ROCK ANCHORS FOR DAMS: A FIVE-YEAR UPDATE

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ABSTRACT

During the period 2004-2006, Bruce and Wolfhope were Co-Principal Investigators on the National Research Program on Rock Anchors for Dams. Several publications resulted, dealing with aspects of over 400 case histories. Since that time, a significant number of additional anchoring projects have been undertaken, including some of the largest projects of their type. This paper updates the previous survey published in 2007, and describes the newer trends and developments of the last few years. The impact of the revised Post-Tensioning Institute's (PTI) Recommendations (2004) on practice is also explored and recent developments in drilling and anchoring techniques and capabilities are described.

INTRODUCTION

The National Research Project on Rock Anchors for Dams was started in the 2004 with final results published in 2007 (Bruce and Wolfhope, 2007a and 2007b). The research focused on three tasks: (1) an analysis of the evolution of anchor practice as illustrated by five successive sets of "Recommendations" published by PCI/PTI; (2) the compilation of a bibliography of technical papers that had been published on North American post-tensioned rock anchor practice; and (3) the compilation of technical details of each of the dams that had been anchored in North America, dating back to 1964 (Bruce and Wolfhope, 2006). The final results included reference to papers through 2005 and dam anchoring case histories through 2004. This current paper describes the results of the updated National Research Project through 2012 for tasks (2) and (3) listed above.

EVOLUTION OF PRACTICE

The evolution of dam anchoring practice in North America has been described in detail by Bruce and Wolfhope (2007a). Since then there have been no further updates to the PTI Manual (2004). PTI is currently finalizing an update. Additional thoughts related to the corrosion protection recommendations in the PTI Manual are discussed in the case history section of this paper.

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A comprehensive literature search and review was undertaken to identify current anchoring practices and methods and to provide additional details on the anchor case studies. Since 2005 there have been 55 technical papers published. These papers have been archived electronically and by hard copy. The majority of the papers identified from 2005-2012 were published through ASDSO, USSD, Canadian Dam Association, and various other conferences and journals. Figure 1 shows the number of publications by year.

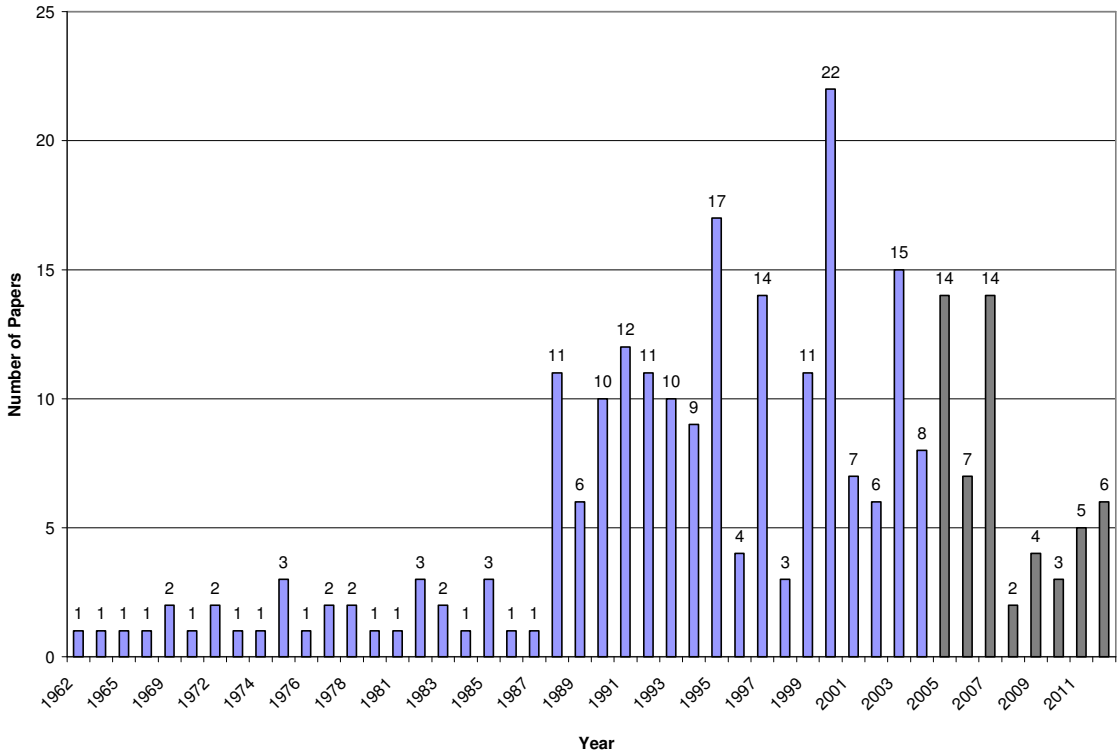
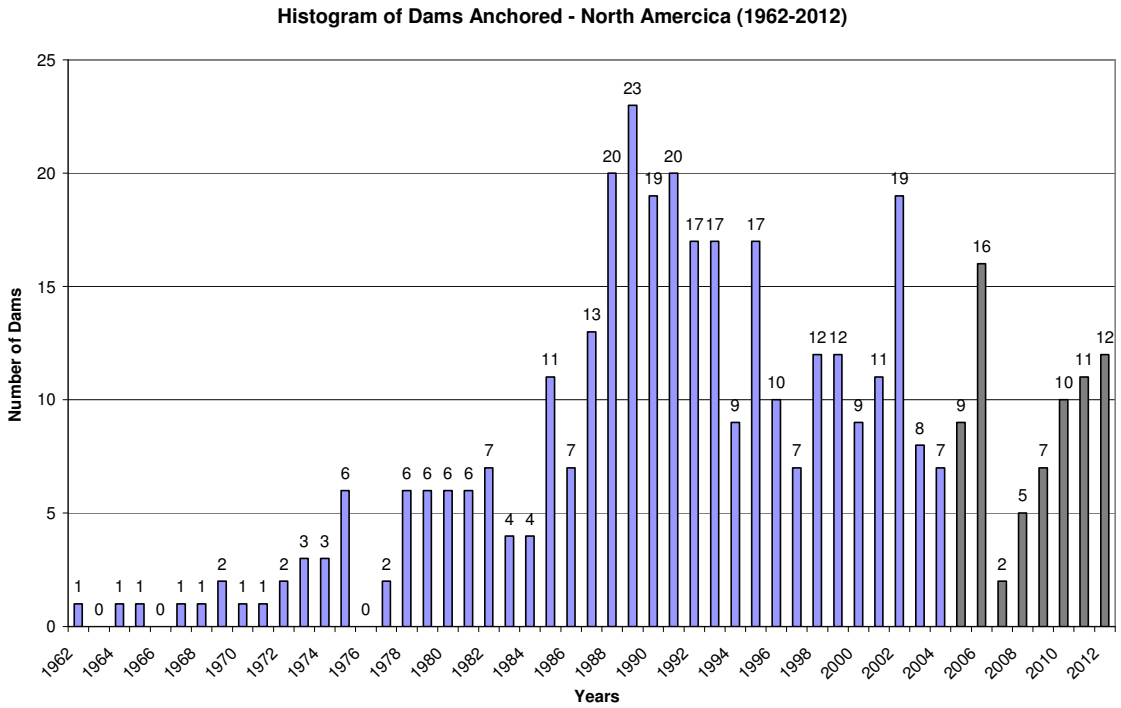


Figure 1. Histogram of dam anchoring publications by year.

Regarding the distribution of Figure 1, in 2007, the International Conference on Ground Anchorages and Anchored Structures was held in London, England leading to the most recent spike in the number of published papers.

ANCHORING CASE STUDIES

From 2005 to mid-2012, over 70 dam anchoring projects in North America were identified and logged in the national database. In addition to these projects, an additional six projects were identified prior to 2005 and which had not been accounted for previously. These projects bring the total number of dam anchoring projects listed in the database to nearly 470. Figure 2 presents an updated histogram of the North American dam post-tensioned anchoring projects.



Notes: 1) Total number of dams shown = 404
2) Does not include 64 anchor case studies where year anchored not reported or as yet ascertained

Figure 2. Histogram of dam anchoring projects by year.

Efforts were made to collect as much detailed information related to each case history. However, complete information was not always accessible. Therefore, the data collection focused on obtaining at least the following key information to characterize the post-tensioning market for dams over the past 8-years:

1. Dam Name
2. Location
3. Year Anchored
4. Number of Anchors
5. Type & Diameter of Anchor Tendon (bar or strand)
6. Number of Strands per Tendon
7. Type of Corrosion Protection
8. Average Length

When the information above was collected, the case study was considered "complete". If one or two pieces of information were missing from the case history, it was considered "near complete". Out of the 72 total case histories, 46 were complete, with 6 near complete. Tables 1 and 2 provide a list of recent anchoring projects identified in Canada and in the USA, respectively. The authors cordially invite colleagues reading this paper to verify if "their" dam has been included. The tracking of any omissions is a goal of publishing this paper.

Table 1. Dam anchoring projects in Canada (2005-2011).

Dam Name	Year Anchored	Dam Name	Year Anchored
Big Eddy Dam	2008	London Street Dam	2006
Blind Slough (Stave Falls)	2005	Mactaquac	2006
Boundary Dam	2010	Matthias Dam	2006
Boundary Dam - test phase	2006	McArthur Falls GS	2010
Brace Bridge Falls	2011	McPhail Dam	2006
Brilliant Dam - Phase 2	2010	Powell Lake Dam	2011
East Musquash Dam	2005	Ruskin Dam	2007
Island Falls GS	2010	Seymour Falls Dam	2006
Kakabeka Falls GS	2006	Thirsk Reservoir	2005
Kelsey Generating Station	2009	Upper Matagomi	2008
Laurie River GS	2006	Water Street Dam	2008
Loch Alva	2006	Wilson Falls GS	2011
Log Falls	2006	Winnepag Floodway	2011

Table 2. Dam anchoring projects in USA (2005-2012).

Dam Name	Year Anchored	Dam Name	Year Anchored
99 Islands Hydro Station	2005	Kentucky Locks	2010
Antietam Dam	2011	Lake Cammack Dam	2011
Barber Dam	2007	Lake Hamilton Dam	2005
Blue Ridge Dam Penstock	2012	Lake Townsend Dam	2007
Bluestone Dam Phase 2B	2011	Marmet Lock & Dam	2005
Canonsburg Dam	2012	McAlpine Lock	2005
Canton Dam	2006	McClure Dam	2005
Charleroi Locks and Dam	2012	Meadow Park Dam	2012
Chickamauga Lock and Dam	2010	Medina Lake Dam	2011
Chickamauga New Lock	2009	Nesbitt Dam	2012
Cortlandt Lake Dam	2012	Old Columbia Dam	2009
Croton Falls Dam	2008	Old Stony Creek Dam	2011
Dalles Dam Spillwall	2010	Olmos Dam Test Anchors	2009
David D Terry Lock	2010	Olmos Dam Production	2011
Dover Dam Emergency Repairs	2008	Prettyboy Dam	2010

Dam Name	Year Anchored	Dam Name	Year Anchored
Dover Dam – Phase 1	2011	Pueblo Dam	2010
Dover Dam – Phase 2	2012	Roanoke Rapids Dam	2010
Emsworth Dam and Lock	2010	T. Nelson Elliot Dam	2012
Fishing Creek Hydrostation	2006	Thorne Dam	2006
Gilboa Dam	2006	Truman Lake Dam	2011
Gilboa Dam – Phase 2	2012	Walnut Creek - Wells Branch Dam	2005
Hebgen Dam	2012	Waterloo Dam	2009
Hoist Dam	2005	Willow Island Dam	2012

Observations from the Case Studies

About sixty percent of the identified projects were located in the United States, while the other projects were in Canada. As shown in Figure 3, the majority of the anchoring projects in the USA are east of the Mississippi River, with several in the Midwest and a few in the Northwest. In Canada, the majority of the project locations are just north of the US/Canada border. The reasons for the anchoring were many, but in general the main reason for dam anchoring is to meet stability requirements due to increased probable flood conditions. Other main reasons include seismic upgrade, AAR mitigation and lift joint stabilization.

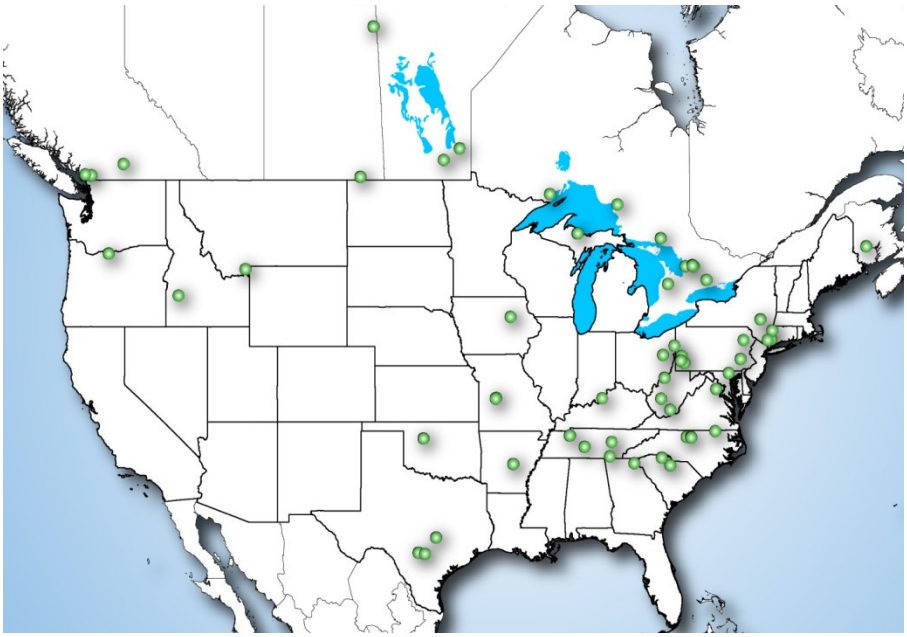


Figure 3. Map Identifying Recent Dam Anchoring Project Locations.

There have been a wide variety of anchoring projects from 2005-2012. Facilities that have been anchored include dams, hydrostations, new and existing locks, intake towers and gatehouses. Based on the "complete" case histories, more than 3,200 stressed bar and multi-strand tendon anchors have been installed. The multi-strand tendon anchors have ranged from 4 to 61 strands in the recent projects and appear to be the preferred anchor type for dam tie-down applications. Bar anchors have been installed mainly for lift joint stabilization or in dam tie down where additional required stabilization forces are lower. The authors offer the following observations on practice since 2005.

Evaluation of Existing Anchors and Re-anchoring Dams

Twelve projects featured anchoring the structure for the second or even third time. Although there has not been enough time or case histories to indicate any trends, there may likely be an increase in the number of re-anchoring as time goes on as the original post-tensioned anchors fail or are deemed defective or insufficient, or as regulations change. The reasons behind the recent re-anchoring projects vary, but include issues related to early anchoring practice which lacked a complete understanding of the importance of corrosion protection, changing regulations (either seismic, stability or PMF increases), and AAR mitigation. Several recent re-anchoring projects included evaluation of existing anchors to estimate remaining anchor capacity and service life, and in several cases reduced the number of supplemental anchors required to meet the project requirements. Two re-anchoring case histories are of particular relevance.

Snyder et al. (2007) described an anchoring investigation and evaluation of existing anchors for two dams in Canada that needed stability improvements. Their investigation revealed that these two dams had been anchored in the 1970's. The existing anchors at the two dams were evaluated using several non-destructive procedures including: spread spectrum reflectometry, half-cell potential, polarization resistance, sonic echo and ultrasonic tests. In addition, lift-off tests were conducted on a few of the anchors. Based on the results of the non-destructive tests and lift-off results the anchors were considered in good condition. Therefore, the number of proposed remedial anchors was reduced from 60 (assuming all existing anchors had no capacity) to 15.

Campbell and Mee (2007) described several rounds of anchoring at Mactaquac Generating Station in Canada. The dam suffers from alkali-aggregate reaction (AAR). During 1988-89, 138 anchors were installed from the face of the dam to the drainage gallery, with an anchor head on each end. Each anchor included polypropylene sheathing and each hole was filled with urethane grout. By 1993, 40 of the anchors had failed. Based on an investigation, it appeared that the polypropylene sheathing had been damaged during installation and due to the cracking in the dam and harsh water conditions the urethane grout had been compromised over time and so the anchors corroded. Since the urethane did not hold up, a neat cement grout was used in the second round of anchoring with greater success but still with some anchor failures over time. Removing and replacing the anchors that had been cement grouted in place proved to be difficult and time consuming prospect. Therefore, the current approach is to install greased and sheathed tendons without any grout in the free length. The rationale is that

no grout corrosion protection will be appropriate for this project since the anchors at this dam will need to be routinely replaced. The cost of replacing an anchor that is not grouted is reduced. The paper also discusses damage to anchor tails so anchors could no longer be de-stressed or load tested. The act of testing or de-stressing the anchors had caused a failure of over 50 anchors. A third failure mode discussed in this paper was caused by using cast steel anchor heads rather than forged steel.

Drilling and Anchor Hole Preparation

Several recent projects have required innovative drilling methods and techniques to meet specified tolerances due to project constraints. Drill hole tolerance was not obtained for all project case histories. However, enough information was obtained for federal, state and privately owned dam anchoring projects to provide a relatively good cross-section of what drill tolerances were required. The authors found a specified range typically between 1:50* and 1:100 but up to 1:150, but also that current drilling methods and skilled contractors are capable of much finer tolerances which, of course, come with a cost premium. The requirements clearly are job specific, with more critical projects or project conditions requiring a tighter drill hole alignment.

One drilling concept used to increase accuracy uses a pilot hole which is then reamed to the specified diameter. Such an approach had been successfully used for long anchors through the intake tower at the Tolt River Dam, WA by Layne Geoconstruction. In Canada, Geo-Foundations, used 89 and 50 mm diameter pilot holes at Ruskin Dam and Blind Slough (Stave Falls) Dam, respectively. The pilot holes were verified for deviation conformance using Boretrak® equipment prior to advancing the full-size anchor holes.

In the United States, Brayman Construction used directional drilling at Bluestone Dam Phase 2B in West Virginia to meet a specified tolerance of 1:150. The tight tolerance was required due to the depth of the anchor holes and adjacent intersecting anchors about 4-feet apart. Anchor holes alignment generally included 8-degrees from vertical on the crest and 45-degrees from vertical on the downstream face of the dam. Rothbauer and Hopple (2011) reported a calculated tolerance of 1:608 using directional drilling at a depth greater than 200-feet in one 8-degree inclined hole. In addition to the real time optical monitoring during drilling, each hole was surveyed after drilling with a Reflex Maxibor® II instrument. In the top of dam anchor holes (8-degree batter), 53% had a surveyed deviation greater than 1:1050 as shown in Figure 4. A tolerance greater than 1:1050 was achieved in 24% of the 45-degree holes however, three holes (4%) were less than specified deviation of 1:150 at depths more than 100-feet. The results indicate an extraordinarily high degree of accuracy can be achieved especially in near vertical holes.

* E.g., a 1-foot deviation in a 50-foot-long hole.

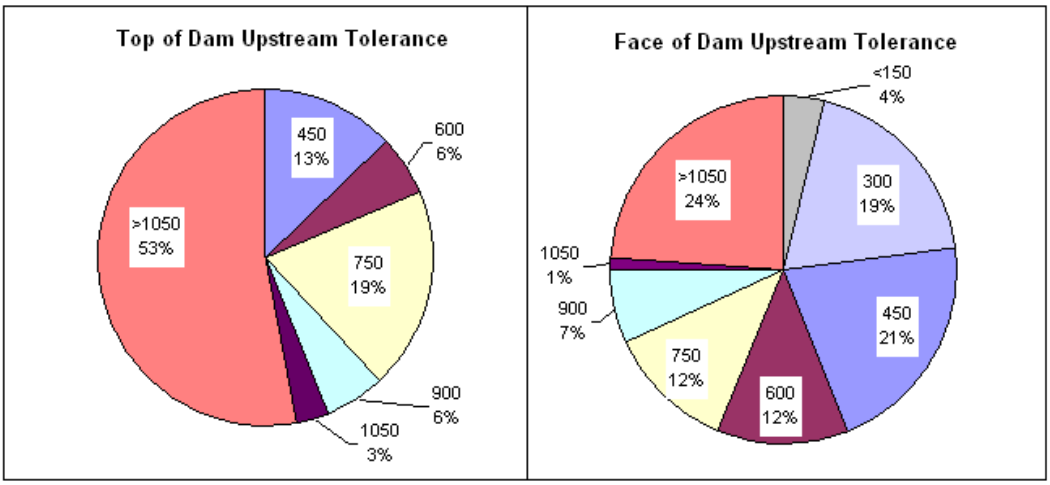


Figure 4 – Drill hole tolerances (reproduced after Rothbauer and Hopple, 2011)

The use of Optical TV or Acoustic televiewers is another technique that is being implemented in increasing frequency to inspect anchor holes prior to tendon installation. Inspecting anchor holes in this manner can provide a "virtual core" that can be used to identify various conditions in an anchor hole, including the verticality of the hole, depth to dam/bedrock interface, "irregularities" or cracking and roughness of the hole. This type of inspection takes little time and can provide very valuable information. Although this type of inspection is not always specified some contractors volunteer to use Optical TV or Acoustic televiewers in anchor holes as their own QA/QC check or proof that the anchor hole meets various specified requirements.

Underwater drilling, grouting and anchor installation is another recent application that has been conducted in a few projects. The anchoring at Prettyboy Dam gatehouse in Maryland was one of the projects that required underwater work. Initially the holes were core drilled under water with modified drilling equipment. Each hole was then roughened using a roller-bit to provide a better bonding surface for the anchor grout. The holes were also video-inspected to confirm the roughness of the hole. Further details on this project including lessons learned are provided in Alvi (2011).

Corrosion Protection and Water Testing

Based on our review of the recent case histories it appears that the nearly all of dam anchoring projects have utilized Type I corrosion protection, as defined in the Post-Tensioning Institute. This is a significant observation that should not be understated. It shows how the industry has evolved to use the best available technology to protect anchors from corrosion. A relatively recent investigation of corroded tendons at the John Day Lock and Dam is described by Heslin, et al. (2009). The tendons installed in 1981 would be classified as "Class II" corrosion protection by current PTI definitions (anchors pre-dated Class I corrosion protection systems). Based on the investigation, deterioration

of the tendons due to corrosion effects were notable. The sealing of the anchor holes by pre-grouting did not protect many of the anchors from exposure to groundwater.

Anchor Monitoring

Elasto-Magnetic sensors are beginning to increase in popularity. These sensors have been used in bridge and building applications prior to entering the dam industry. The sensors slide over an individual tendon and measure the permeability of the steel. The permeability can be translated into the load remaining within the tendon. These sensors last much longer than load cells and are much easier to use. Further, the sensors do not "disturb" the anchors like a lift-off test. There is much time and money to be saved by using these types of sensors instead of lift-off testing. This type of monitoring will help owners and engineers quickly and easily assess the capacity of an anchor as it ages.

CONCLUSION

The National Research Program on Rock Anchors for Dams has been updated to include anchors installed through mid-2012. Based on the bibliography and case history information the following conclusions can be drawn:

- Technical papers related to dam anchors have been published at a rate of at least four to five papers per year over the last several years. These papers help advance the industry and document current practices.
- Over 70 North American dam anchor case studies were identified from 2005 to mid-2012 bringing the total to nearly 470 case studies since the early 1960's.
- The long-term performance of older anchors is variable. Case histories and published papers have been prepared documenting excellent performance of some anchors installed in the 1970's and also poor performance of anchors with questionable installation procedures in harsh conditions.
- Contractors are meeting and exceeding the challenges of difficult projects and design requirements which increasingly require exceptionally accurate anchor hole alignment tolerances.
- Current trends indicate that water testing, and Optical or acoustic inspection of anchor holes are becoming more prevalent.
- The vast majority of current post-tensioned anchors in dams include Class I corrosion protection in accordance with the 2004 PTI Manual recommendations.

ACKNOWLEDGEMENTS

The authors would like to thank and recognize Geosystems, Freese and Nichols, and Schnabel Dam Engineering for their support of this research. Additionally, tendon suppliers DSI, Con-Tech and Williams-Form Engineering and anchor contractors Brayman, Coastal Drilling East, Judy, Geo-Foundations, and Nicholson among others were a great help and provided much information throughout this research.

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