Post-Tensioned Rehabilitation of Hydropower dams: Continuously Improving on an Anchor Program

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Introduction

The Lower Colorado River Authority (LCRA) operates six hydropower dams on the lower Colorado River in central Texas. As part of a $50 Million modernization program, post-tensioned anchors were used to stabilize four of the six Highland Lakes hydropower dams. The use of anchors for the rehabilitation of each structure evolved by incorporating lessons learned on the previous dams. The anchoring program was tailored for the unique challenges of each facility. The analysis of the difficult conditions encountered during rehabilitation of the first dam, Wirtz Dam, provided an opportunity to improve the stabilization design of the remaining dams. Through the use of extensive field investigations, test anchor programs, and peer review, the post-tensioned anchor details and specifications were progressively improved for each rehabilitation project.

Post-tensioned anchors provide an excellent means to increase the stability of a hydro-power structure to withstand larger loads than anticipated during original design. Post-tensioning projects typically cost a fraction of other stabilization methods while preserving the historic appearance of the structure. Although each application is unique and requires investigation and testing to establish the details and specifications, the post-tensioned stabilization program used on LCRA's dams can be easily adapted to a wide range of hydro-power structures. This paper discusses the lessons learned installing over 300 anchors on four high-hazard dams and developments made during the anchoring program. The model followed in this paper can be applied in response to unique hydropower configurations and site specific challenges to build a successful post-tensioned anchor rehabilitation program.

Background

In the early 1990's the LCRA and Freese and Nichols, Inc. completed preliminary studies that determined that four of the six Highland Lakes Dams needed improvements to meet modern design standards. As a result of these studies, the LCRA began its $50 million, 10-year program to perform detailed investigations, design modernization improvements, and complete construction of improvements for four of the dams. Under the Texas Administrative Code, all six of the Highland Lakes Dams are classified as large, high hazard dams. State regulations require all high hazard dams to safely pass the probable maximum flood (PMF). Wirtz Dam, Buchanan Dam, Inks Dam, and Tom Miller Dam required stabilization to withstand flood events as low as the 500 year event for certain failure modes. All four of the reservoirs are multipurpose reservoirs providing hydroelectric power to cities located in Central Texas, municipal water supply, and recreational uses for the area. Risk and failure mode analyses were used to prioritize the dams for modernization, with the modernization of Alvin Wirtz Dam being completed in 1998, Buchanan Dam in 2000, Inks Dam in 2001, and Tom Miller Dam in 2004. The use of custom tailored post-tensioning programs at each of the four dams allowed LCRA to complete the modernization of the Highland Lakes Dams within budget and ahead of schedule.

Description of Projects Sites

Originally constructed from 1949 to 1951, **Wirtz Dam** is a concrete and earthen gravity dam with two gated spillways impounding Lake LBJ. The dam is approximately 5,580 feet long and includes a concrete spillway controlled by a single radial gate, a second concrete spillway controlled by nine radial gates, a powerhouse and intake section with two hydroelectric generation units, a roller compacted concrete plated embankment section, and interconnecting concrete bulkhead sections. The entire dam is founded on granite. Prior to the recent modernization, the dam was last upgraded in 1970 to add the single-gate spillway and repair scour damage adjacent to the powerhouse. Figure 1 provides an aerial photograph of Wirtz Dam.

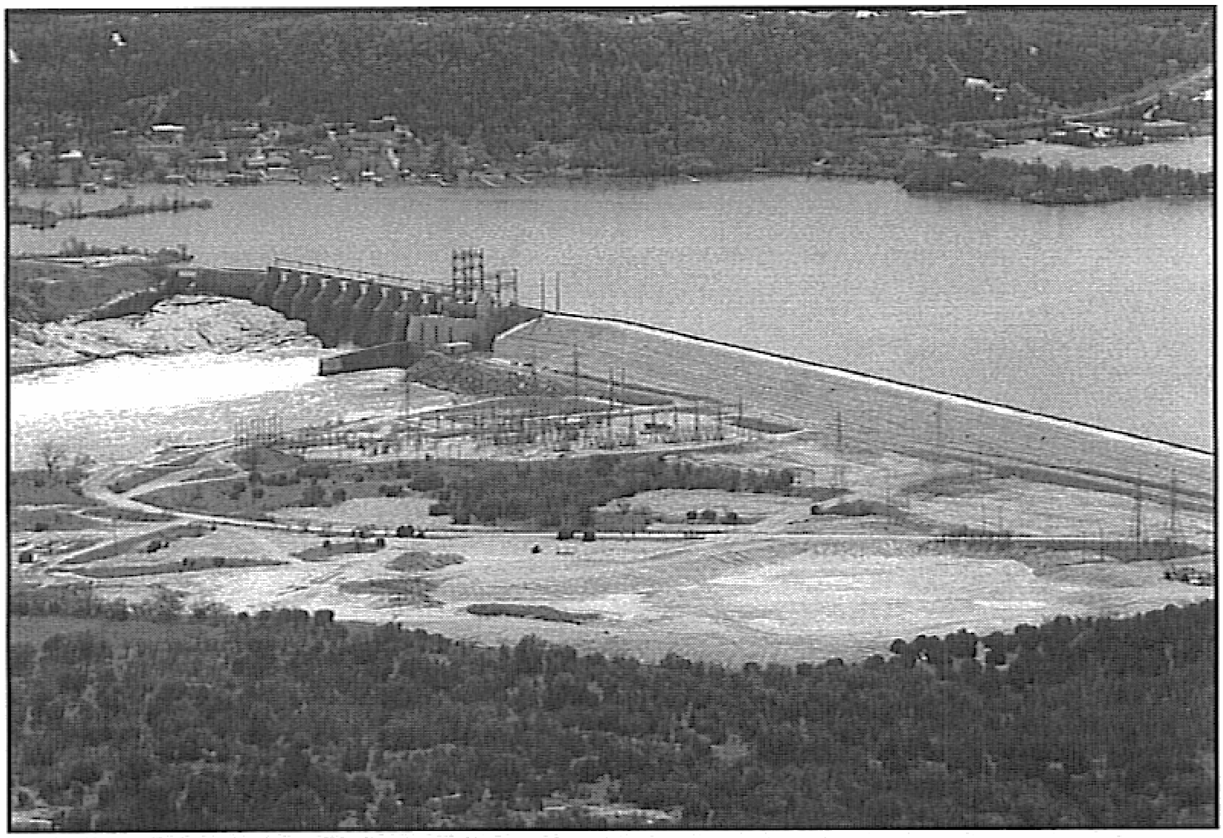

Figure 1 – Aerial view of Wirtz Dam

Buchanan Dam, is an impressive structure approximately two miles long combining elements of concrete and earthen gravity dams and arch dams. The dam impounds Lake Buchanan, the first lake in the chain of Highland Lakes. Buchanan Dam was constructed from 1931 to 1936 and consists of two multiple buttressed arch sections, three separate concrete gravity spillways controlled by 7, 14, and 16 radial gates respectively, a uncontrolled ogee-shaped concrete gravity spillway, a powerhouse with four hydroelectric generation units, interconnecting non-overflow concrete gravity bulkhead sections, and an earthen embankment section. The dam is founded on a massive granite formation. Figure 2 provides an aerial photograph of Buchanan Dam.

Figure 2 – Aerial view of Buchanan Dam

Located just downstream of Buchanan Dam, **Inks Dam** is approximately 1550 feet long and impounds Inks Lake. The dam consists of an uncontrolled ogee shaped concrete gravity spillway, a powerhouse with a single hydroelectric generation unit, and a non-overflow concrete gravity bulkhead section. Inks Dam was constructed from 1936 to 1938, immediately following the completion of Buchanan Dam. The dam is founded on granitic-gneiss and a large rock outcrop forms the left bank of the dam. As a result of the rock outcrop, the foundation of the spillway rises nearly 75 feet in elevation from the center of the river channel to the left abutment. Figure 3 provides an aerial photograph of Inks Dam dam.

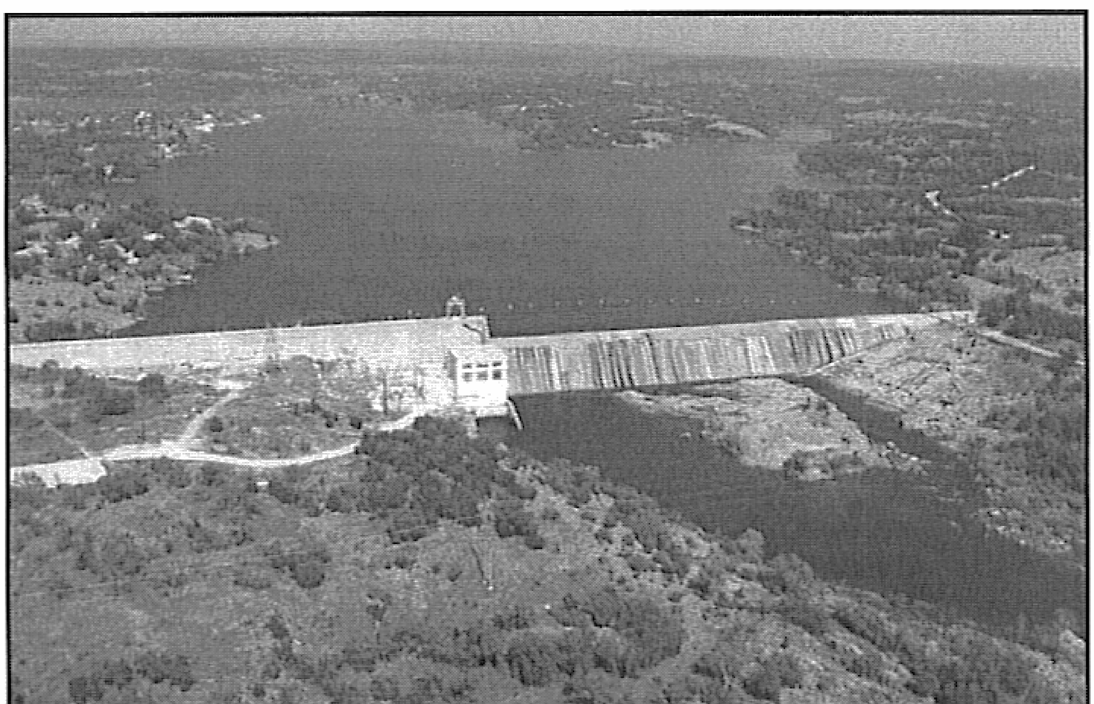

Figure 3 – Aerial view of Inks Dam

Tom Miller Dam is a unique structure with an interesting history. The last in the series of Highland Lakes dams, the dam was originally constructed in 1893 by the City of Austin, failed catastrophically in 1900, was re-built and failed again between 1912 and 1915, and was re-constructed in 1938 to 1941 by the LCRA. The dam is approximately 1440 feet long and combines elements of all three construction efforts. The major features of the dam include an embankment section with a concrete core wall, a powerhouse and concrete gravity intake structure (built on top of portions of the original masonry dam and 1912 flat slab-and-buttress dam) with two hydroelectric generation units, a concrete flat slab-and-buttress spillway controlled by nine radial gates, and an uncontrolled ogee-shaped concrete gravity spillway comprised of the original cyclopean limestone masonry dam overlaid by a reinforced concrete cap. Tom Miller Dam is located within a very complex geologic setting known as the Balcones Fault Zone. The dam is founded on weathered limestone with severely fractured and highly permeable zones.

Tom Miller Dam serves the primary purpose of passing water released from the large upstream hydro-generation facilities to maintain Lake Austin (City of Austin's primary water supply). Figure 4 provides an aerial photograph of Tom Miller Dam.

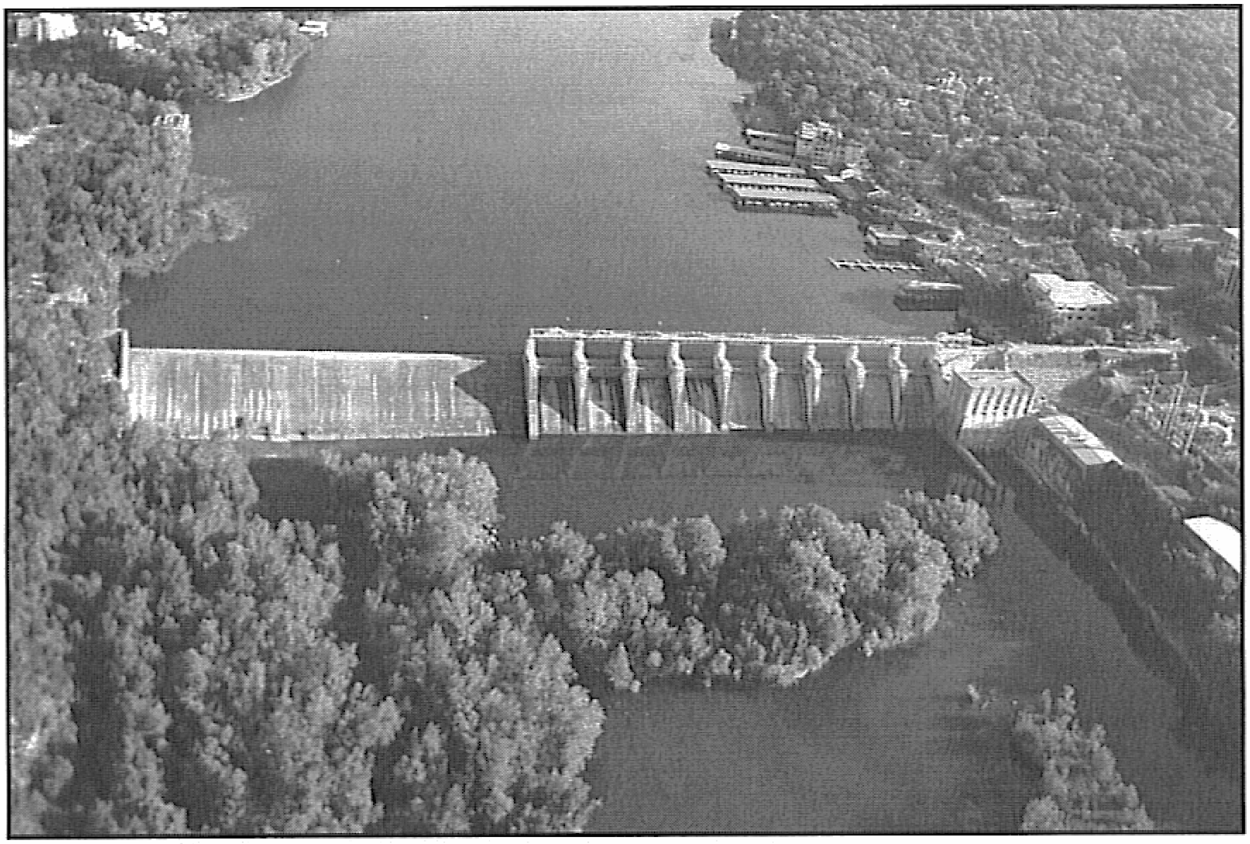

Figure 4 – Aerial view of Tom Miller Dam

Table 1 summarizes the key features of the four Highland Lakes dams stabilized using post-tension anchors.

Table 1: Features of Stabilized Dams

Name of Dam	Post-Tensioned Anchor Stabilized Sections	Type of Structure (Stabilized Sections)	Combined Length of Stabilized Sections	Primary Foundation Type
Wirtz Dam	Gated Spillways and Bulkhead Sections	Concrete Gravity	1200 Feet	Granite
Buchanan Dam	Non-Overflow Bulkhead Sections	Concrete Gravity	3700 Feet	Granite
Inks Dam	Uncontrolled Overflow Spillway	Concrete Gravity	880 Feet	Granitic-Gneiss
Tom Miller Dam	Uncontrolled Overflow Spillway and Powerhouse Intake Section	Cyclopean Masonry Overlain with Concrete	560 Feet	Weathered Limestone

Anchor Stabilization Program

Post-tensioning programs were customized for each of the four dams to be stabilized. Multiple-strand tendon anchors were installed at all four dams. The number of strands per anchor and anchor spacing were selected based on the required stabilization forces, geometric limitations, structural configuration, and foundation characteristics of each dam. Each of the anchor programs was specified according to the Post-Tensioning Institute's (PTI) published *Recommendations for Prestressed Rock and Soil Anchors (1996)*. Site specific requirements were developed for each dam including corrosion protection details, treatment of the foundation, protection of the structural elements, restrictions on drilling methods, and various other design details. For each dam, lessons learned from the previous dams were incorporated into the subsequent designs. Strict qualification requirements were used in bidding each project to select specialized anchor contractors experienced in similar post-tensioned anchoring projects. To supplement the quality control programs implemented by the contractors, each individual anchor test was witnessed by the Owner/Engineer representatives.

Wirtz Dam Stabilization

While Wirtz Dam was the last of the modernized dams to be constructed, risk assessment prioritized Wirtz Dam as the first dam to be modernized. Wirtz Dam was also the LCRA's first endeavor into post-tensioned anchoring. At Wirtz Dam, 78 multiple-strand tendon anchors were used to stabilize the gated spillways and interconnecting gravity non-overflow sections, including:

- 72 twenty-seven strand anchors with a lock-off load of 1110 kips (70% GUTS)
- 6 eighteen strand anchors with a lock-off load of 740 kips (70% GUTS) .

The post-tensioned anchors consisted of a bonded length in the foundation bedrock and an unbonded or free length extending from the top of the bond zone to the anchorage at the top of the dam. The anchor tendons ranged from 56 to 148 feet in total length with 30 feet bond zones. The multi-strand tendon anchors were installed in a drilled hole approximately 9-inches in diameter extending up to 50 feet into the bedrock. The drilled hole inclination ranged from 69 to 90 degrees from horizontal. Drilling restrictions and tolerances were specified to reduce the potential for damaging the existing foundation drain system during drilling and grouting operations.

Corrosion protection was provided through the use of epoxy coated strands. This provided what is known in the industry as Class I (encapsulated) corrosion protection, often referred to as double corrosion protection. The unbonded length of the anchor was encapsulated in a grease-filled sheath and grouted along with the bond zone in a single stage. The anchors placed in the gated spillways were recessed in pockets to avoid interfering with the discharge flow. The design provided for the anchor head and wedges to be protected by a grease-filled metal vault. Concrete was then placed flush with the spillway surface following stressing of the tendons.

The anchor system was designed using a finite element model of the structure and foundation rock to confirm that loads imparted on the dam from the post-tensioning forces would not cause binding of the radial gates preventing proper operation during flood releases. The structural deformation analyses considered a fault passing diagonally to the axis of the dam with variations in foundation properties on each side of the fault. The anchors were spaced to avoid differential settlement of the structure occurring during stressing. Extensometers and precision surveys were used to verify that excessive deformations did not cause adverse affects on the structure and gates. Permanent load cells were installed on representative anchors in each section of the dam for long term performance monitoring.

During construction, issues related to manufacturing quality control of the anchor strand surfaced. In response, careful re-engineering of the contractor's quality control program reduced the occurrence of wedge slippage after testing and lock-off of the post-tensioned anchors. Also, in response to wedge slippage, the anchorage was modified to add a secondary gripping mechanism achieved by fully grouting the strand tails in high strength epoxy grout. Despite difficulties with the anchor strand, the project was completed on-time and within budget. Following construction, the load cells were monitored for the one year warranty period. All load cells indicated load loss to be within the ASTM limits for seven-wire strand relaxation and within the projected design performance based on a fifty year service life.

Buchanan Dam Stabilization

The lessons learned at Wirtz Dam were incorporated into the anchor program for the next dam, Buchanan Dam. A test anchor program was developed and conducted during the design phase. This program established the rock strength parameters used in sizing and configuring the anchors. Four test anchors were installed and performance tested in accordance with PTI criteria. Extended creep tests were performed on each of the test anchors and anchor loads were monitored for 1000 hours to determine that the relaxation of the tendons was within limits prescribed by PTI. Data from the performance tests were used to determine that the load carrying capacity of the test anchors was sufficient for the design loads, the observed extension of the tendon was within limits prescribed by PTI, and the rate of tendon creep would stabilize within the time limits prescribed by PTI. The performance tests demonstrated average rock/grout bond strengths in the granite foundation up to 370 psi without any signs of failure. Due to the competent nature of the foundation at Buchanan Dam, none of the tendons could be tested to failure within the 80% guaranteed ultimate tensile strength (GUTS) limit of the steel.

At Buchanan Dam, 138 multiple-strand tendon anchors were used to stabilize the non-overflow concrete gravity bulkhead sections, including:

- 42 twenty-one strand anchors with a lock-off load of 861 kips (70% GUTS)
- 96 five-strand anchors with a lock-off load of 205 kips (70% GUTS)

Seven-wire bare strand was selected for use in the Buchanan anchors. Post-tensioned bar anchors were also bid as an alternate to the smaller five strand anchors. Due to the length of the anchors, all bidders provided lower pricing for the multiple strand anchors than bar anchors. The anchor tendons ranged from 70 to 130 feet in total length and were installed with a vertical orientation. The multi-strand tendon anchors were installed in a drilled hole approximately 7-inches and 11-inches in diameter for the five-strand and twenty-one strand anchors respectively.

Corrosion protection at Buchanan Dam was developed to provide protection of the bare strand. Heavy-wall corrugated HDPE pipe provided an encapsulation around the tendon for Class I (encapsulated) corrosion protection. The annulus of the corrugated pipe was pre-grouted into the anchor hole prior to installing the anchor. Greased sheaths and grease filled anchor head vaults were not used at Buchanan Dam. Instead, the tendons were installed and only the bond zone grouted prior to stressing. The specifications required the contractor to use power seating to ensure uniform seating of the strand wedges. Following testing and acceptance, the entire tendon was fully grouted.

The contractor had a severely restricted work area on the top of the dam requiring the use of drilling equipment smaller than four feet in width. Project specifications required that the contractor demonstrate the adequacy of his drilling, installation, and quality control procedures on one 5-strand and one 21-strand test anchor prior to proceeding with any other anchoring work. As a result of the demonstration, the contractor refined his procedures and successfully installed137 anchors without a single failure.

Inks Dam Stabilization

Having similar foundation conditions to Buchanan Dam, the same corrosion protection system, anchor configuration, and foundation strength parameters from the Buchanan test anchor program were used at Inks Dam. The primary challenge at Inks Dam was that the concrete crest of the uncontrolled overflow spillway was in poor shape, highly fractured in irregular patterns. The only significant difference in the Inks Dam and Buchanan Dam programs was developing a method for transferring the stabilization forces into the Inks structure in the form of a highly reinforced stressing beam.

Approximately 2000 cubic yards of concrete were excavated from the dam's crest to facilitate construction of the stressing beam and replacement of the spillway crest. Steel sleeves were placed in the stressing beam to facilitate drilling the 11-inch diameter anchor holes and to eliminate interference with the beam's reinforcing steel. At Inks Dam, 46 twenty-four strand tendon anchors with a lock-off load of 985 kips (70% GUTS) were used to stabilize the uncontrolled ogre-shaped concrete spillway. The anchor tendons ranged from 60 to 130 feet in total length and were installed with drilled hole inclination of three degrees from vertical to avoid interfering with the existing foundation underdrain system. The number of strands was increased from the 21 used at Buchanan to 24 strands based on the required stabilization loads. Figure 5 shows the anchoring approach including the stressing beam, anchor configuration, and cap replacement.

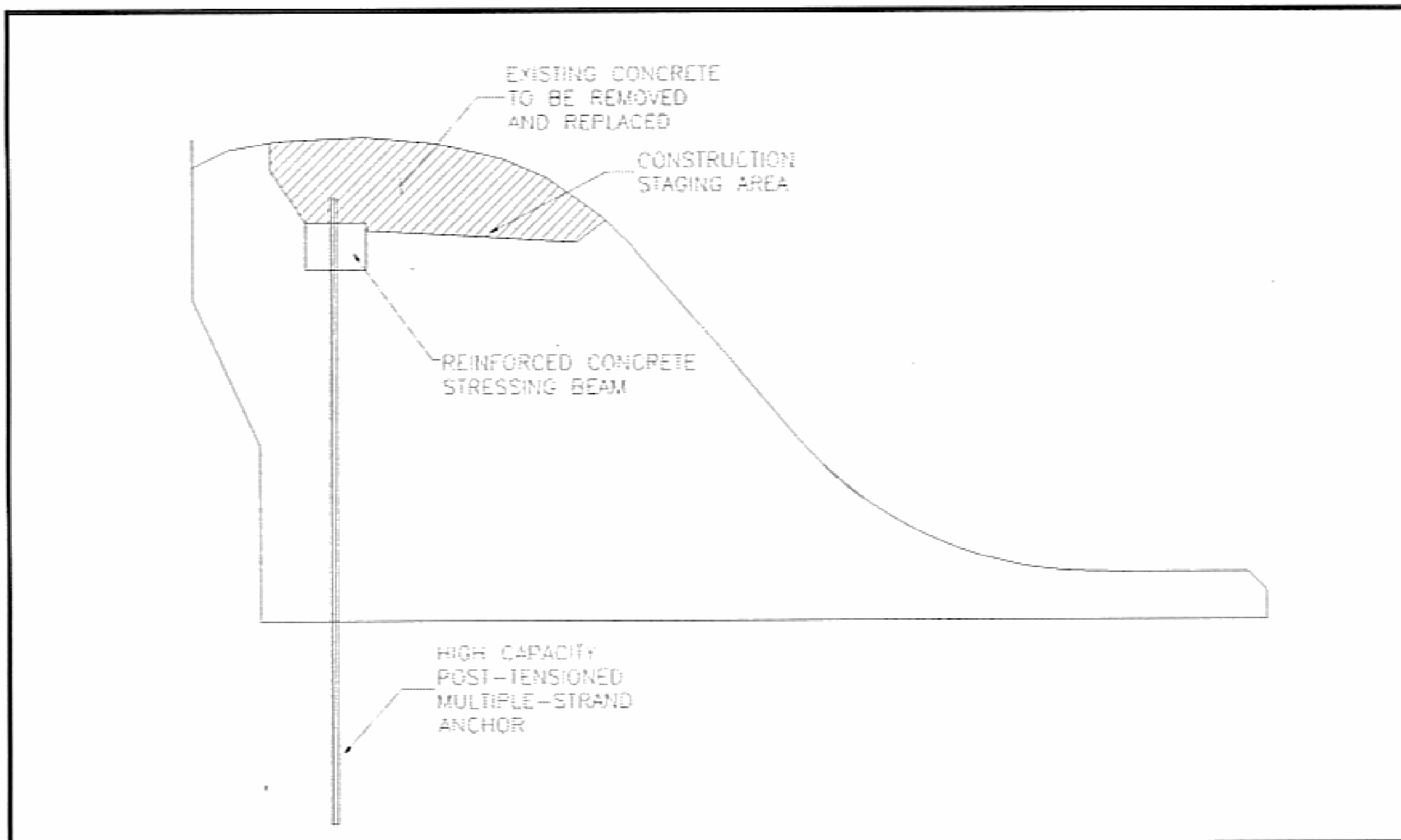

Figure 5: Inks Dam Post-Tensioned Anchoring Approach – Typical Cross Section

Tom Miller Dam Stabilization

The last to be stabilized, Tom Miller Dam certainly presented the most challenging site conditions. Special design studies were required to overcome the significant challenges posed by the complicated geology and composite construction of the dam. The moderately weathered limestone foundation has several highly weathered zones in horizontal planes below the structure. Large voids and highly permeable zones were noted in the drill logs throughout the geotechnical investigation program. The stabilized portions of the dam consisted of mortared irregular limestone blocks capped with concrete. The limestone was quarried from a site adjacent to the right abutment of the dam, thus the limestone is of a similar quality as the foundation rock beneath the dam. The powerhouse intake section is further complicated by portions of the flat slab-and-buttress dam that extend upstream of the section.

Fifty-five 18-strand tendon anchors were installed at Tom Miller Dam to stabilize the uncontrolled ogee-shaped spillway and the powerhouse intake structure. Each anchor had a lock-off load of 740 kips (70% GUTS). The anchor tendons ranged from 130 to

150 feet in total length and were installed in vertical, eight-inch diameter drilled holes. The anchor design was carefully developed to handle the difficult geologic and structural conditions that would often be considered detrimental to construction of post-tensioned anchor systems, including zones of poor quality, severely weathered, fractured, decomposed, cavitated, or highly permeable rock showing evidence of significant water movement through the core of the dam and foundation rock formation.

As with Buchanan and Inks Dams, a test anchor program was used during design to provide data for sizing and configuration of the production anchors. Two anchors were tested to failure and two were performance tested. The performance tests demonstrated average rock/grout bond strengths in the limestone foundation exceeding 200 psi without any signs of failure. The anchors tested to failure showed ultimate bond strengths up to 430 psi. The bond length for the production anchors was set at 30 feet based on a 2.0 safety factor and an adjustment for expected random zones of highly weathered rock as observed in the geotechnical sampling across the dam.

Based on the observations made during the test anchor program, a program was developed for the production anchors to pre-treat each anchor hole in the dam and bedrock by gravity grouting using a sand cement mixture. The holes were then re-drilled, watertightness tested, and neat cement grouted (where necessary) to enable the anchors to be installed in accordance with the PTI watertightness criterion for the bond zone (2 ½ gallons loss in 10 minutes at 5 psi excess head). To provide Class I corrosion protection, a corrugated heavy wall HDPE pipe was then pregrouted into the hole prior to tendon insertion. A grease-filled sheath was used on each of the anchor strands to provide an unbonded length of the anchor to make certain that the post-tensioning forces were transferred into the foundation in a zone of relatively competent limestone and away from the masonry core of the dam. A length of bare strand was provided at the top of the anchor beneath the anchor head to provide fully grouted tendons bonded in the concrete cap.

A three-dimensional finite element model was used to verify that the post-tensioning forces would not have an adverse affect on the masonry core of the dam considering the irregular character of the masonry core and to determine the range of anticipated structural deformations. Restrictions were also specified for the contractor's drilling methods to make sure the drilling did not damage the masonry core. Vertical extensometers were installed adjacent to the test anchors to verify that the application of the post-tensioning forces did not adversely affect the structure. By following a disciplined quality control program, the contractor successfully demonstrated that the holes could be drilled within the specified alignment tolerances, the foundation rock treated to meet watertightness criteria, the tendons effectively installed and grouted, and the anchor tested and locked-off in accordance with the acceptance criteria. Based on observations of the site specific field conditions, several improvements were made to the fabrication and installation program to enhance the construction of the remaining 53 anchors. The two test anchors were accepted as production anchors and the remaining anchors were released for hole drilling and tendon fabrication. To gain a familiarity with the groutability of the masonry core and foundation, grouting procedures were refined based on a series of trial mix batches to enhance the effectiveness of the remaining grouting operations. Despite the challenging site conditions, the anchors were drilled, grouted, tested, and stressed efficiently without any anchor failures, allowing the project to be completed on schedule and within budget. Figure 6 presents a cross section of the anchor configuration at Tom Miller Dam.

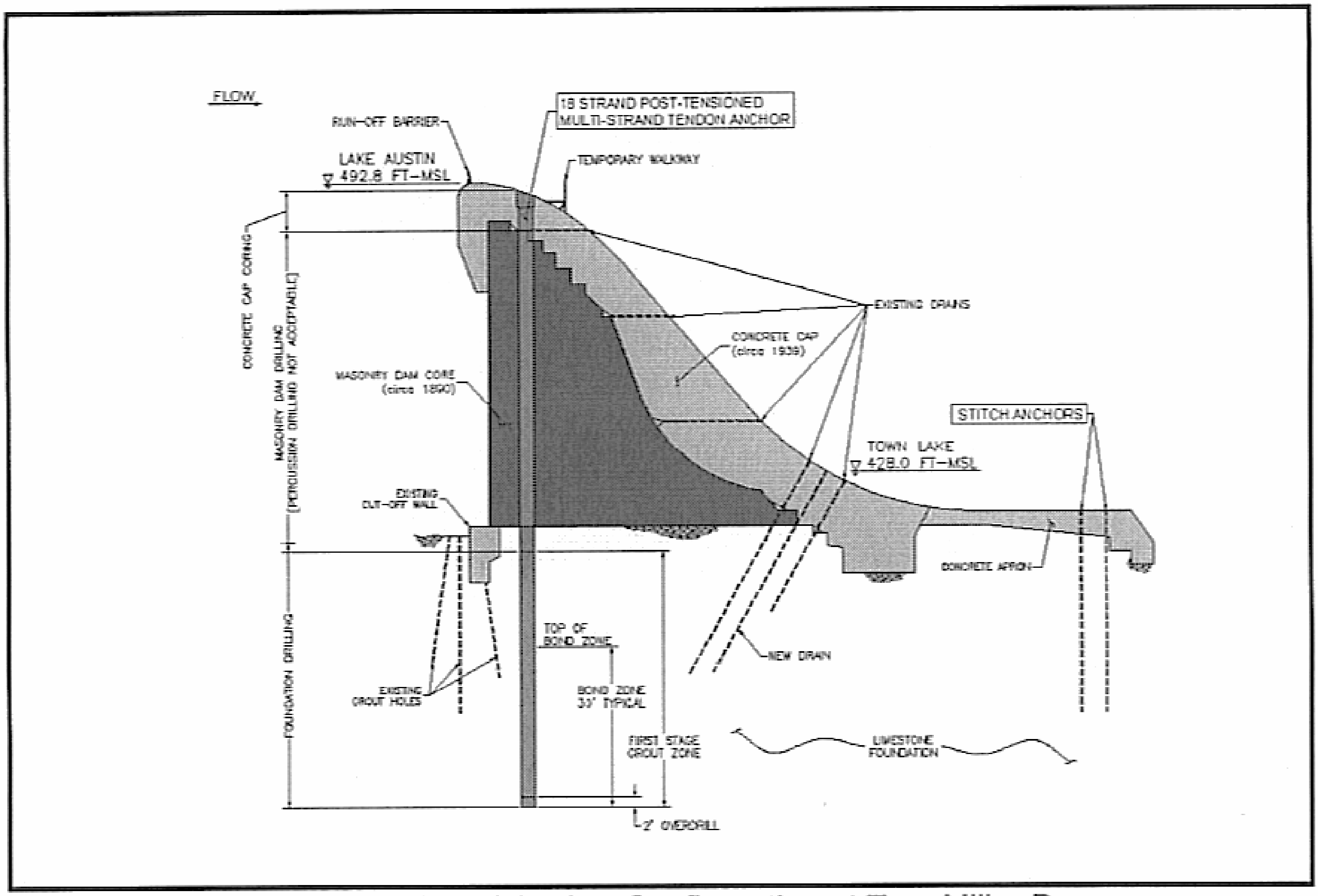

Figure 6 – Typical Post-tensioned Anchor Configuration at Tom Miller Dam

Conclusions

Post-tensioned anchors provide a cost-effective and adaptable method for stabilizing structures to safely withstand increased loadings. When post-tensioned anchors are selected as the stabilization method, it is imperative that the unique characteristics and configuration of each structure control the design of the anchor system. With appropriate design, qualified contractors, and adequate quality control, post-tensioned anchor systems can be efficiently installed and tested with minimal chance of failure. Despite the challenging geologic, structural configuration, and site access conditions associated with the four LCRA dams, post-tensioned anchors were successfully installed within budget and on schedule. Through the installation of over 300 anchors on the modernization program, the anchors have demonstrated that they can carry the design load and provide necessary stabilization forces even after all creep or relaxation losses are considered. As a result, the LCRA dams have extended their useful lives by more than 50 years.

Author Information

Gregor Forbes is a senior program manager at the Lower Colorado River Authority. Mr. Forbes managed the Highland Lakes Dam Modernization Program. Mr. Forbes has over 34 years of experience in managing the design and construction of dams, hydroelectric facilities, tunnels, and transmission facilities associated with water and wastewater. His responsibilities include all aspects of project development, including program planning, design, and construction.

John S. Wolfhope, P.E. is a project manager and associate at Freese and Nichols, Inc. in Austin, Texas. Mr. Wolfhope was a lead engineer and project manager for the Highland Lakes Dam modernization program. His experience includes fifteen years in the design and construction of significant public works projects, including dams, hydraulic structures, water transmission facilities, and instrumentation systems. Mr. Wolfhope is currently the co-principal investigator in the National Research Program for Rock Anchors in Dams.

Donald Bruce, PhD. is a the president of Geosystems, L.P.. Dr. Bruce assisted with the design and customization of the post-tensioned anchor programs for the Highland Lakes Dams. He has over 30 years experience with the design and construction of post-tensioned rock anchors and grouting systems for dams. Dr. Bruce is currently the co-principal investigator in the National Research Program for Rock Anchors in Dams.

M. Leslie Boyd, P.E. is a senior engineer and associate at Freese and Nichols, Inc. in Austin, Texas. Mr. Boyd served as a lead engineer and resident construction manager for the Highland Lakes Dam Modernization Program. He oversaw the installation of all of the post-tensioned anchors for the Highland Lakes Dams. Mr. Boyd has over 30 years experience in dam design, rehabilitation, and construction management.

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