Rock Anchors for Dams, The National Research Project: The Evolution of Post-tensioned Anchors on Hydropower Dams

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ABSTRACT

Rock anchors provide a cost-effective and low maintenance solution for strengthening hydropower dams. Prestressed rock anchors have been used to stabilize dams and appurtenant structures in North America for over three decades. During this period, the anchor industry has evolved through the completion of nearly four hundred projects. The goal of the National Research Program on Rock Anchors for Dams is to advance the awareness and understanding of the use of post-tensioned anchors throughout the dam and hydropower industries. The prime objectives are to: a) produce a definitive and detailed list of all the North American dam anchor projects, b) trace the evolution of practice via an analysis of codes and specifications, and c) to project the market for post-tensioned anchors on large dams and hydropower facilities.

Over 390 case studies have been collected and studied so far to identify trends and lessons learned through the practice of engineering and constructing rock anchor systems. Through an interactive web-based database system, a collaborate effort was made to identify the numerous sources of information amassed over the past 30 years, exchange information between the various industry organizations, construction companies, engineering firms, government agencies, and hydropower producers, and extract relevant information on each anchored dam. Special attention was given to information providing insights into the long-term performance of anchoring systems on dams and hydropower facilities. The industry guidelines, from the first tentative recommendation document to the latest Post-Tensioning Institute *Recommendations*, were studied to characterize the evolution of anchoring practice in North America. Finally, national databases of nearly 80,000 dams in the United States and over 900 large dams in Canada were analyzed to predict the market for post-tensioning projects in North American dams. The National Research Project has been funded by the cooperative support of private industry and trade/professional associations. This paper presents the findings of the first phases of the National Research Project completed in 2005.

Background of National Research Program on Rock Anchors for Dams

Prestessed rock and soil anchors have become a predominant technology for repair and upgrade of dams and hydro-electric generation facilities. While many case studies on dam anchoring projects have been published in various journals and conference proceedings, an enormous wealth of information exists in the archives of owners, engineers, material suppliers, and contractors. The continued merger and acquisition of many engineering and construction firms over the past decade as well as the occurrence of natural disasters such as floods that have damaged some existing record sources threaten the preservation of this information. These factors, as well as the occurrence of material quality control issues related to the use of epoxy-coated strand during the 1990s (ASDC 2003) led the authors to recognize the need for an industry-wide research program to collect and analyze information on pre-stressed rock anchors for dams.

The research approach for the National Research Program was as follows:

- Conduct Survey of dam anchoring practice.
- Collect all published books and technical papers.
- Develop an Internet-based interactive database repository of information related to anchoring of dams.
- Review the evolution of North American anchoring practice and technical guidance documents.
- Characterize the market for prestressed rock anchors in dams.

The first phase of the research program involved gathering lists of projects and project records from post-tensioned anchor suppliers and specialty contractors. A web-based database was developed to provide a central information store for the anchoring project records. The database includes general information on the dam and the anchor program, specific information on the anchored sections of the dams, and detailed records of the various anchor configurations. Electronic and physical files were developed for each identified dam anchoring project. Where possible, copies of anchor detail drawings and technical specifications were obtained for use in developing the case study file.

A comprehensive literature survey was completed to identify all published dam anchoring case studies, as well as various publications documenting North American anchor practices and construction methods. Over 180 published articles and books were catalogued and information was extracted for inclusion in the case study database. The published articles were used to obtain background case study information such as the purpose and engineering justification for the anchors, geologic conditions, site investigation programs; to identify anchor system configurations, descriptions, and anchor schedules; as well as to confirm information found in contractor and supplier records.

Evolution of North American Practice: Codes and Specifications

Prestressed rock anchors have been used in the United States since the early 1960s, and as permanent installations in dams since 1968. The early post-tensioning specialists each had their own proprietary practices and systems, from which emerged a need for a nationally acknowledged document of guidelines for American practice. The first such American document was published in 1974 by the Post Tensioning Division of the Prestressed Concrete Institute and was adopted for republication by the United States Army Corps of Engineers (USACE). This Division soon afterwards broke away to form the Post Tensioning Institute (PTI), and published successive *Recommendations* documents in 1980, 1986, 1996, and 2004. From the initial document published in 1974 containing general guides for construction and applications to PTI's sophisticated recent 2004 update of the *Recommendations for Prestressed Rock and Soil Anchors*, the guidelines and practices have been improved and refined based on the advancements in technical knowledge and lessons learned from completed anchoring projects. All aspects of anchoring practice have received scrutiny through the evolving releases of the PTI recommendations.

As part of the National Research Program on Rock Anchors for Dams Phase I studies, a report was issued reviewing the evolution of the American recommendations documents. The report includes a general comparison of the composition of the drafting committees and a subjective evaluation of the relative quality and completeness of the major chapters of the documents. From the initial committee comprised mostly of post-tensioning suppliers to the recent committee comprised evenly of suppliers, engineers, contractors, and owners, the detailed coverage of practices and methods have expanded significantly while the general discussions of applications have been eliminated. The primary areas of improvement were grouped into the following categories based on the significant aspects of the documents for more thorough analysis:

1. Materials
2. Design Practices and Site Investigation
3. Corrosion Protection
4. Construction Methods
5. Stressing and Testing
6. Records and Submittals
7. Specifications and Procurement

Each of these seven topics evolved from minimal coverage in the initial documents to detailed and logically presented coverage in the most recent publication. Some aspects of practice however including design assumptions of rock bond values and bond zone stress distribution have not changed over the 30-year evolution of the *Recommendation* documents. Certain aspects such as grouting have remained mostly the same except for the move from proprietary blends to neat cement grouts with the use of special admixtures for specific applications. Other aspects of practice including corrosion protection, stressing and testing practices, and quality control have evolved significantly to provide detailed step-by-step guidance for post-tensioning practice. In the 1990's,

issues related to epoxy-coated strand impacted the industry and led to revised guidelines and refined quality control practices as presented in the Epoxy Coated Strand Supplement of 2004. For more detailed information on the evolution of the *Recommendation* documents, the reader is referred to the *Task 1 Report: Analysis of Rock Anchor "Recommendation" Documents1974 – 2004*.

Application of Post-Tensioned Anchors to Hydropower Facilities

From a cost and constructability perspective, post-tensioned anchors are often the only practical solution for upgrading hydropower facilities. Two common applications identified throughout the hydropower facility case studies were:

- Providing stabilizing forces to increase the global stability of the hydropower facilities against overturning, sliding, and seismic loading conditions, and
- Providing stabilizing forces to increase the structural stability of individual concrete monoliths at construction joints within the structure.

Due to the space constrained configuration of most hydropower facilities, it is usually not practical to add mass to a powerhouse intake structure to provide increased stability. Power lines, utility service connections, and mechanical hoisting devices are typically located along the top the intake structures. Post-tensioned anchors are routinely installed in tight spaces, through thin concrete walls, from the top of narrow access walkways, underneath stairways and support superstructures. Figure 1 shows an example of specialized drill equipment used recently on a powerhouse intake at Tom Miller Dam in Austin, Texas.

Figure 1 – Drill Rig Operating at Powerhouse Intake

On this project, post-tensioned multistrand tendon anchors were installed to stabilize the composite concrete and masonry intake structure despite difficult foundation conditions, unusual access conditions, and limited work area. The anchors were installed between the gate piers and the intake penstocks, extending vertically through the facility's masonry core into the underlying karstic limestone formation.

Anchors have been installed in dams regulated by the Federal Energy Regulatory Commission (FERC) and other regulatory agencies with a wide variety of anchor sizes and configurations, ranging from simple low capacity fully-grouted bar and multiple-strand tendon anchors with design working loads below 100 Kips per tendon to sophisticated high capacity re-stressable anchors with lock-off loads exceeding 2500 Kips per anchor. Beyond the common application where vertical anchors are installed from the crest through the structures into the foundation rock, numerous case studies were identified were inclined anchors were installed in FERC regulated facilities. In general, post-tensioned anchors have been installed effectively and efficiently using a wide variety of anchor configurations and capacities. Whereas it was not uncommon as late as the early 1990's for grout to be the only medium for corrosion protection of the tendon, contemporary tendons are protected by combinations of impervious coatings and sheathings, as well as grout. Projects are bid and run by contractors using post-tensioning suppliers and specialists as close support.

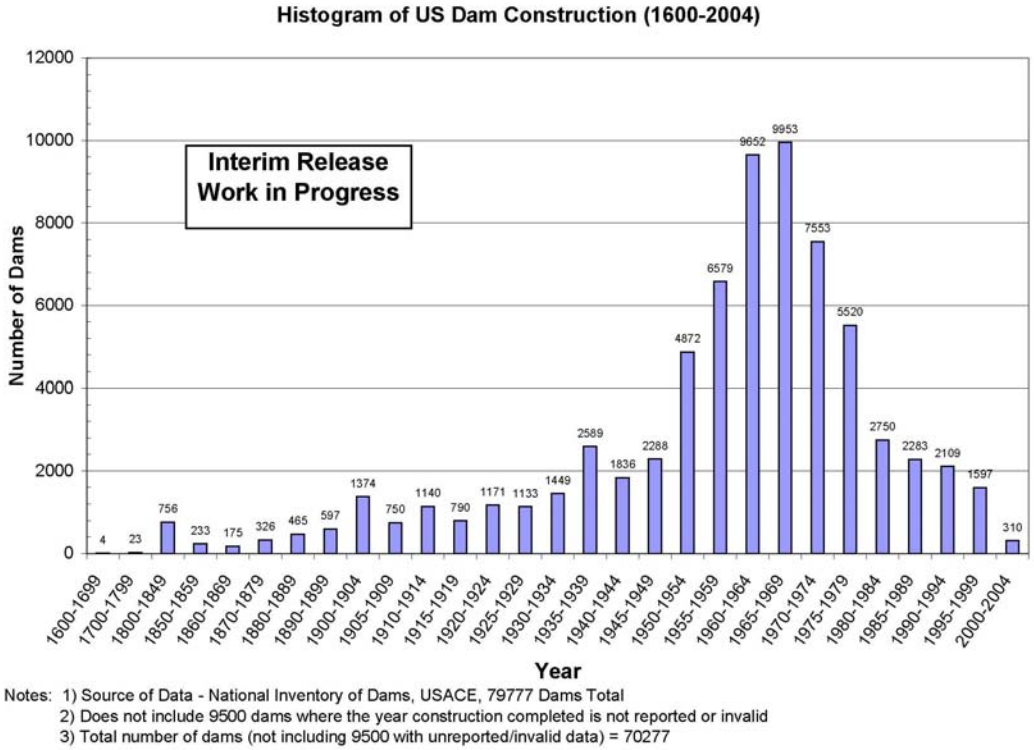
Market for Post-tensioned Anchoring of Dams and Hydropower Facilities

An important focus of the National Research Program is to characterize the market for pre-stressed rock anchors in dam, including:

- Review history of North American dam construction industry.
- Examine history of dam anchoring industry.
- Assess where we are in the industry life-cycle.

Figure 3 presents a histogram of dam construction in the United States.

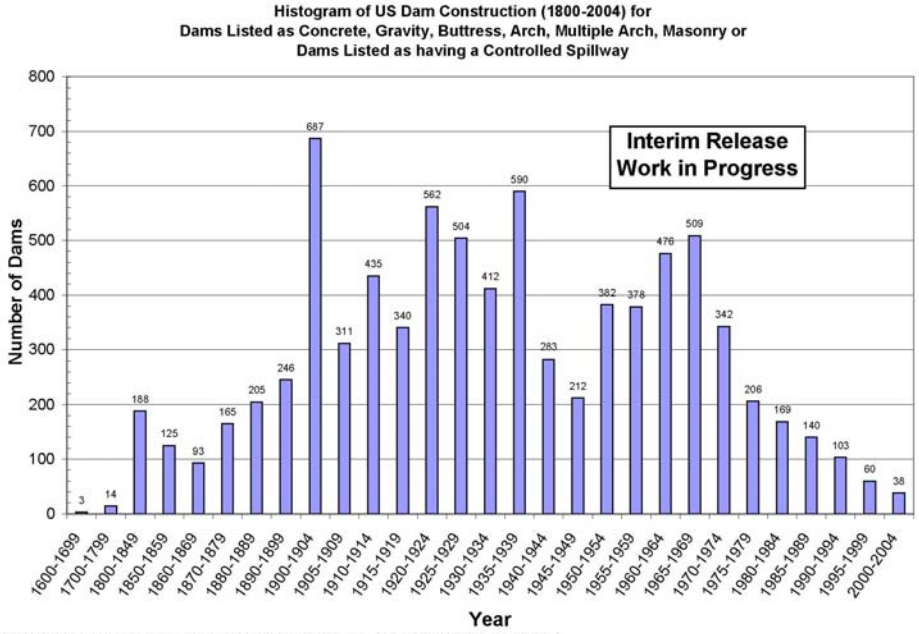
Figure 3 Histogram of U.S. Dam Construction



Notes: 1) Source of Data - National Inventory of Dams, USACE, 79777 Dams Total
2) Does not include 9500 dams where the year construction completed is not reported or invalid
3) Total number of dams (not including 9500 with unreported/invalid data) = 70277

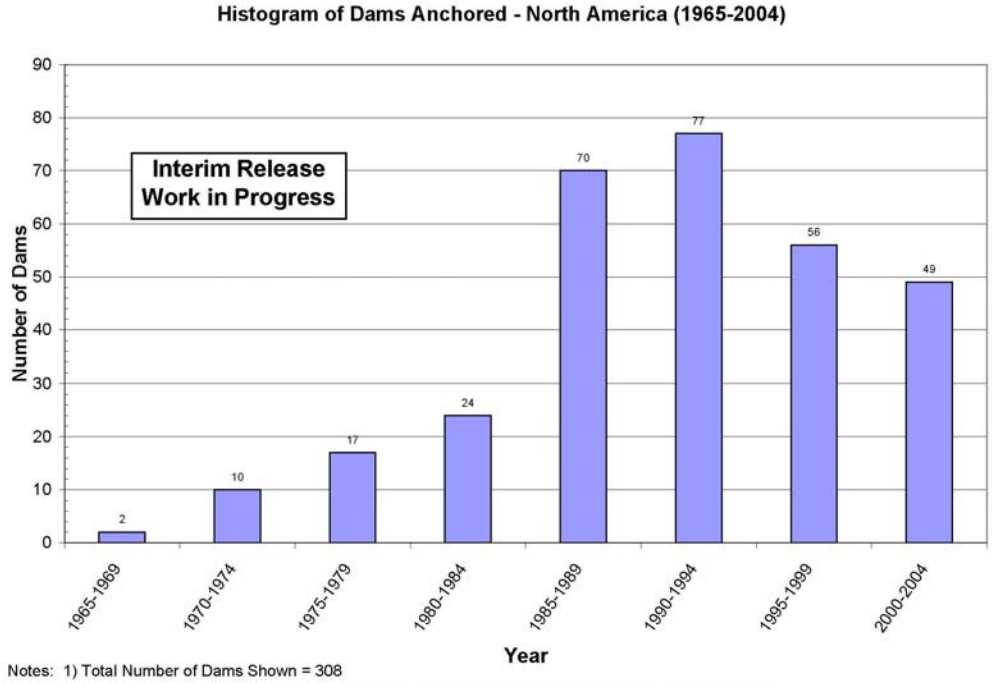
The construction market was further studied with respect to type of dam structure and height of dam. Figure 4 presents a histogram of U.S. dam construction for the type of dams typically subject to the application of pre-stressed rock and soil anchors, particularly dams listed as concrete, buttress, arch, multiple arch, and masonry. These statistics will be updated based on the planned release of the 2006 National Inventory of Dams by the USACE. Figure 5 presents a histogram of dam anchoring projects so far logged in North America.

Figure 4 Histogram of U.S. Dam Construction by Type of Dam



Notes: 1) Source of Data - National Inventory of Dams, USACE, 79777 Dams Total
2) Does not include 9500 dams where the year construction completed is not reported or invalid
3) Total Number of Dams (not including 9500 with unreported/invalid data) = 8178

Figure 5 – Histogram of Anchored Dams



Notes: 1) Total Number of Dams Shown = 308
2) Does not include 82 anchor case studies where year anchored not reported or as yet ascertained.

As shown in the above graphs, most US dams were constructed before the end of the 1960's. ASCE recently published the following report card summarizing the rehabilitation needs for US dams:

> "For dams, the grade remained a D. Federally-owned dams are in good condition and there have been modest gains in repair of small watershed dams. However, since 1998, the number of unsafe dams has risen by 33 percent to more than 3,500. It will take $10.1 billion over the next 12 years to address all critical non-federal dams, dams which can pose a direct threat to human life should they fail."

FERC regulates over 1700 non-federal dams in the United States. The Commission issues licenses to operate hydroelectric projects for periods between 30 and 50 years. It is reported by FERC that the greatest amount of authorized generating capacity - approximately 7,420 megawatts - will come up for re-licensing in 2007. As part of the re-licensing program for hydropower facilities, the design floods are re-evaluated and the structures are re-evaluated to withstand associated hydraulic and dynamic loadings. Post-tensioned anchors have been routinely installed in FERC regulated dams over the past 30 years as part of rehabilitation programs. One of the most prevalent applications for post-tensioned rock anchors identified throughout the case studies is providing stabilization forces required to meet FERC acceptability criteria.

CONCLUSIONS

The first phase of the National Research Program on Rock Anchors for Dams is complete. Information has been gathered and analyzed to characterize the North American dam anchoring industry. The significant findings include:

- Prestressed rock anchors have been used successfully over the past thirty years on nearly four hundred dams and hydropower facilities in North America.
- Prestressed rock anchors provide a cost-effective, environmentally acceptable low maintenance solution for rehabilitating dams to meet modern design standards.
- North American practice has evolved substantially over the past four decades through emphasis on codes, technical specifications, and improvements in construction techniques. Particular attention has been paid to corrosion protection.
- Post-tensioned anchors have a long history of being successfully applied on FERC regulated hydropower facilities in a wide range of geometries and capacities.

The track-record of successful anchor projects, the refinement of engineering practices and construction techniques, and the versatility of anchored solutions has established post-tensioned anchors as a forefront technology in dam rehabilitation. As financial resources become increasingly stretched to meet the needs of the rapidly aging hydropower infrastructure, post-tensioned anchors are well positioned to be a major

component of the North American dam rehabilitation market. Special thanks is given to the supporters of this research effort, particularly HCI Publications, United Society on Dams (USSD), Association of State Dam Safety Officials (ASDSO), Canadian Dam Association (CDA), the Post Tensioning Institute (PTI), the Deep foundation Institute (DFI), the US Army Corps of Engineers (USACE), the US Bureau of Reclamation (USBR), and the Federal Energy Regulating Commission (FERC).

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