# ANCHORS IN THE DESERT

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*Post-tensioning a thin-arch concrete dam to improve its seismic resistance is not a traditional safety modification. In fact, it had never been done until this year, when anchors were used to stabilize Stewart Mountain Dam on the Salt River near Phoenix.*

The Southwest desert isn't usually thought of as a hotbed of seismic activity, but earthquakes have occurred there. And if Arizona's Stewart Mountain Dam, a double-curvature thin-arch concrete dam on the Salt River, were to fail in one, it would have catastrophic consequences for Phoenix, just 30 mi downstream. To stabilize the dam to withstand the maximum credible earthquake, the Bureau of Reclamation (BuRec) chose post-tensioning. Many concrete gravity dams have been post-tensioned to improve their stability, but this is the first time anchors have been installed on a multicurvature concrete arch dam.

The $6.5 million project also featured several other innovations. These included an extensive anchor test program to verify bond lengths and load transfer mechanisms in each of the three major foundation zones, extremely tight drilling tolerances and frequent downhole surveys, use of epoxy-coated strands to provide primary corrosion protection for the tendons, and meticulous monitoring of the behavior of the potentially delicate structure during every phase of construction.

Under its Safety of Dams Program, BuRec designed the post-tensioned tendons and served as construction manager. Nicholson Construction, Inc., Atlanta, was awarded the contract to furnish and install the tendons in November 1990 through a negotiated procurement as the contractor providing the best combination of technical and cost proposals—another novel feature of the project and a major factor in its success. Work began in January 1991 and was substantially complete by September, with final work concluding this month.

Stewart Mountain Dam was constructed from 1928 to 1930 by the Salt River Valley Water Users Association at a cost of $2.3 million. The Salt River Project, which has funded 15% of the cost of modifications, operates the dam as part of a water-storage and power-generation system on the Salt and Verde rivers. The dam is 583 ft long, a maximum of 212 ft high, 8 ft thick at the crest and 34 ft thick at the base. There are concrete gravity thrust blocks at each abutment, from which wing dams extend into the abutment. The service spillway on the right abutment has a capacity of about 90,000 cu ft/sec, and the auxiliary spillway on the left abutment has a capacity of about 110,000 cu ft/sec. The 10 MW powerplant is fed by a 13.5 ft diameter penstock through the dam. There is a 7 ft diameter opening through the dam for bypass outlet works.

Unbonded horizontal planes within the arch concrete were the main cause of the dam's instability. At the time it was built, the importance of good cleanup on the horizontal construction joints was not recognized, so the joints were left untreated. This resulted in a layer of laitance on these joints, which compromised the bond across them.

A three-dimensional finite element analysis of the dam's performance during seismic and other loading conditions indicated that the dam would lose arch action during the maximum credible earthquake of 6.75 on the Richter scale occur-

**STABILIZING THE DAM AGAINST THE MAXIMUM CREDIBLE EARTHQUAKE REQUIRED 62 TENDONS IN THE ARCH AND 22 IN THE LEFT THRUST BLOCK.**



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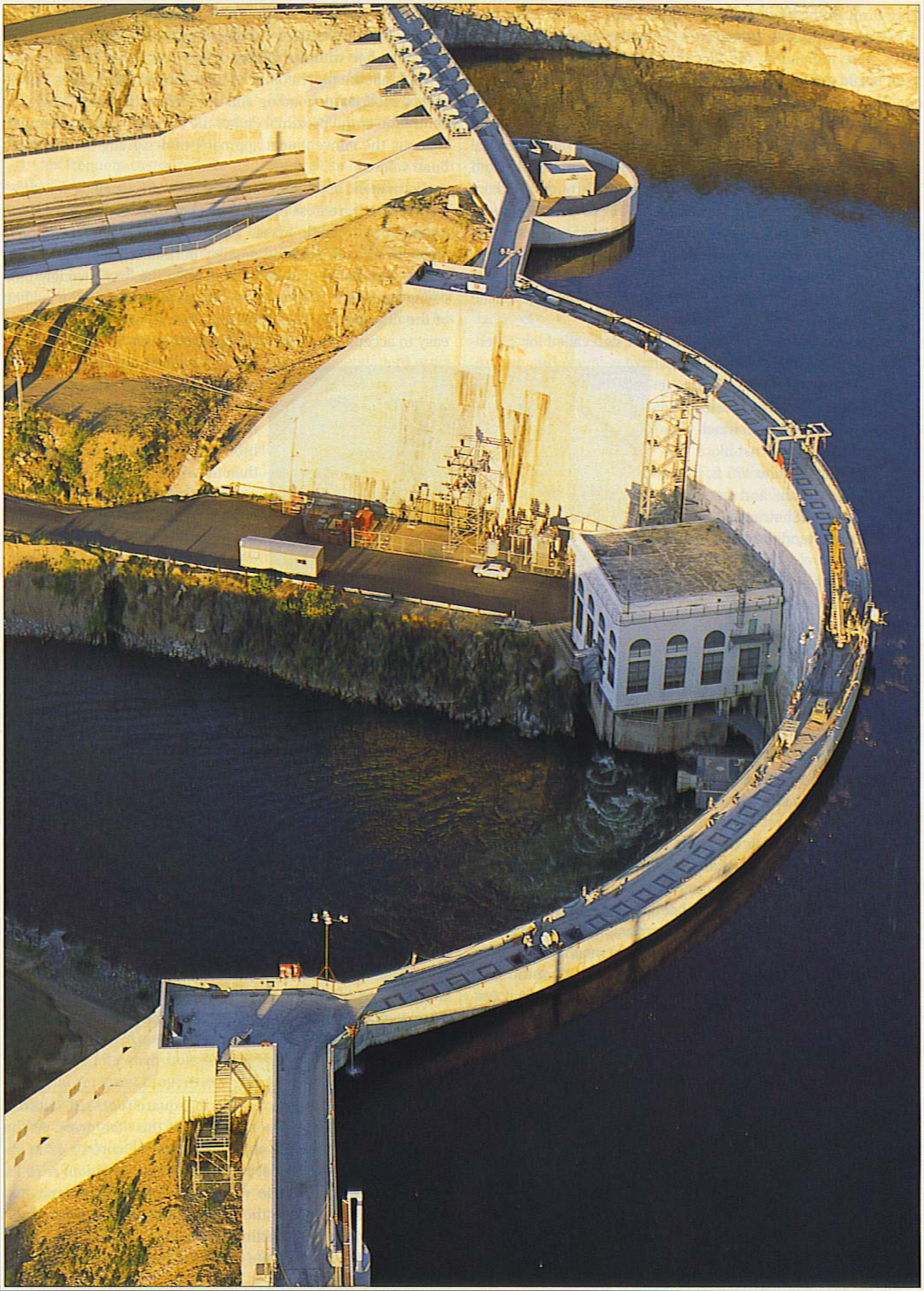

ring 9 mi from the dam. This would leave vertical cantilever sections to support themselves. Because the horizontal lift lines were unbonded, the blocks in the upper portion of the dam would then be free to displace.

To stabilize the arch, we installed 62 tendons at about 9 ft centers, with free lengths ranging up to 216 ft and bond lengths from 30 to 45 ft. Their inclination varied from vertical to 8 deg. 40 min from vertical. All but seven tendons, located immediately above the outlet works opening through the dam, were anchored in the dam foundation. These seven anchors were bonded into concrete. Each arch tendon was composed of 22 epoxy-coated strands, each 0.6 in. in diameter. Design working loads averaged about 665 kips (a range of 545–740 kips) per tendon, equivalent to about 50% guaranteed ultimate tensile strength (GUTS).

In addition to the arch tendons, the design called for 22 tendons to be installed in the left thrust block of the dam to stabilize it against failure at or just below the structure/foundation contact. The free length of the thrust-block tendons varied from 40 to 125 ft, plus a 40 ft bond length, and each was composed of 28 strands. Design load for each tendon was 985 kips (60% GUTS).

Most of the arch dam foundation consists of hard, pre-Cambrian, medium-grained quartz diorite. The diorite is cut by irregular dikes of hard, medium-grained granite that vary in orientation and thickness. A fault divides the arch dam foundation into three distinct zones with unique mechanical properties, joint systems and permeabilities: (1) to the right of the fault, (2) to the left of the fault and (3) in the fault zone itself.


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The rock underlying the right portion of the dam is hard, slightly weathered to fresh and generally of excellent quality. To the left of the fault, including the left thrust-block foundation, the rock is slightly inferior, being more fractured, sheared and weathered. The fault and the surrounding zone is very intensely fractured and moderately to slightly weathered.

During the design phase, we assumed that 32 of the arch tendons would be anchored in the right foundation zone (excluding seven cables anchored in the dam concrete), 15 in the left foundation zone and eight in the fault zone. All 22 thrust-block tendons were founded in the left foundation zone.

## TEST ANCHOR PROGRAM

We installed pairs of vertical "research" anchors 12 ft apart in each of three test sites representative of the three major rock zones expected to underlie the dam. The nominal bond lengths at each site were 10 ft and 20 ft. Each anchor was cyclically tested in 25% design working load (DL) increments to the safe maximum test load—or failure. All achieved the maximum test load of 133% DL—that is, 1,310 kips (80% GUTS)—with relative ease, with one exception: Anchor 3A, the shorter anchor in the worst rock, underwent grout/rock failure at 968 kips.

The relative amounts of apparent tendon debonding were exactly in line with the quality of the rock mass. Basically, this proved that the more competent the rock mass, the less the extent of apparent debonding and the higher the bond stress concentration at the proximal end of the anchor—and the more erroneous the conventional approach of designing on "average" bond values.

Permanent bond zone movements were smallest for site 1 anchors and greatest in site 3 anchors, reflecting the overall quality of the rock mass. In addition, the second anchor stressed at each site had smaller permanent movements (as well as less debonding and creep) than the first, strongly indicating some type of rock mass improvement during the loading of the first anchor. Clearly demonstrated, this phenomenon is easy to accept and understand, but to our knowledge it has not been previously documented. This is significant when assessing relative production anchor performance, since later anchors may exhibit better stressing performance than those installed earlier.

Creep was not significant at sites 1 and 2. Interestingly, however, while creep generally increased with load, the highest amounts were at 75–100% DL, decreasing at higher loads. Also, while test anchor 3A showed the classic progressive failure pattern, 3B showed creep values at 133% DL lower than at 100%—0.057 in. in 10 min as opposed to 0.064 in. in the same period. When restressed to 133% DL a second time, the creep was lower still (0.45 in. in 10 min).

These data point to an irregular "ratchet"-type rock mass response at odds with the smoother, more predictable performance assumed in theory and usually found in soils. We believe this rock mass improvement was due to a tightening up of the fissures and joints in the mass, in the region around and above the bond zone. We don't consider crushing of the rock itself feasible, given its material strength.

Overall, the test verified that the originally designed bond lengths had satisfactorily high safety factors in the rock at sites 1 and 2, but merited a slight increase when installed in the poorest-quality site 3 material. Work on the production anchors proceeded accordingly.

## PRODUCTION ANCHORS

Under a previous contract, 4 ft 9 in. square recesses, approximately 2 ft deep, had been formed in the dam crest. At the precise location, bearing and inclination, we cored a 12 in. diameter hole about 5 ft deep at each anchor position. A 10 in. diameter steel guide tube was then surveyed and cemented into this hole to ensure the anchor-hole drilling would have the exact prescribed starting orientation. Angles were measured by independent state-of-the-art methods to within minutes of accuracy.

A down-the-hole hammer mounted on a new Nicholson Casagrande C12 long stroke, diesel hydraulic track rig then drilled the 10 in. anchor holes. Special hammer and rod attachments promoted hole straightness. In accordance with BuRec specifications, we measured the position of each hole at 10 ft intervals in the upper 50 ft, and every 20 ft thereafter to final depth—a maximum of 270 ft.

This frequent measurement and the precision required—to within 3 in. in 100 ft—demanded very special attention. Eastman Christensen, Bakersfield, Calif., adapted their Seeker 1 rate gyro inclinometer, normally used in oil-field applications, to this project. With the Seeker, we could accurately measure the drill bit's position through the drill rods. Modification of its computer software allowed us to demonstrate the acceptability of the hole's progress within minutes at the hole collar. This minimized downtime in the construction cycle.

As a further check, BuRec personnel ran independent precision optical surveys on randomly selected holes. These confirmed the immaculate straightness of the holes, and their acceptable bearing and inclination.

We ran another series of tests during early drilling operations, in which geophones and crack meters were fixed at the downstream face of the dam immediately adjacent to the drill hole and constantly monitored during drilling. They proved that the maximum fissure apertures and vibrations induced by drilling were tiny—barely of the order induced by natural temperature fluctuations. This has major significance for dam engineers. Even on a "delicate" dam structure, drilling a hole by rotary percussion within 5 ft of a free face had minimal effects. This drilling method is extremely cost-effective, helping keep anchors an economical solution for a variety of dam stabilization problems.

For the thrust-block holes, we erected a massive frame up the face of the structure. The Casagrande drill mast was affixed to platforms carried on the frame. Again, we took special precautions to ensure hole correctness and direction.

Every hole was water pressure–tested, and pregrouted and redrilled if necessary, prior to the final acceptance survey. Most test stages, which ranged in rock and concrete from 50 to 130 ft, proved tight, but other stages required as many as three pretreatments to meet the specifications of 0.02 gpm per foot of hole at 5 psi excess pressure for the free length and half that for the bond length.

We placed the epoxy-coated strand tendons, supplied by DSI, Inc., Lemont, Ill., in reels on special uncoilers and transported them to the holes. Taking extreme care to prevent abrasion of the epoxy coating, we slowly placed each tendon to full depth and tremied a specially researched, high-strength, plasticized grout into each hole to provide the exact bond length. Fluid and set grout properties were rigorously recorded as routine quality control.

Stressing commenced a minimum of 14 days after grouting. To verify in detail the correct operation of the tendons, we subjected 12 to cyclic performance tests, according to Post-Tensioning Institute (PTI) recommendations. The remaining anchors were tested simply, under PTI proof test provisions. Given the high loads and long free lengths, we recorded net elastic extensions as long as 16.2 in. at the test load on the longest tendons. Creep and lift-off checks rounded out the initial verification of the anchors. In all aspects, every anchor proved to have outstanding qualities, with details closely mirroring the results of the test program.

Each anchor was proved to 133% of design working load, prior to interim lock-off at 117% DL. Monitoring of the dam during stressing confirmed no significant structural deflections caused by this extra manual load. This was probably helped by BuRec's idea of building up the load gradually in each block of the dam to minimize any loading impact. Anchor 60 was followed by anchor 58, then anchor 6 by anchor 4, then 13 by 11, and so on. Final lock-off at 108.5% DL, and full secondary grouting of the free length, followed the 100-day observation period.

## Lessons

Several features of the Stewart Mountain Dam project are unique and promise to make it one of the key dam rehabilitation projects of the decade:

- Application: The project represents the first use of high-capacity anchors to strengthen a double-curvature thin-arch dam to resist seismic effects.
- Research and development: The intensive test program confirmed many of the intricate theories of load transfer in hard rock anchors and—surprisingly—provided a clear reminder that even hard rock masses can be altered by prestressing.
- Drilling technology: Using appropriate planning, tooling, equipment and expertise, 10 in. holes can be drilled fast and extremely straight and accurately through both concrete and rock to depths of over 270 ft. Such methods appear to have absolutely no deleterious effects on the structure. And more—systems now exist to pinpoint this accuracy to within inches at this depth.
- Tendon technology: The relatively new product of epoxy-coated strands appears workable in the field and seems to give excellent bonding characteristics.
- Anchor/structure interaction: If Stewart Mountain is typical of the current quality of such dams, then we can conclude that the application of tens of thousands of tons of prestress causes no structural distress to double-curvature thin arches.

Despite these technological conclusions, one of the lasting lessons of the Stewart Mountain Dam project may have been the procurement and contracting procedure. Far in advance of bidding, BuRec researched current practices and experiences in all facets of the industry. As a consequence, the specifications, though by necessity very rigorous, were both eminently practical and right up to date.

The decision to invite separate technical and price proposals—independently assessed—assured that not only was the best qualified contractor for this job chosen but that it was also motivated to contribute "heart and soul" to every stage of the project's execution. As a consequence, the work was carried out virtually as an engineering joint venture, at site and head office levels, between equally committed parties.

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