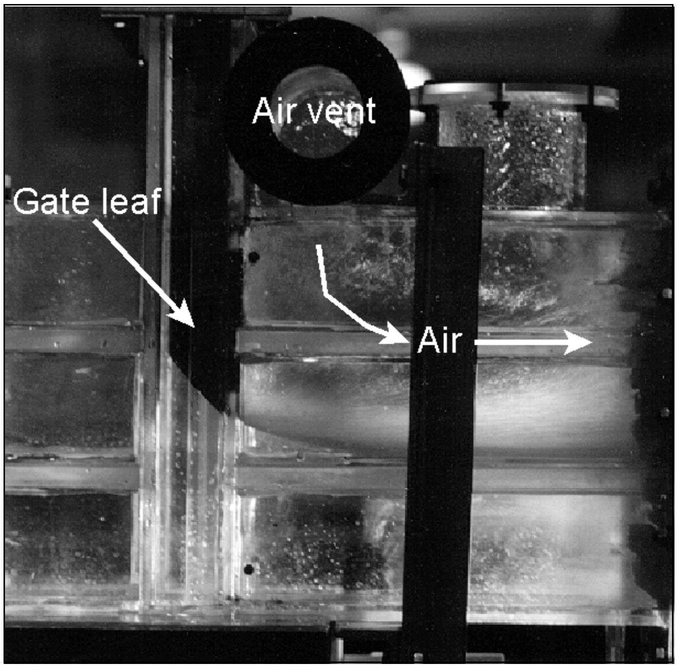
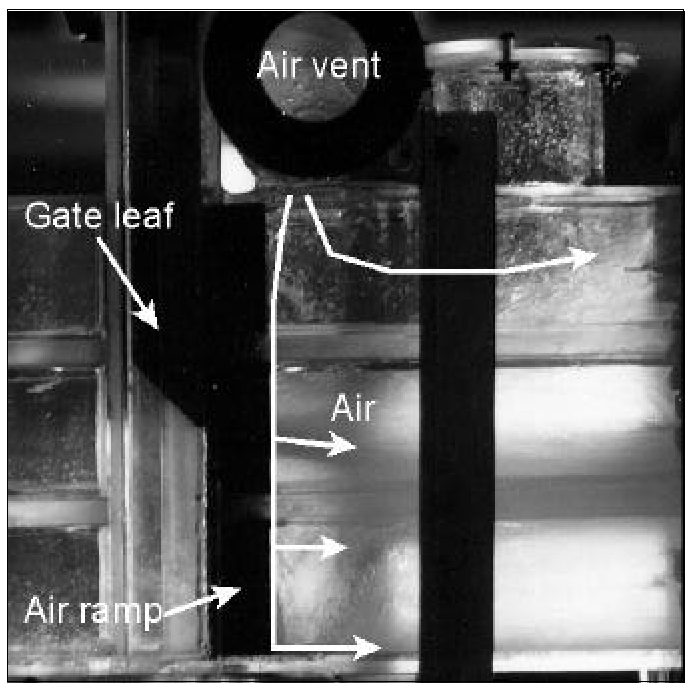


Figure 14.—Comparison of as-built and final design for a gate opening of 90 percent at a head of 450 feet.



a) Gate position 50 percent, head 450 feet, as-built configuration. Note that aeration appears to be localized at the free surface.



b) Gate position 50 percent, head is 450 feet. Insert No. 3 aeration ramp installed. Note that air is carried down to the conduit floor, allowing for aeration over the entire fluid stream.

Figure 15.—Comparison of as-built configuration with the final design aeration ramp. Gate position 50 percent (5.5 feet open) at a head of 450 feet.

NONDESTRUCTIVE TESTING OF LARGE CONCRETE DAMS

by William F. Kepler, P.E.[1]

It is not very likely that the Bureau of Reclamation (Reclamation) will build a new concrete dam in the foreseeable future. Since a majority of Reclamation's large concrete dams have reached their 50-year design life, we have been focusing our efforts on evaluating and repairing our existing infrastructure. The primary focus of a large concrete dam evaluation is to determine the structure's ability to withstand a major earthquake or flooding conditions. The dam's reaction depends on the mechanical strength developed throughout the complex discontinuous mass of the structure. One of our biggest concerns during the evaluation is that we have no idea of what is going on inside a large dam.

The traditional method for determining the physical properties of a concrete dam is to extract large core samples drilled from the top of the dam down to the foundation and then destructively tested to determine strength and elastic modulus. This information is then used in a finite element model to simulate responses of the structure to various loading conditions. Depending on the size of the structure, two to four drill holes are cored down to the foundation, often a distance of more than 300 feet. Large-diameter cores (10 to 12 inches in diameter) are required to provide representative samples. Extracting this amount of large diameter concrete cores is very expensive. In addition, although a coring program of this magnitude is considered sufficient, it only samples a very small percentage of the dam volume, typically less than 0.1 percent. This procedure cannot, therefore, be expected to find most local anomalies, such as regions of disbonded lift lines, cracks, or weak areas. A new testing procedure is required that will provide a more thorough evaluation of the physical properties of the dam and that is less expensive than a full coring program.

In 1994, while working with researchers at the University of Colorado, the Materials Engineering Laboratory developed a radical new concept for looking inside large concrete dams. We combined aspects of ultrasonic nondestructive testing of small concrete structures, nondestructive evaluation of interfaces, and shallow seismic surveying into "Acoustic Travel Time Tomography," (ATTT).

Acoustic testing can provide reliable estimates of the modulus of elasticity and compressive strength of hardened concrete. This method uses a sparse array of receivers and an impulse source. The proposed procedures can not only determine both local and global bulk modulus and strength values of a structure but can also locate cracks, voids, and anomalies within the structure. ATTT increase the percentage of the dam volume inspected and is cheaper than a full-blown coring program.

---

[1] Materials Engineering and Research Laboratory, D-8180, Bureau of Reclamation, Denver, Colorado 80225; phone: (303) 445-2386; e-mail: wkepler@do.usbr.gov

The basic premise of our new testing procedure is that the velocity of sound remains fairly constant in concrete. The velocity is a function of the density of concrete, the modulus of elasticity, and Poisson's ratio. In good concrete, these three properties do not vary. However, in cracked concrete, the velocity drops significantly. In addition, sound waves cannot travel through a crack larger than 0.003 inch thick.

By placing sensors on the top and sides of the dam, and possibly in the adits (as shown in figure 1), we can measure the velocity within the structure. We generate the sound wave by hitting the dam with a hammer connected to the data acquisition system. By using a simple, off-the-shelf, tomographic program, we can map the velocities as they change within the dam. This allows us to find weak areas, cracks, and other anomalies inside the structure. It is just like performing a CAT Scan on a dam—only simpler.

Now we have had our fair share of detractors ("experts" who said it could not be done). But, with a lot of hard work, and more than a little late night ingenuity, we developed a working system. It has been so successful that we have applied for a patent on the technique.

This has been a fun and exciting research project because we were doing something that had never been done before, and it had a direct effect on how we looked at large concrete dams. The research program was divided up into four phases: in the first phase, we developed the basic concept and tested it in the laboratory; in the second phase, we tested the concept on a section of a concrete dam; in the third phase, we went back to that concrete dam and improved our testing techniques and equipment and compared our test results to core taken from the structure; in the fourth phase, we determined the accuracy and reliability of the testing technique. I wanted to make sure that I was not just "blowing smoke" about the test results.

In the beginning, we tested a piece of concrete core sample in the laboratory. This sample was broken in half and then grouted back together, leaving a crack that went half way through the core, as shown in figure 2. We placed transducers on each end and made simple velocity measurements through the uncracked concrete and through the cracked section. The results were "bang on" to the expected values. At the same time, we were testing concrete core from Hoover Dam. That concrete was in great shape. It was so good that we could not find a lift line in the core. This is a group of engineers and technicians that look at concrete for a living, and we could not find a lift line to save our lives. We knew where it was supposed to be, but that did not help either. We even x-rayed the core and had no luck. So, on a lark, we connected up our sensors to the core and tested it. The results are shown in figure 3. The lift line determined by the nondestructive testing was within 1.0 inch of where it was supposed to be.

The next step in the testing process was to go to a concrete dam and test a section just to see if our method would work on the large scale. We selected Barker Dam (owned by Public Service) because it is close to our lay, it is easy to get to the top of the dam, and it's design and construction are similar to Reclamation dams. In this phase, we only tested the top 20 feet of the dam. This part of the dam has a rectangular shape, which made it easier to reduce the data.

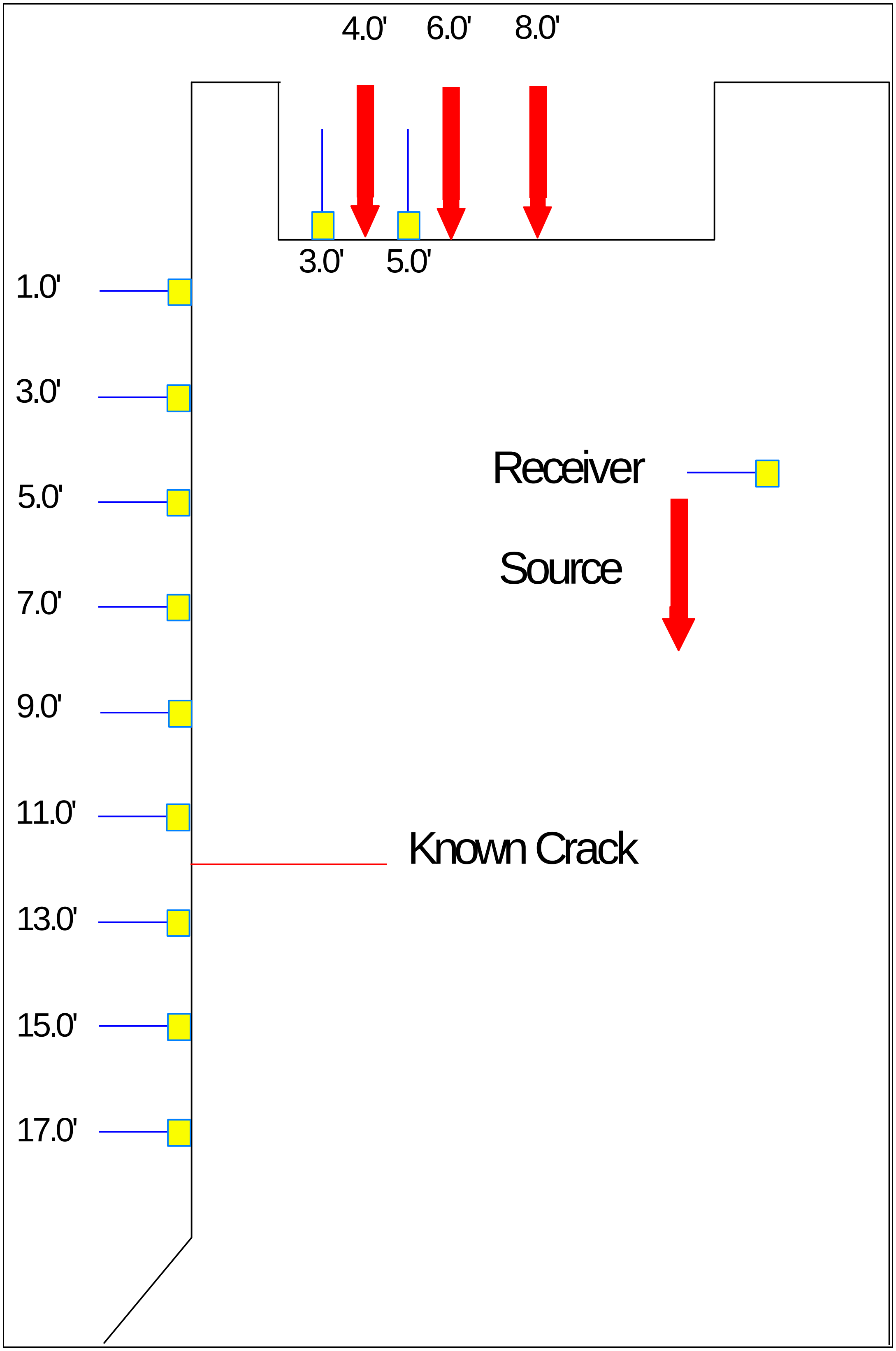


Figure 1.—Source and receiver locations.

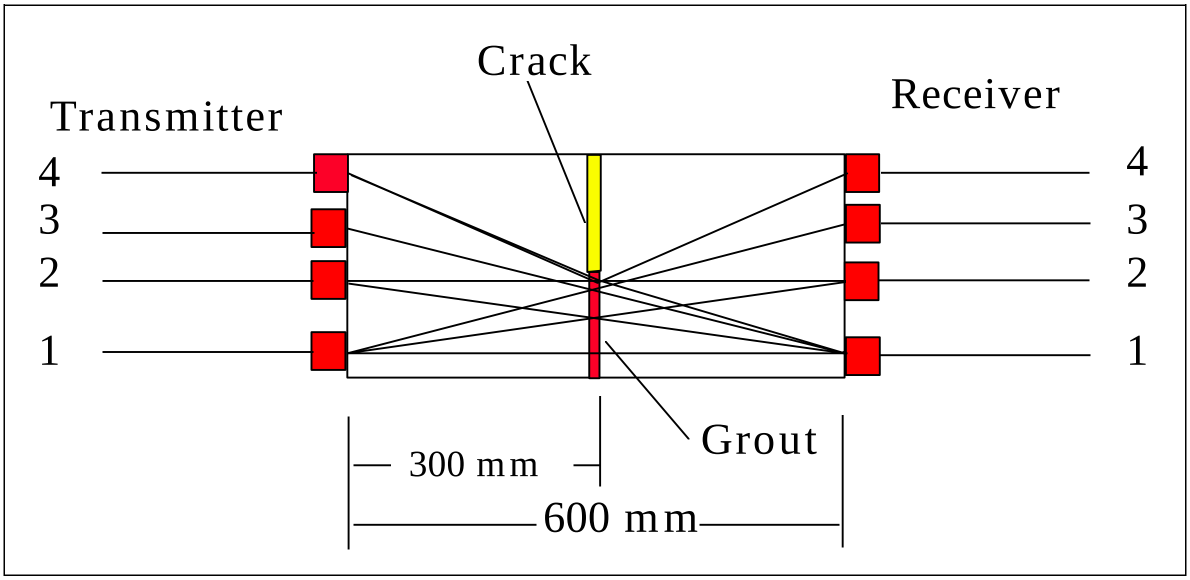


Figure 2.—Laboratory tests on a partially cracked piece of concrete core.

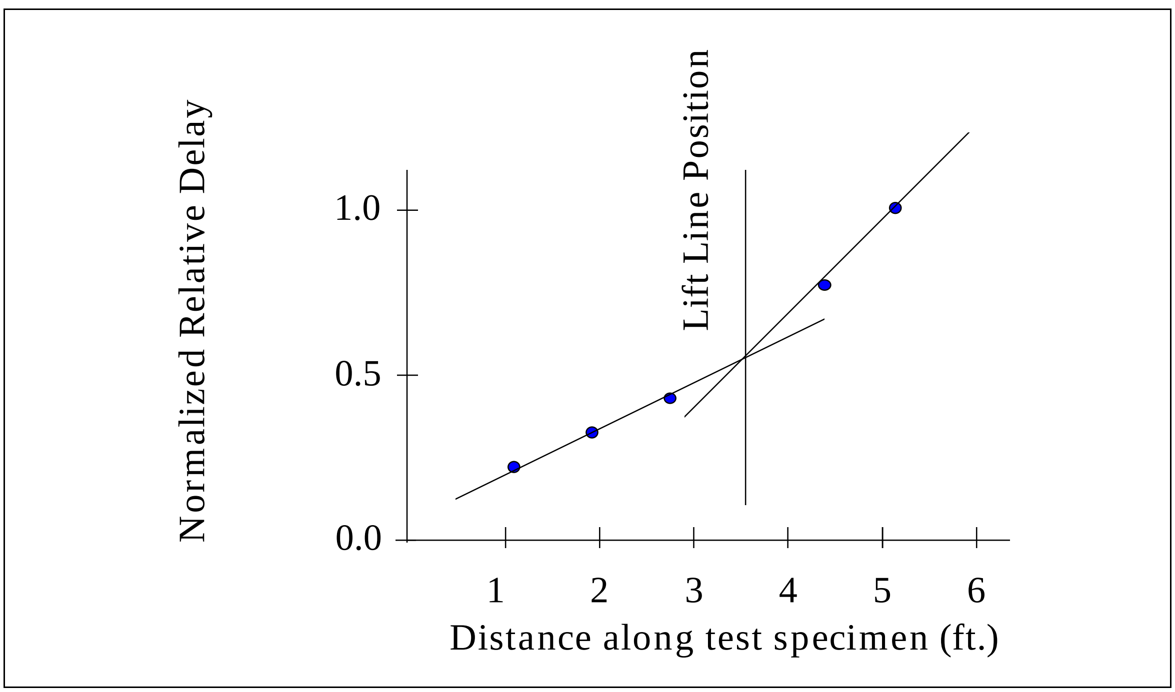


Figure 3.—Travel time measurements on a piece of Hoover Dam core.

The acoustic receivers were placed in pairs along a vertical line on the downstream face by members of Reclamation's Climb Team, as shown on figure 4. They used a two rope system to descend each line. A chain ladder was also used to assist in ascent.

Figure 4.—Photo of the climbers.

Sensor pairs were spaced on approximate 2-foot centers, as shown on figure 5. The sensors were attached to the dam with petroleum jelly, then the leads of each sensor were hot glued to the dam. Additional sensors were placed on top of the dam—one at 3 feet and one at 5 feet from the downstream face. The wires from each sensor were bundled together with the wires from the other sensors so that the sensors would hang down at the appropriate intervals. The wire bundle then was connected to a data acquisition system in the testing van.

We used 20 1-inch-diameter piezoelectric PZT type 5a sensors in this phase. The sensors were connected with a LeCroy 6810 digitizer. The system can sample 1 million samples per second, with a capacity of 128,000 samples per channel.

The impact source was an 8-pound sledge hammer with an accelerometer attached to one end of the head. We moved the impact source along the top of the dam to provide a mesh of lines through the dam.

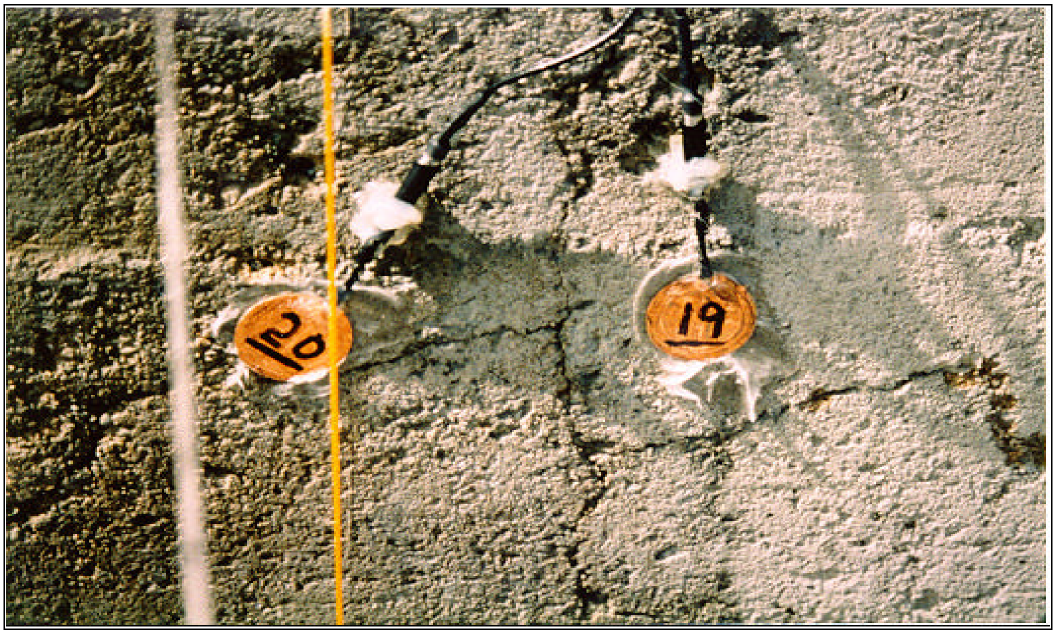


Figure 5.—Photo of the receivers.

It worked! As you can see in figure 6 and the following table, the basic concept worked.

Comparison between known horizontal crack locations and the tomographic estimate of the crack locations in the top 17 feet of Barker Dam. Shown is the vertical distance from the top of the dam in feet.

Block 4-14 North		Block 4-24 North	
Known crack location	Tomographic estimate of crack location	Known crack location	Tomographic estimate of crack location
2.0	3.0	1.5	1.8
4.5	Not apparent	4.5	4.6
8.4	8.3	8.4	8.6
10.8	10.8	10.8	10.5
14.5	14.5	14.4	14.4

We went back to Barker Dam the next year to improve our testing techniques. We placed transducers on the top and downstream face of the dam and then hit it with a sledge hammer on the upstream face. This gave us a much better test mesh, as shown on figure 7.

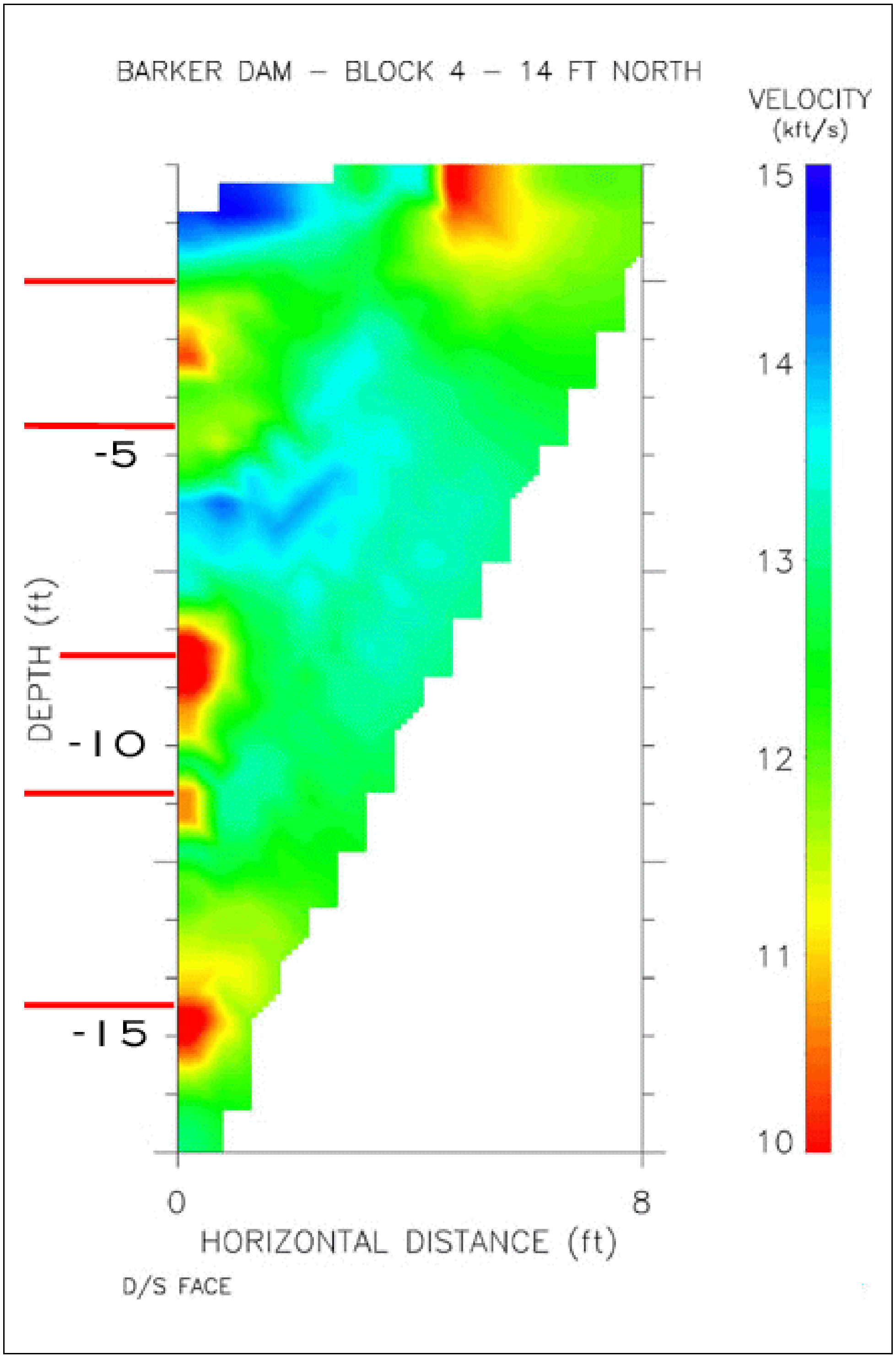


Figure 6.—Initial tomograph of Barker Dam.

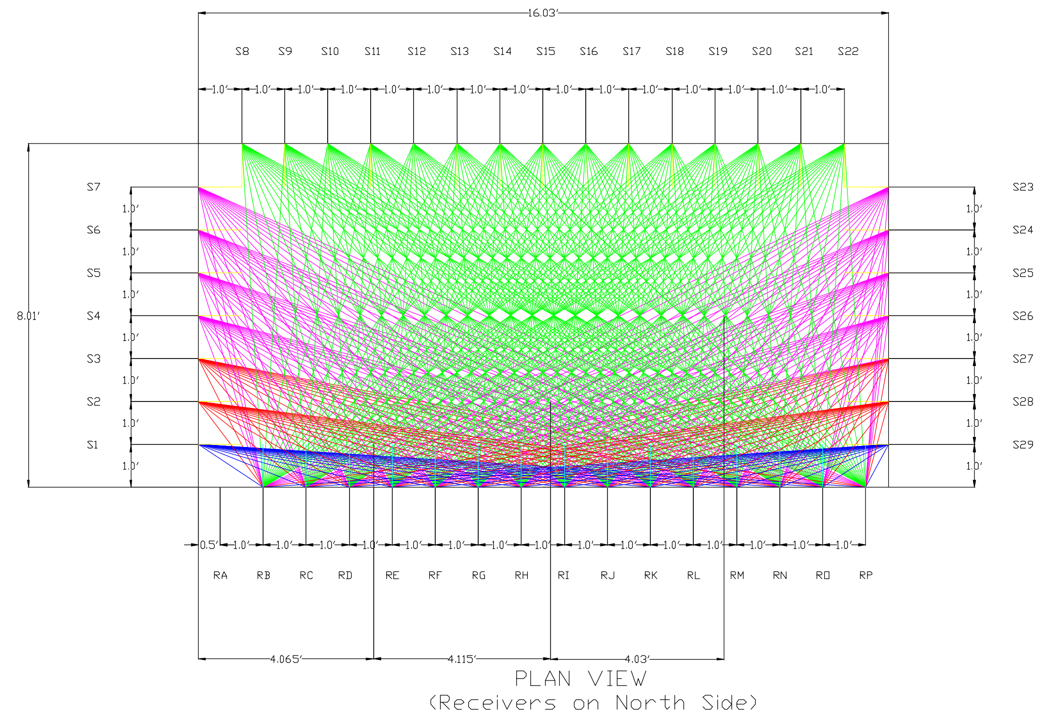


Figure 7.—Straight ray paths through test specimen.

We also figured out some other things. First, the type of source and transducer really does not matter. What really matters is that the data acquisition system must be capable of taking at least 1 million points a second. When you are measuring the time it takes for the sound to travel from the hammer to the sensor, accuracy is everything. We also learned that an inexpensive off-the-shelf tomographic program works just as well, if not better, than one that runs on a work station. By using off-the-shelf computer programs, we have reduced the time it takes to analyze the data from months to hours.

The last phase of the research program was to determine the accuracy and reliability of the testing procedure. This was a tough problem. How do you determine if a nondestructive test is accurate? You compare it to destructive tests. It would be very difficult to convince someone to let me test their dam and then tear it down to see if I was right. So, the first thing we did was take some core from Barker Dam. It was cracked just where the nondestructive testing said it should be. But that was not enough.

So, we cast a model concrete dam in the lab. The model was 16 feet long, 8 feet wide, and 2 feet thick. It contained three cracks, each about 0.010 inch thick, on “downstream” face, each crack going entirely through the thickness of the specimen. The first crack extended into the model 1.0 foot, the second crack extended in 2.0 feet, and the third crack extended in 4.0 feet. We then tested the model just as we would a real dam. Then, we compared the actual test results with the theoretical travel time from the source, around each crack, to the sensor.

As any lab hand knows, concrete is not easy to test. Test results never match up well—any time the correlation between two tests is greater than 60 percent, we are happy. The correlation for this nondestructive testing technique is 99.5 percent. Figure 8 shows the measured travel time compared to the theoretical travel time. This figure also shows the ±10 percent lines. Ninety-five percent of the actual data are within ±5.6 percent of the theoretical travel times.

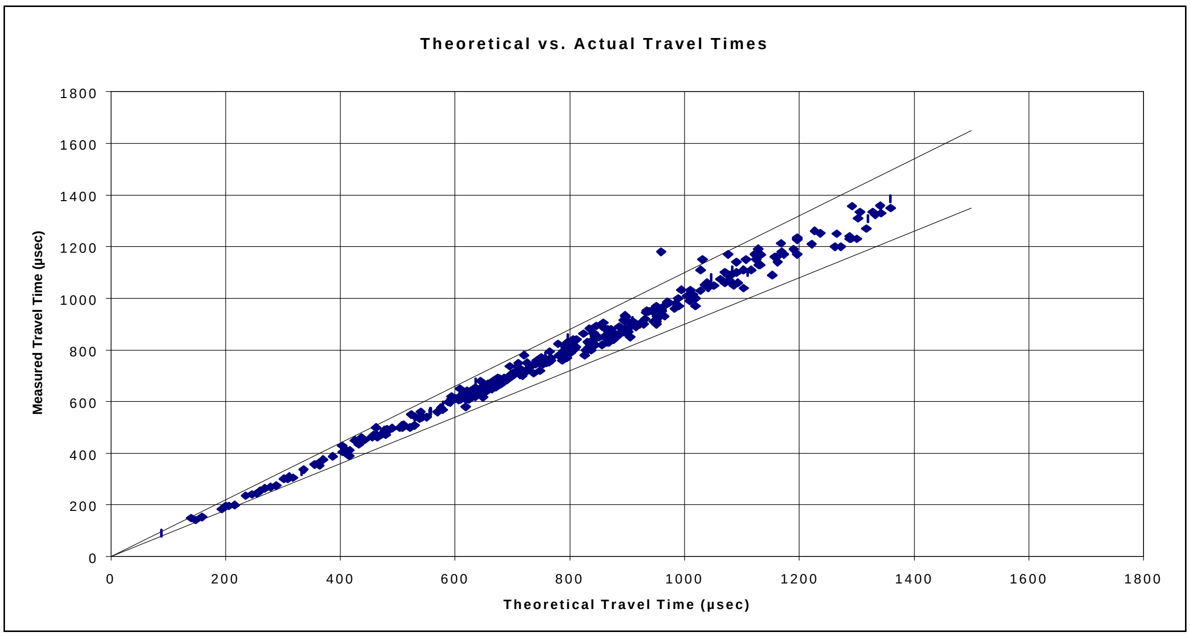


Figure 8.—Theoretical travel time versus actual test measurements (±10 percent lines are also shown).

Conclusions

The Materials Engineering and Research Laboratory has developed a new way to look inside a concrete dam by measuring the velocity of sound as it passes through the structure. The technique is inexpensive and very accurate. The techniques we have developed can also be used on other structures.

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) 445-2748, FAX (303) 445-6381; email: jfischer@do.usbr.gov

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) 978-5229, FAX (916) 978-5290

Bob Sabouri, Lower Colorado Region, ATTN: BCOO-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) 524-5499

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