WATER OPERATION AND MAINTENANCE BULLETIN

No. 201 September 2002

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UNITED STATES DEPARTMENT OF THE INTERIOR Bureau of Reclamation

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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 Bureau of Reclamation personnel and water user groups in operating and maintaining project facilities.

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Cover photograph: *Gerber Dam under construction.*

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OPEN TRENCH FAILURES CONTINUE TO RISE

Are Municipalities Neglecting Safer Alternatives?

by Del Williams[1]

Construction worker Jose Gonzalez was killed while working on a sewer project in Gilbert, Arizona, on June 21, 2001. The open trench he was working in collapsed, burying him alive. Another co-worker was severely injured in the accident. A similar death occurred in Scottsdale, Arizona, just weeks before.

Unfortunately, this scenario is not uncommon. Despite the fact that hundreds of people are killed and severely injured in open-trenching accidents throughout the United States every year, most municipalities continue to award construction contracts to companies utilizing open-trench methods, when safer trenchless technology is available to them.

The Occupational Safety and Health Administration (OSHA) rates water, sewer and pipeline construction, essentially open-trench work, as the fourth most deadly occupation in the United States for the period 1999–2000. This information is per the 2001 OSHA Industry Profile report on occupational fatalities, injuries, safety violations and assessed penalties for the prior 12-month period.

The Occupational Safety and Health Administration rates water, sewer and pipeline construction as the fourth most deadly occupation in the United States during 1999-2000. (Photo courtesy of TrenchSafety.org.)

OSHA has been keenly aware of the high death rate associated with open-trenching since 1973 and the difficulty gaining compliance from trenching contractors to OSHA safety regulations. In a special report issued by the Administration in 1985 specifically regarding open-trench safety violations, OSHA stated, "Trenching work creates hazards to workers that are extremely dangerous. Although it would be expected that, after more than 12 years of enforcement activity, most employers would be adhering to shoring and sloping requirements, experience has shown that such is not the case. Compliance with OSHA construction standards applicable to such operations is frequently bypassed."

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The OSHA report further states, "Because of the continuing incidence of trench collapses and accompanying loss of life, the agency has determined that an increased OSHA enforcement presence at worksites where such operations are being conducted is warranted."

Sections of pipe await placement at one trenchless project. Increasingly, municipalities throughout the United States are specifying that contractors employ trenchless technologies for installing sewer and water lines.

Despite the increased OSHA emphasis on safety standards enforcement in the mid-80s, open-trenching contractors continued to dominate the construction industry in OSHA standards violations. In a 1995 OSHA report listing the 100 most frequently cited OSHA construction safety violations, open-trenching rated in the top five.

Since then, the situation has not improved. Following the recent open-trenching death in Gilbert, Arizona, a senior OSHA spokesperson for the state noted that open-trenching fatality incidents are rising. According to the 2001 OSHA Industry report,

- Open-trenching has the highest number of OSHA safety violations of all heavy construction industries for the period 1999–2000,
- The highest number of safety violations in the utility, communications and power line construction industries for this period, and
- The highest number of violations of all U.S. occupations for non-compliance to OSHA safety training and education requirements.

Further, open-trenching leads all of the above categories in dollar-volume of assessed penalties by OSHA.

OSHA statistics demonstrate that open-trenching is one of the most hazardous and deadly occupations in the United States, largely because of trenching contractor's non-compliance to OSHA safety standards. Another factor is that the open-trenching process is inherently unstable. Excavated soil stockpiled on the edge of a trench increases the pressure to trench walls. Vibrations from nearby excavation equipment such as backhoes increase the likelihood of a cave-in. Even trench wall sloping, shoring and worker shielding offers only limited protection when collapsing soil can weigh more than a ton per cubic yard. Most trenching deaths and serious injuries result from cave-ins, toxic fumes, drowning, electrocution and explosions.

The question is why are not more municipalities turning to trenching alternatives that avoid many of its inherent dangers? The technologies exist, with a proven track record not only for safety, but also for cost savings. Many of these technologies for trenchless construction have already been adopted outside the U.S. In parts of the world, such as Japan and Germany, trenchless construction is utilized due to the heavy urbanization and the impact open-trenching causes.

Sewer construction using pilot tube technology provides a safer alternative to open trenching.

Microtunneling and soil piercing pilot tubes are two existing trenchless methods that are gathering support. A microtunneling pipeline installation involves microtunneling excavation, a subterranean, unmanned tunneling method that uses a laser-guided “mole” to lead the way for sewer pipe installation through sections of soil spanning 300 to 500 ft. The only excavations on the surface of the ground are construction pits located at either end of a pipeline section. The pipes are precisely pushed through the soil from one pit to the other. In new sewer pipe systems, an auger is used to perform the tunneling.

The process of installing a sewer using pilot tube technology is similar to the microtunneling process, especially when clay pipe is used. Since 1992, NO-DIG (a company specializing in trenchless technology) has installed more than 220,000 linear feet of pipe using microtunneling techniques.

Today, more and more municipalities throughout the United States are specifying that contractors use trenchless technologies that are inherently safer and accrue substantially less liability. As an increasing number of local governments are becoming self-insured, interest in using safer methods is becoming more prevalent.

The Oregon Department of Transportation even has a trenchless technology expert to help employees and contractors keep current with new techniques that can eliminate the need to excavate. The department saved a total of $1.5 million on six recent trenchless projects, according to the Portland, Oregon, Daily Journal of Commerce.

Yet, incidents such as the Gilbert cave-in remain a tragic reminder that trenching is dangerous, despite all of OSHA's efforts. While not a panacea, trenchless technology has come of age and deserves a closer look by both municipalities and the contractors they employ.

Reprinted from *WEM*, March 2002.

GATE OPERATION AT THE FINGERTIPS

by Bill Bouley[1]

Medford Irrigation District employees used to travel 1 hour each way to Fish Lake Dam, just to make a small adjustment in their outlet works gate openings. This dam, in southern Oregon, is in the mountains east of Medford and has no resident dam tender. Therefore, to make gate adjustments, district employees had to lose a valuable part of a day. Once at the dam, the employee had to attach the handcrank, turning it several hundred times to raise the gate to the desired setting. When employees once again reached a resting pulse rate, they could safely return to their other duties (provided there was still enough daylight to continue them). In the peak summer months, traffic from recreationists slowed this commute further. At times, water losses and inefficiencies occurred because gate adjustments took too long to be effective.

The Pacific Northwest Region's water conservation program provided cost sharing to help the irrigation district automate its regulating slide gates at the dam. Regional staff, in cooperation with Provo Area Office water conservation staff, designed and installed a remote gate operating system that meets the needs of this area. Provo Area Office water conservation staff provided similar systems on canals that are separate from the commercial power grid (see *Water Operation and Maintenance Bulletin* No. 172).

The remote gate operating system uses a cellular telephone in a control cabinet to receive data communications from the district office. From there, the CR10X data logger translates the message to operate an electric motor the desired length of time to raise or lower a regulating gate. Each regulating gate can be operated independently or simultaneously with the other gate. The Medford Irrigation District normally runs only one gate at a time. However, last year, at the tail end of the season, the district ran both gates simultaneously to reach the required outflows. So far this year, the district is only running one gate.

The power for the system consists of a 20-watt solar panel, mounted on the gatehouse, that recharges a 12-volt truck battery (100 ampere-hours), thereby eliminating the need to run commercial power to the site located in a national forest. The battery provides the necessary power to operate a 12-volt Grainger electric motor that uses a drive chain to turn each regulating gate pedestal. The motors are not very large, providing 1/15 horsepower at 200 revolutions per minute, but they can raise a 3.5-foot-wide by 5-foot-high slide gate. Because of the remote gate operating system, it is critical that the district adhere to its

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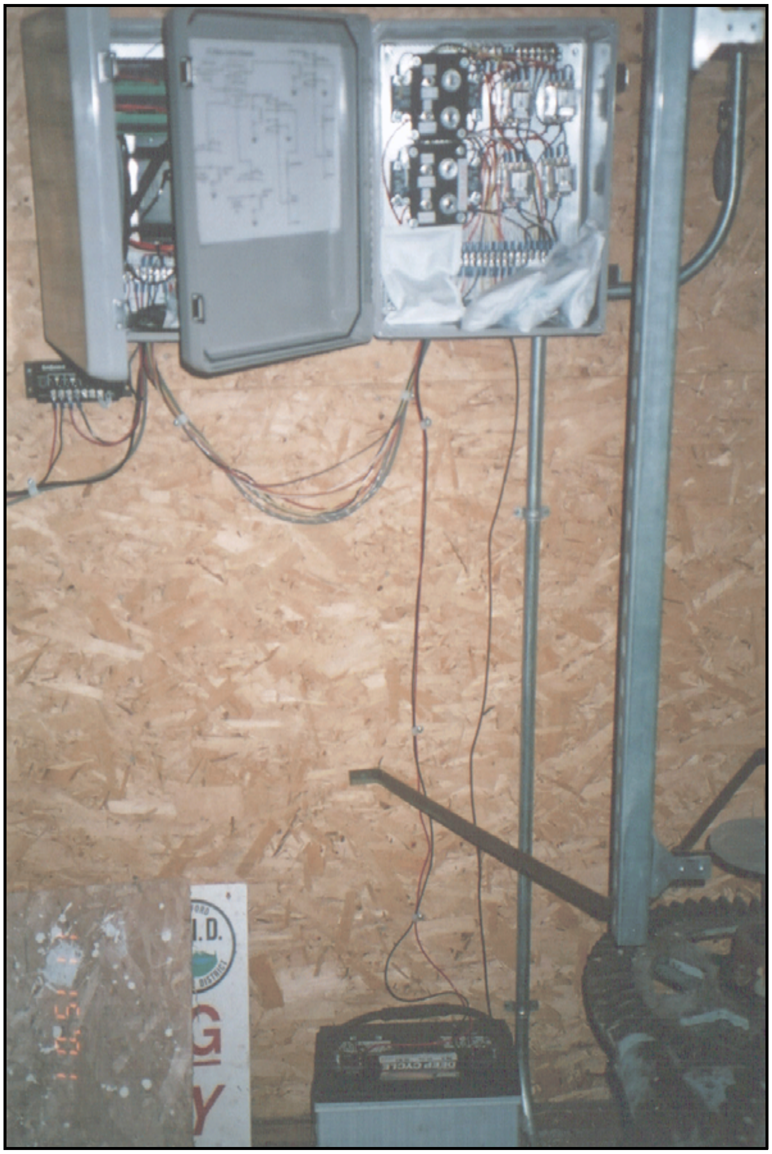
maintenance on the gate guides to prevent any debris from increasing the friction factor. The battery also powers the cellular telephone and data logger.

Operating the electric motors for both regulating gates can overtax the ability of the battery. On a recent Comprehensive Facility Review, the battery was nearly exhausted by the end of the day, after having cycled both regulating gates.

Vandalism is a normal concern with most solar panel installations in remote areas. In the summer, the district allows a camper to stay at the dam in exchange for their service as a volunteer caretaker of the dam. This presence deters mischief.



Data logger cabinet and the adjacent cellular telephone cabinet above the battery.

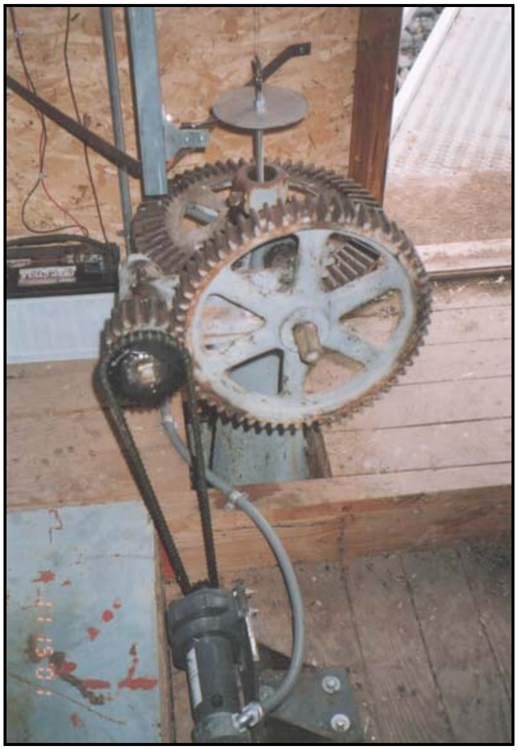
The entire system was designed and installed at a cost of under $10,000, including labor and travel costs. Another remote gate operating system was installed at nearby Emigrant Dam to operate three high-pressure gates. The Emigrant Dam system cost just under $20,000 to install because of the complexity of the solenoid switches and adjustments needed to ensure compatibility with existing equipment.

The handcrank is still available to operate the emergency gates and the right regulating gate, and it can be used as a backup to operating the left regulating gate. After using the remote gate operating system, the district employees do not seem eager to return to their old procedure, which is still needed to operate the emergency gates. A portable generator set

Solar panels mounted on the outside wall of the gatehouse. Bird screens are attached to the roof eave above the panels to restrict bird nesting and subsequent debris. Note the lack of organic coatings on the gatehouse siding in the vicinity of the solar panels.

with an electric driving device could easily raise or lower the emergency gates at a fraction of the time the handcranking requires. The remote operation of the left regulating gate has resulted in substantial savings for the district in time, labor, and water conservation.

For more information on these automated gate operating systems, contact Shane Livingston, in the Pacific Northwest Regional Office, (208) 378-5044, or one of the Provo Area Office water conservation staff: Joe Whittaker at (801) 379-1169 or Arlen Hilton at (801) 379-1162.



Motor- and chain-driven gear drive for operating the left regulating gate hoist.

District employee enthusiastically demonstrates the proper operation of the handcrank mechanism on an emergency gate hoist.

HIGH DAMS AND LARGE RESERVOIRS – THE EVOLUTION OF CONCRETE DAMS AT THE BUREAU OF RECLAMATION

by Gregg A. Scott[1], P.E., M. ASCE; Larry K. Nuss[1], P.E., and John H. LaBoon[1], P.E.

Abstract

Over the past 100 years, the Bureau of Reclamation has made significant contributions to the advancement and evolution of concrete dam design, analysis, and construction. This paper chronicles some of those achievements.

Introduction

As the Bureau of Reclamation (Reclamation) celebrates its centennial (1902 – 2002), it is a good time to look back at the engineering accomplishments of the organization. This is nowhere more evident than in the advancements made in the area of concrete dam design, analysis, and construction. Reclamation has designed and constructed over 50 major concrete storage dams throughout the Western United States. This paper discusses some of the contributions made by Reclamation along the way, beginning with the early masonry dams, and proceeds through applying the advances in technology to dam safety modifications.

The Early Years

Reclamation's long history of concrete dam design and construction began in September 1903 at a conference of Reclamation Service engineers in Ogden, Utah. It was recognized there that Reclamation would be required to build masonry dams of great height to store the water required to reclaim the arid lands of the West. This lead to the unique design and construction of Pathfinder Dam on the North Platte River in central Wyoming (Wisner, 1905). Due to the narrow granite canyon in which the dam was to be constructed, it was decided that an arch should be built, and that the arch action could be relied upon. It was recognized that masonry dams were far from rigid and that temperature was an important problem. The modulus of elasticity and coefficient of thermal expansion were estimated for a composite of rock blocks and concrete. Using these properties, the dam was designed as a combination of horizontal arches and a vertical crown cantilever. The load was distributed between the arch and cantilever to produce equal deflections at their point of intersection. The stresses from the deflections were then calculated and the cross-section proportioned accordingly. This was the beginning of what was later to become known as the "trial load" method of analysis.

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Although facilitated by steam power, many of the construction techniques adopted for the construction of Pathfinder Dam are still in use today. A large tunnel was constructed to divert the flow of the river and was later used for the outlet works. A key component to the foundation excavation and dam placement was an overhead cableway. An aggregate crushing plant and concrete batch plant were constructed onsite. It was recognized that an impervious dam could be built at the same cost as a leaky dam (the main difference being more rigid inspection and an understanding at the start that only first-class work would be allowed). This became the practice for all Reclamation concrete dams. All foundation rock and material to be placed in the dam was thoroughly washed and cleaned. Granite stone from the spillway excavation was set and vibrated into place between masonry courses on the upstream and downstream face, with concrete and smaller rocks worked into the joints to produce a well-consolidated solid mass. Construction of the dam began in 1906 and was completed in 1909. This became Reclamation's first masonry dam. The dam is 65.2 meters (214 feet) high and stores a reservoir of about 1.23 x 10^9 m^3 (1,000,000 acre-feet).

Completed in 1910, a similar cross-section and arch shape was adopted for the highest dam in the world at the time (99.1 meters, 325 feet) across the Shoshone River in northwestern Wyoming. Originally called Shoshone Dam, it later became known as Buffalo Bill Dam. Concrete was placed between wooden forms, as shown in figure 1. The concrete was placed in 8-inch layers, and granite plum rocks, comprising about 25 percent of the concrete volume, were placed in the concrete and shaken or rammed into final position, solidifying the mass to a considerable degree. Spading and tamping was performed to work the concrete into all the cavities and ensure consolidation against the forms. The plum rocks projected above the cleaned lift surface for bonding to the next layer.

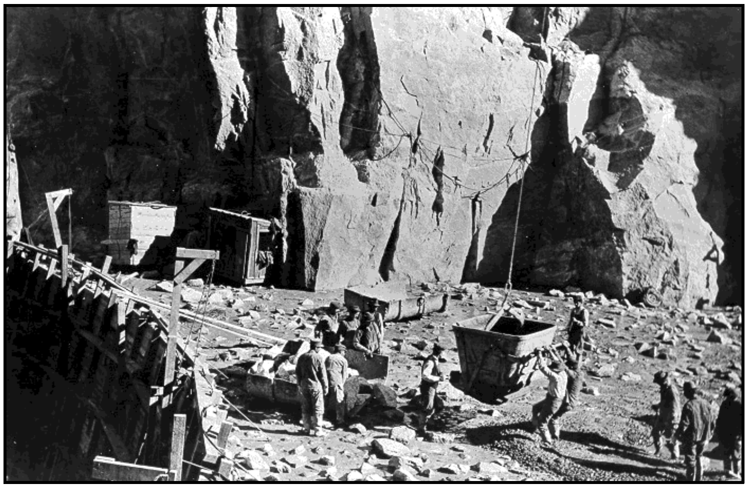

Figure 1.—Concrete placement at Buffalo Bill Dam.

The first use of radial contraction joints occurred at East Park Dam in northern California, as shown in figure 2. The radial joints were spaced at 6.1 meters (20 feet), and a shear key 0.15 meter (6 inches) deep by 0.61 meter (2 feet) long was constructed in the joints about 6 feet from the upstream face. Although there is no indication that waterstops were installed in the joints, a system of 102-millimeter (4-inch) diameter tile drains was constructed downstream of the keys to convey water from the joints to the outlet tunnel. This dam was also constructed entirely of concrete. The original design called for sandstone blocks to be imbedded in the concrete to make up 20 to 30 percent of the mass. However, the sandstone was of poorer quality than first believed, and the sandstone blocks were omitted from the construction. A conservative gravity arch design was adopted for this structure, completed in 1910, at 42.7 meters (140 feet) high.

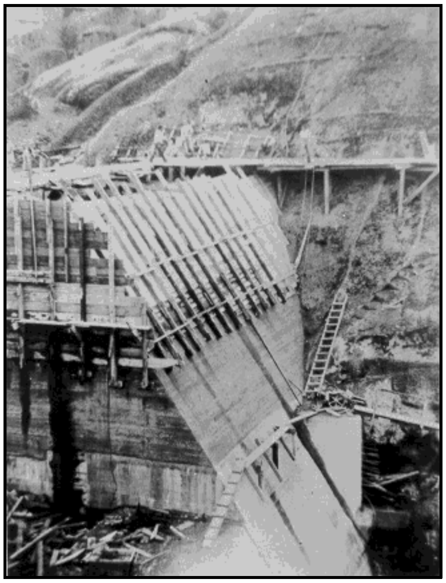

Figure 2.—Construction of East Park Dam.

The reign of Shoshone Dam as the world's highest dam was short-lived. In 1916, Arrowrock Dam was completed by Reclamation in Idaho, to a height of 106.4 meters (349 feet) (Reclamation, 1954). The gravity arch design made use of radial contraction joints. Three vertical wells were formed in each joint, which were later filled with concrete during cold weather, after the dam had undergone contraction. A Z-strip annealed-copper waterstop was installed in each joint 5 feet from the upstream face. Immediately downstream of this strip, a triangular drain was formed to collect water and transport it to galleries constructed within the dam. The concepts of vertical formed drains within the concrete and foundation drainage and grouting appear at Arrowrock Dam. "Sand cement," containing an equal amount of Portland cement and pulverized sand, reground to such fineness that 90 percent would pass a No. 200 sieve, was used in constructing the dam. Although this saved on the quantity of cement used, the concrete did not attain as much strength, and, as a result, the durability suffered. Therefore, this concept was abandoned.

The Amazing Arch and Developments of the 1920s

During the 1920s, materials were relatively expensive, and there was a desire to minimize the amount of concrete used in constructing dams. Independent arch theory became the order of the day for designing concrete dams in narrow canyons where the thickness of the arch at any given elevation was designed independently. Thinner dams resulted from this method of design.

In 1925, Reclamation completed Gerber Dam, a 25.9-meter (85-foot) high thin arch dam on Miller Creek in southern Oregon. The concrete was placed in 1.2-meter (4-foot) lifts between keyed contraction joints spaced at 15.2-meter (50-foot) centers. To facilitate cooling and contraction of the dam, closure slots were left on each side of the central overflow spillway section, as shown in figure 3. Concrete was placed in these slots at low temperature conditions once the dam had cooled. Extensive field testing was used for quality control, including sieve tests of the sand and aggregate, compression tests on concrete cylinders of concrete taken from the forms, and slump tests. A slump up to 3 inches was permitted to allow the concrete to flow through the placement chutes. Gerber Dam represents the first use

Figure 3.—Gerber Dam under construction.

of instrumentation in a Reclamation concrete dam. Electric resistance thermometers, Berry strain gages, and survey targets were installed in the dam. Despite the success of the thin arch dams of the 1920s, Reclamation would opt for thicker and more massive structures throughout the next few decades.

Prelude to Hoover Dam

Hoover Dam was on the drawing boards in the late 1920s, and it was recognized that with the great size of this dam would come additional problems. In preparation for this enormous project, important developments occurred during the design and construction of Owyhee Dam, which was completed in 1932, immediately preceding Hoover Dam. At 127.1 meters (417 feet) high, this gravity-arch structure was another world's highest. Independent arch analysis was abandoned in favor of a gravity arch section analyzed by the trial load method, which advanced throughout the 1920s.

The materials and construction techniques were similar to earlier structures, but a few items were notably different—these largely related to the temperatures generated by the hydrating cement and the possibility for cracking if not handled properly. Large 8- to 9-inch cobble rock aggregate was added to the concrete mix to reduce the cement per unit volume of concrete. A system of pipes was installed along the vertical contraction joints, spaced at 15.2 meters (50 feet), to cool the concrete mass. Cement grout was then forced into the joints under pressure through the piping system to lock in the arch action when the concrete was at its coolest point. Grout zones were 30.5 meters (100 feet) high and isolated with 20-gage soft copper sheets. Experimental cooling systems were installed at various locations, whereby cooling coils were placed on the top of concrete lifts and cold water circulated through the system. Measurements were taken to determine the effectiveness of these systems to reduce the heat and thermal gradients in the concrete and to open the contraction joints for grouting. The systems were effective, and the information was put to good use during the design and construction of Hoover Dam.

Hoover Dam – Quantum Leaps Forward

There is no question that Hoover Dam was the crowning achievement that came to represent Reclamation's world-renowned expertise in concrete dam design and construction (figure 4). At 221.6 meters (727 feet) high, Hoover Dam was the highest dam in the world for quite

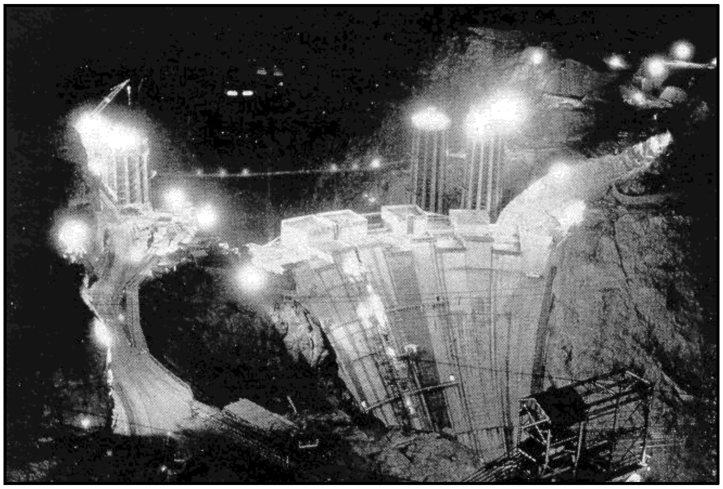

Figure 4.—Hoover Dam after 15 months of concrete placement.

some time. It is still the second highest dam, and the highest concrete dam in the United States. When designs for Hoover Dam began, it was to be more than double the height of Arrowrock Dam, then the highest dam in the world. As such, it was evident from the start that many new problems in design and construction would require solutions before the dam could be built. As a result of intensive research, improvements were made in practically every aspect of the design of the dam, waterways, and appurtenant structures. The work is published in a series of reports, which represents some of the most comprehensive and finest documentation of its kind (Reclamation, 1938–48). It would not be possible to do justice to this body of work in a short paper such as this.

Extensive use was made of analytical and physical models in the design of Hoover Dam. Thermal analyses were developed based on data obtained from Owyhee Dam. The trial load method was brought to maturity and used for extensive analyses of the dam. These calculations were checked by the use of two- and three-dimensional physical models. Two-dimensional slab analogy experiments of a cantilever and arch were used to obtain stress functions usable in the trial load analyses. Stresses in the slab are proportional to twist and curvature in the slab under the applied boundary loading. Three-dimensional model studies showed stress concentrations at the top of the dam where there was a change in arch length. As a result, fillets were added to increase the thickness of the dam near the abutments.

Extensive research was conducted into the cement and concrete mix to be used in the dam. Large concrete cylinders, 0.9 meter (3 feet) in diameter by 1.8 meters (6 feet) high, were cast and tested to examine the effects of the 229-millimeter (9-inch) maximum size aggregate. One of the major problems was controlling the temperatures that would result from the rapid construction and unprecedented size of the dam, locking in temperatures that would take more than 100 years to dissipate on their own. As a result, low heat cement was developed for most of the construction. Still, the mass concrete needed to be artificially cooled by circulating cold water through cooling pipes placed at the top of each 1.5-meter (5-foot) high lift of the 15.2-meter (50-foot) by 15.2-meter (50-foot) construction blocks. A 2.4-meter (8-foot) wide slot was left open down the middle of the dam for the extensive system of cooling pipes. The cooling slot was filled and the contraction joints grouted once the dam had cooled. Due to the size of the dam, large plants had to be erected to process aggregate and sand, and to batch the concrete in large quantities. The 2,485,000 m^3 (3,250,000 yd^3) of concrete were placed from June 1933 to May 1935 (23 months).

Hydraulics for High Dams

The unprecedented size of the spillways and hydraulic head at Hoover Dam without question resulted in a major breakthrough in spillway design. In particular, research and development of methods to design the “ogee” spillway crest is still used for spillway designs around the world (Brandley, 1952). A second major breakthrough occurred with the first printing of Engineering Monograph No. 25 in 1958 (Peterka, 1984). This publication summarized 23 years of research and design experience and provided a generalized and practical design tool for sizing stilling basins and other energy dissipating structures. Prior to this time, attempts to generalize data from hydraulic model studies lead to inconsistent results. A third major advancement in evaluating hydraulics for high dams involved an understanding of cavitation. Cavitation is the result of formation and collapse of vapor cavities at abrupt changes in geometry of the flow surface, which can result in severe erosion and damage to concrete and rock. The large flow velocities associated with high dam waterways makes them more susceptible to cavitation. Reclamation had investigated cavitation damage and implemented repairs as early as 1941. However, it was not until much later that Engineering Monograph No. 42 was published, providing common-sense guidance on how to identify and mitigate cavitation potential (Falvey, 1990).

World War II – Large Gravity Dams

The United States entered World War II in 1941, and electric power was needed to fuel war production factories. The design and construction technology developed at Hoover Dam was put to work in completing large multipurpose dams with associated powerplants. Many of these were constructed on large and wide rivers, where it became necessary to construct concrete gravity dams. The largest, and perhaps best known, is Grand Coulee Dam (figure 5) in Washington State, which has been studied and emulated around the world (Reclamation, 1953). As finally constructed, this structure is 550 feet high and nearly 1 mile long. The central spillway section is capable of passing a flow of 28,300 m^3/s (1,000,000 ft^3/s). Three-dimensional trial load twist analyses, fully developed during the design of Hoover Dam, were performed for the high gravity dam design. Due to stress concentrations in the

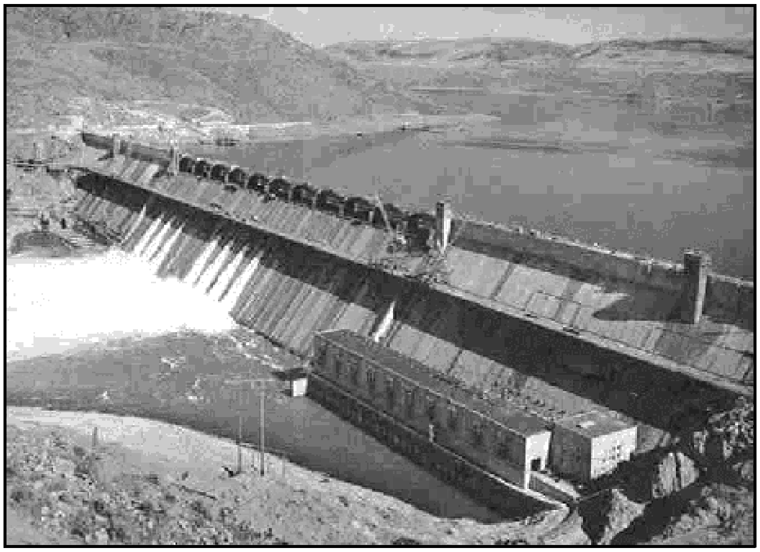

Figure 5.—Grand Coulee Dam under construction.

portion of the dam adjacent to the sharply rising abutments and concerns for potential cracking, vertical "twist slots" were constructed in the abutment sections to provide flexibility and to allow the dam to adjust to the rising reservoir levels. The slots were initially filled with sand, and after the reservoir had filled, the sand was removed and the slots filled with concrete. By this time, Reclamation's 22,200-KN (5,000,000-pound) testing machine was installed in the Denver laboratory at the U.S. Customs House and was used in testing the strength of the large aggregate concrete used in the dam, using cylinders 0.9 meter (36 inches) in diameter. Many of the same construction techniques used at Hoover Dam, including the use of low heat cement and cooling coils, were again used at Grand Coulee. Two batch plants were constructed, one on each side of the canyon. At the peak of production, 15,814 m^3 (20,684 yd^3) of concrete were placed in a single day. With the completion of the Forebay Dam and Third Powerplant in 1974, the total volume of concrete in the dam is well over 7,600,000 m^3 (10 million yd^3), and the total power generating capacity is over 6,000 megawatts.

The Post-War Boom – Developments Continue

Following World War II, the country entered into a boom period. During this period, problems that developed with concrete durability at some earlier structures were solved. Concrete dams in cold climates, particularly those constructed with wet concrete mixes, suffered from freeze-thaw deterioration. This was addressed by the use of air-entraining admixtures in the concrete mixes. Alkali-aggregate reaction occurred in some structures, where the concrete aggregates chemically reacted with the alkali in the cement, resulting in expansion and cracking of the concrete. The use of low alkali cement in the concrete mix was found to alleviate this problem. Extensive instrumentation systems became standard for measuring the response of the structures. Thermal analysis became standard (Townsend, 1981). These advancements, and the technology developed from building large concrete dams and powerplants, was quickly put to use in building several more monumental concrete arch dam structures. Hungry Horse Dam is a 172-meter (564-foot) high structure on the South Fork of the Flathead River in Montana; Glen Canyon Dam is a 216-meter (710-foot) high structure on the Colorado River upstream of the Grand Canyon; Yellowtail Dam is a 160-meter (525-foot) high structure on the Bighorn River in Montana; and Flaming Gorge is a 153-meter (502-foot) high structure on the Green River in Utah.

Rock Mechanics and Foundation Design Emerge

The 1959 abutment sliding failure of Malpasset Dam in southern France made the profession recognize the need for more rigorous foundation investigations and analytical design methods. Shortly after this, Reclamation began developing rock mechanics methods in application to concrete dam foundation design and analysis. However, it was not until the foundation designs were underway for Auburn Dam in the late 1960s that the foundation exploration, analyses, and design were coherently integrated. Although Auburn Dam was never completed, this work was an enormous contribution to the profession and formed the basis for future evaluations within Reclamation (Reclamation, 1977–78).

The Auburn damsite consists of complex metamorphic geology. Careful diamond core drilling using split inner tube core barrels, trenching, and excavation of exploratory tunnels and drifts was performed to define the geologic conditions. The results were portrayed on geologic plan, section, and structural contour maps to provide a complete three-dimensional picture of the foundation and the discontinuities within the rock. Weathering profiles were developed, and fracturing was characterized to determine appropriate excavation depths. Methods were developed to extrapolate results from large-scale in-situ deformation testing to develop deformation properties for the entire foundation. From this, the deformation properties of the foundation were defined for input to finite element and trial load structural analyses of the concrete arch dam. Potential modes of instability were identified and analyzed by examining discontinuities (faults, shears, joints, foliation planes, etc.) within the foundation. This "failure mode assessment," as it is sometimes called, was developed fully in the rock mechanics arena and has been a valuable contribution to other areas of engineering. Based on this testing and analysis, foundation treatment was designed to mitigate any area of concern, be it controlled by deformation, seepage characteristics, or stability of the rock mass.

The Double-Curvature Arch – A New Standard for Efficiency

Figure 6.—Upstream face of Morrow Point Dam during construction.

Beginning in the 1960s, a new concept for shaping arch dams found its way to Reclamation (Boggs, 1975). This shape, termed "double curvature," provided for more efficient distribution of loads within the structure. A double-curvature arch is curved in section view as well as plan view. This results in somewhat of a "bowl" shape. The undercutting at the heel of the dam and the inward curvature on the downstream face that results from this shape eliminate areas where tensile stresses typically develop in arch dams.

The first double-curvature dam constructed by Reclamation is Morrow Point Dam (figure 6). At a height of 143 meters (468 feet), the dam is located in a narrow section of the Black Canyon of the Gunnison River in Colorado. The trial load method of analysis provided information that was used in shaping the dam. Several other double-curvature arch dams were successfully designed and constructed by Reclamation in the 1960s and 1970s. One that bears mention is Nambe Falls Dam, a 45.7-meter (150-foot) high structure on Rio Nambe in New Mexico. The arch is part of a composite structure, with a massive concrete thrust block on the left abutment that ties into an embankment dam. It was difficult to design for the temperature conditions at the site. Therefore, a series of flat jacks were installed in the crown cantilever joint, and the flat jacks were pressurized to prestress the dam into a state of compression that could handle all loading conditions adequately. Reclamation also pioneered the development of elliptical arches by the use of "three-centered" geometry. The elliptical arches are approximated by a central section with a smaller radius, flanked by abutment sections with larger radii. This allows double-curvature arch dams to be designed for wider canyons. Although none of these were built by Reclamation, the method was developed, and several designs were completed.

Structural Analysis Developments

Prior to the availability of digital computers in the 1960s, trial load analyses were performed by engineers operating mechanical "adding machines" and filling in values on large tables. They would work in pairs, and one would check the other's computations as they were performed. One analysis would take a pair of engineers 6 to 8 weeks. As such, not many load combinations were analyzed. The seating arrangement in the Analysis Unit was like a Viking ship with the rowmaster (Unit Head) behind the rowers (Engineers). As computers became available, procedures were developed to solve the "trial load" problem directly, and the computer program ADSAS (Arch Dam Stress Analysis System) was developed for this purpose.

In the 1970s, the country became more aware of the potential hazard associated with earthquake loading. Although ADSAS had some limited seismic analysis capability, it lacked the ability to perform modern response analyses. During the design of Auburn Dam, the finite element method was used to perform linear elastic, three-dimensional, response history modal superposition analyses (Reclamation, 1977–78). Since that time, every concrete storage dam in Reclamation's inventory has received similar analysis. Evaluating the results of dynamic finite element analyses required advances in estimating concrete strengths under seismic loading. Rapid loading laboratory tests were developed and performed, which confirmed that an increase in tensile strength of about 50 percent can be expected under dynamic loading.

Continued advances in the finite element and finite difference techniques have accompanied advances in computer capabilities. Frequency domain solutions were developed at the University of California, Berkeley, for seismic analysis incorporating coupled hydrodynamic and foundation interaction. Nonlinear finite element codes allow modeling of contraction joints and nonlinear concrete material behavior. Although it is more difficult to interpret the results from such analyses, they more realistically represent dam behavior and are capable of predicting actual failure modes. Stress and load distribution can change dramatically when geometric and material nonlinearities are incorporated. Some recent dam safety evaluations have incorporated these programs and capabilities.

Roller-Compacted Concrete – Rapid Construction for Gravity Dams

The concept of roller-compacted concrete (RCC) involves placement of a lean and dry concrete mix by spreading it in thin layers with a bulldozer and compacting it with vibratory drum rollers. The lean mix reduces the generated heat, and rapid production rates can be achieved using a mechanized construction process. Reclamation began testing a high paste (cement plus flyash) RCC mix in 1980. This resulted in a strong and stiff material with similar properties to conventional concrete and allowed gravity dams of this material to be designed using conventional methods. In 1985, placements began at Upper Stillwater Dam, Reclamation's first RCC dam and, at the time, the world's largest. The straight gravity dam is about 85.3 meters (280 feet) high, 823 meters (2,700 feet) long, and contains over 1,220,000 m^3 (1,600,000 yd^3) of concrete. Laser-guided slip forms were used to place concrete elements forming the upstream and downstream face of the dam. RCC was placed between the facing elements. The RCC contained more than twice as much flyash as cement. In 1986, over 547,000 m^3 (715,000 yd^3) of RCC was placed in less than 5 months, and the peak shift placed over 4,100 m^3 (5,400 yd^3). The major drawback to the design and construction of Upper Stillwater Dam was the exclusion of contraction joints. This resulted in formation of vertical cracks through the structure and significant leakage, requiring remedial measures. Methods were subsequently developed to include joints and waterstops in RCC structures.

Transitioning to Dam Safety – Applying Technology to Reduce Risk

As construction of new concrete dams was winding down, renewed emphasis was placed on dam safety due to an Executive order issued in April 1977. The aim of Reclamation's Dam Safety Program is to ensure that the agency's dams do not pose an unacceptable risk to the downstream public. Reclamation has used concrete dam design, analysis, and construction technology developed over the past century to meet this objective. The most recent involved stabilizing Pueblo Dam on the Arkansas River in southern Colorado. Nearly horizontal foundation shale layers beneath the massive head buttresses of the dam daylighted in the large stilling basin excavated at the toe of the dam. The reservoir had never fully filled. Due to the large population downstream of this dam, potential sliding of the structure on these shale layers posed a high risk. An RCC plug and toeblock anchored with double corrosion protected high strength rock bolts were constructed in the stilling basin to block the potential sliding planes (figure 7). State-of-the-art distinct element and probabilistic stability analyses were performed to ensure the RCC geometry would be effective in stabilizing the dam. Contraction joints were formed in the RCC by vibrating steel plates into the freshly compacted lifts. The contraction joints in the cross-canyon direction needed to be grouted

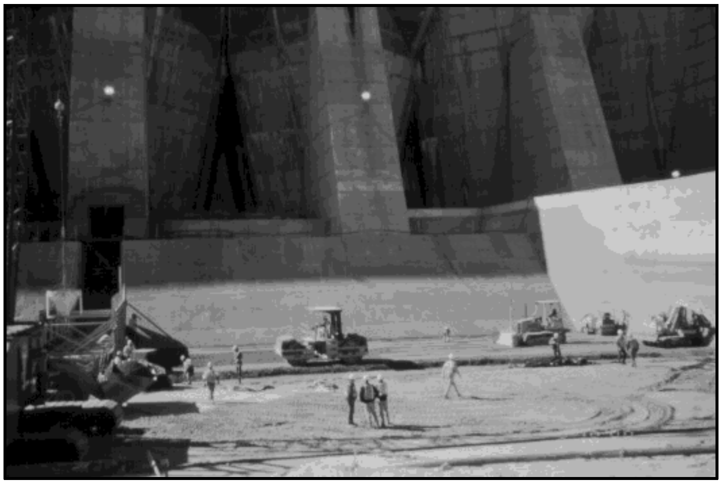

Figure 7.—RCC placement at Pueblo Dam.

to ensure that load could be transferred from upstream to downstream with minimal displacement. Six-inch diameter holes were drilled along the joints in locations where the steel plates had been omitted. Tubing was designed and installed in the holes to provide grout supply and return lines and venting to remove air and water from the system. Grouting of the joints was performed the second winter following RCC placement when joint meters indicated sufficient joint opening for the grouting operations. The grouting was successful, and the joints did not close the following summer, indicating good filling of the joints.

Final Thoughts

We hope you have enjoyed this tour of the evolution of concrete dam design, analysis, and construction within Reclamation over the past century. There is no question that the early pioneers in this effort were extremely talented and set the stage for some of the great feats of human engineering that were to follow. Monumental projects like Hoover and Grand Coulee Dams are still "wonders" today. During the heyday of dam construction in the United States, Reclamation developed a reputation as a world leader in concrete dam technology. The construction of large dams in the United States is winding down now after a century of extensive development. Reclamation can be proud of the legacy, expertise, and technology it has left the Nation and the world in concrete dam design and construction.

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Mission

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