ROCK ANCHORS FOR DAMS: A FIVE-YEAR UPDATE

Dr. Donald A. Bruce, Ph.D, C.Eng. 1
John S. Wolfhope, P.E. 2
Jesse D. Wullenwaber, P.E. 3

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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1 President, Geosystems, L.P., P.O. Box 237, Venetia, PA 15367, (724) 942-0570, dabrucke@geosystemsbruce.com
2 Principal, Freese and Nichols, Inc., 10814 Jollyville Road, Building 4, Suite 100 Austin, TX 78759, (512) 451-7955, jsw@freese.com
3 Project Engineer, Schnabel Engineering, LLC, 1380 Wilmington Pike, Suite 100, West Chester, PA 19382 (610) 696-6066, jwullenwaber@schnabel-eng.com

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BIBLIOGRAPHY

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.
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.

Figure 2. Histogram of dam anchoring projects by year.
Table 1. Dam anchoring projects in Canada (2005-2011).

<table>
<thead>
<tr>
<th>Dam Name</th>
<th>Year Anchored</th>
<th>Dam Name</th>
<th>Year Anchored</th>
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<tbody>
<tr>
<td>Big Eddy Dam</td>
<td>2008</td>
<td>London Street Dam</td>
<td>2006</td>
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<tr>
<td>Blind Slough (Stave Falls)</td>
<td>2005</td>
<td>Mactaquac</td>
<td>2006</td>
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<tr>
<td>Boundary Dam</td>
<td>2010</td>
<td>Matthias Dam</td>
<td>2006</td>
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<tr>
<td>Boundary Dam - test phase</td>
<td>2006</td>
<td>McArthur Falls GS</td>
<td>2010</td>
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<tr>
<td>Brace Bridge Falls</td>
<td>2011</td>
<td>McPhail Dam</td>
<td>2006</td>
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<tr>
<td>Brilliant Dam - Phase 2</td>
<td>2010</td>
<td>Powell Lake Dam</td>
<td>2011</td>
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<tr>
<td>East Musquash Dam</td>
<td>2005</td>
<td>Ruskin Dam</td>
<td>2007</td>
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<tr>
<td>Island Falls GS</td>
<td>2010</td>
<td>Seymour Falls Dam</td>
<td>2006</td>
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<tr>
<td>Kakabeka Falls GS</td>
<td>2006</td>
<td>Thirsk Reservoir</td>
<td>2005</td>
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<td>Kelsey Generating Station</td>
<td>2009</td>
<td>Upper Matagomi</td>
<td>2008</td>
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<td>Laurie River GS</td>
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<td>Water Street Dam</td>
<td>2008</td>
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<td>Loch Alva</td>
<td>2006</td>
<td>Wilson Falls GS</td>
<td>2011</td>
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<td>Log Falls</td>
<td>2006</td>
<td>Winnepag Floodway</td>
<td>2011</td>
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Table 2. Dam anchoring projects in USA (2005-2012).

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<thead>
<tr>
<th>Dam Name</th>
<th>Year Anchored</th>
<th>Dam Name</th>
<th>Year Anchored</th>
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<tr>
<td>99 Islands Hydro Station</td>
<td>2005</td>
<td>Kentucky Locks</td>
<td>2010</td>
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<td>Antietam Dam</td>
<td>2011</td>
<td>Lake Cammack Dam</td>
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<td>Barber Dam</td>
<td>2007</td>
<td>Lake Hamilton Dam</td>
<td>2005</td>
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<td>Blue Ridge Dam Penstock</td>
<td>2012</td>
<td>Lake Townsend Dam</td>
<td>2007</td>
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<td>Bluestone Dam Phase 2B</td>
<td>2011</td>
<td>Marmet Lock &amp; Dam</td>
<td>2005</td>
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<td>Canonsburg Dam</td>
<td>2012</td>
<td>McAlpine Lock</td>
<td>2005</td>
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<td>2006</td>
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<td>Dam Name</td>
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<td>Year Anchored</td>
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<tr>
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<td>2011</td>
<td>Pueblo Dam</td>
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<td>Dover Dam – Phase 2</td>
<td>2012</td>
<td>Roanoke Rapids Dam</td>
<td>2010</td>
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<td>Emsworth Dam and Lock</td>
<td>2010</td>
<td>T. Nelson Elliot Dam</td>
<td>2012</td>
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<td>Fishing Creek Hydrostation</td>
<td>2006</td>
<td>Thorne Dam</td>
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<td>Gilboa Dam</td>
<td>2006</td>
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<td>Gilboa Dam – Phase 2</td>
<td>2012</td>
<td>Walnut Creek - Wells Branch Dam</td>
<td>2005</td>
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<td>Hebgen Dam</td>
<td>2012</td>
<td>Waterloo Dam</td>
<td>2009</td>
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<td>Hoist Dam</td>
<td>2005</td>
<td>Willow Island Dam</td>
<td>2012</td>
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**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.](image-url)
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.
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.

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REFERENCES


