# Rock Anchors for North American Dams: The National Research Program Bibliography and Database

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## Abstract
This paper describes two of the three major goals of Phase 1 of a National Research Program dealing with rock anchors for North American dams. The study commenced in 2005 and has, to date, found approximately 400 case histories spanning four decades, and 230 technical papers. A review of the bibliography is provided with special emphasis on the evolution of the philosophies and details of corrosion protection. This focus is maintained when analyzing the information in the database, while data are also provided on costs and prices.

## Introduction
During the period 2005-2006, Phase 1 of the National Research Program into the use of rock anchors for North American dams was undertaken. This work had three goals:

(i) complete a bibliography of all technical papers published on the subject of dam anchoring in North America;
(ii) create a database containing as much information as possible on each dam anchored in North America; and
(iii) conduct a comparative review of each of the five successive versions of the national "recommendations" documents which have been published in the U.S. since 1974;

This paper describes the results of the first two research goals with a particular focus on the evolution of corrosion protection concepts and details. The findings of the third research goal are presented in the companion paper, "Rock Anchors for North American Dams: The Development of the National Recommendations (1974-2004)," also published in these Conference Proceedings. The current authors were the Co-Principal Investigators for this project, funded by a consortium of American and Japanese interests. They relied heavily on the cooperation of specialty contractors and specialist post-tensioning suppliers who provided access to historical records.

## The Bibliography
### General
A comprehensive literature survey was completed to identify published dam anchoring case studies and various publications documenting the evolution of North American dam anchoring practices and construction methods. A total of 230 technical papers have been compiled relating to North American post-tensioned rock anchoring projects. Hard copy and electronic versions of each have been collected. Figure 1 shows the number of publications by year indicating that over the first five years of the twenty-first century, industry has been publishing at a rate of about 13 papers per year. These papers relate to over 200 dams.

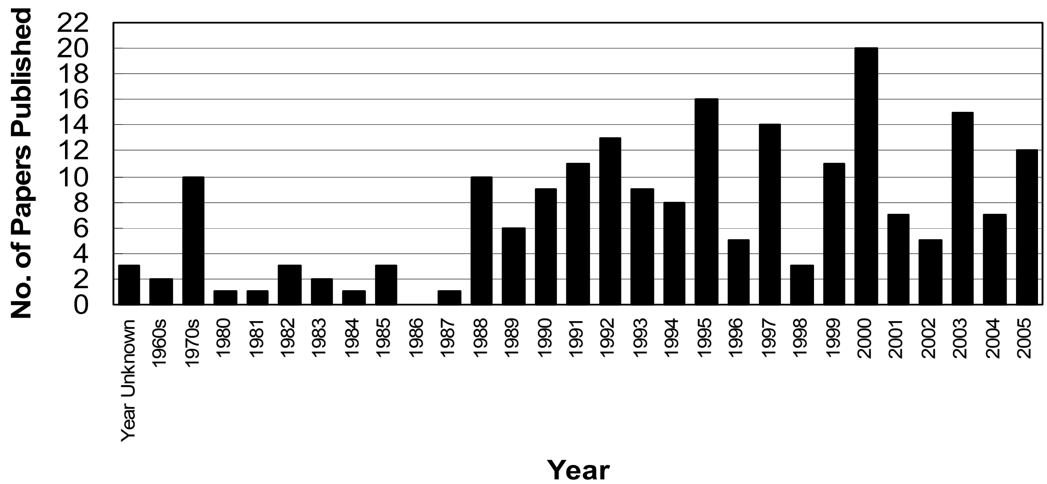



Figure 1. Numbers of technical papers on dam anchoring published per year

**Observations on Corrosion Protection**

When analyzing these technical papers, one occasionally wins fascinating insights into contemporary thinking regarding corrosion protection issues. The following is provided by way of illustration: no commentary is necessary and no claim is made that this is anything other than a sampling. The papers are presented in date order of project completion.

- Thompson (1969) (John Hollis Bankhead Dam, AL, 1968). Based on chemical analyses of the groundwater "…the laboratory concluded that the risk of corrosion would probably be no more than that of a coal free environment." "During the 12 months when the anchors were loaded [i.e., primary grouted and stressed only] their wires and the grout pipe developed corroded areas just below the anchor head. The wires subjected to flowing water had lost considerably more weight per unit of length than the wires in the still water." "…it was concluded that a good cover of cement grout would adequately protect the anchor wires."
- ENR (1971) (Ryan Dam, MT, 1970). "…the stressing length of the anchor was filled with grout to protect against corrosion."
- Buro (1972) (Libby Dam, MT, 1971). "After all the stressing procedures were completed, the anchor was secondary grouted — that is, the space between the top of the bond length and the stressing anchorage was filled with grout to provide the steel with positive and complete protection against corrosion." The concept of providing a greased and sheathed free length for "measuring anchors" is introduced.
- Bruce (2003) (Rock Island Dam WA, 1975). This dam had been anchored with fully bonded multiwire tendons in 1975. With considerable foresight on the part of the designers, four anchors were equipped with greased and sheathed "minitendons," each comprising 4 wires, which could be lifted-off in the future.
- Sharma and Sasaki (1985) (Pacoima Dam, CA, 1976). Eight of 35 anchors "were equipped with hydraulic lift-off load cells to monitor the working force in the stressed tendons. The monitored anchors were greased and sheathed with plastic tubing in the stressed secondary zone to insure free movement. All anchors were grouted in the secondary zone to provide corrosion protection."
- ENR (1977) Conowingo Dam, VA (1977-1978). "To finish the job, each hole receives a lean grout mixture to prevent corrosion of the tendon…"
- Troka and Lane (1988) (Bagnell Dam, MO, 1982). "Also, since second stage grouting would arrest any further corrosion…"

- Standig (1984) (Delta Dam, NY, 1983). "A double corrosion system includes a continuous plastic duct enclosing the strands, in addition to grout. Single stage grouting was specified…around the strands and between the duct and the drill hole simultaneously. In the free length of the anchor, the smooth duct and a grease and plastic coating on the strands prevents their being bonded to the grout. This permits tensioning later." The "VSL Double Corrosion Protected Rock Anchor," which was specified, was in fact identical in all respects to the anchors installed from 1978-1980 in Tarbela Dam, Pakistan, where Mr. Standig had worked before engineering the Delta Dam remediation.
- Corns and Jansen (1988) (Elkhart Dam, IN, 1986). The strands were individually greased and sheathed in the free length, and a full length corrugated tube was provided. However, "Openings at the bottom of the corrugated pipe were provided to allow the grout to flow around the pipe." Secondary grouting comprised "a weak grout (cement and bentonite) to provide corrosion protection."
- McWhorter and Meeks (1990) (Nacoochee Dam, GA, 1987). The purpose of the second stage grouting in the free length was described thus: "The grout not only functions as a load-carrying structural component but it also serves as <u>the</u> corrosion protection for the bare strand."
- Bruce (1988) General Commentary on Anchors for Dams. Notes Graber's (1981) report detailing cracks (radial and longitudinal) of up to 2 mm aperture at 100 mm centers in the grout of a Tarbela Dam test anchor installed in 1980. Plastic sheathing was found to be effective in arresting crack propagation to the steel. "Anchorages for dams can nearly always be regarded as permanent. By all international standards, such anchors must be properly protected against corrosion." "Corrosion protection of the fixed anchor length by applying an outer corrugated plastic sheath is becoming increasingly more common."
- Mishalanie (1990) (Newton Falls Upper Dam, NY, 1989). "Due to the corrosive environment of the reservoir water, all anchors were fully encapsulated with corrugated polyethylene tubing."
- Paolini and Petrovsky (1991) (Lighthouse Hill Dam, NY, 1992). "A chemical analysis of the reservoir water showed that a water aggressivity to steel was low (pH = 7.4, resistivity = 2,600 ohm-cm, chlorides = 2.4 mg/l, and nitrates = 0.87 mg/l). As a result, a single corrosion protection system was chosen for the tendon anchorage." (This is assumed to mean that no protective sheathing was specified around the bond zone.)
- Bruce and Nicholson (1994) General Review. "Virtually every rock anchorage installed in a dam is regarded as permanent. Corrosion protection is therefore a vital and integral part of anchorage design and construction. On the global stage, it is perhaps only in this aspect that U.S. practice is perceived as being deficient, even though considerable advances have been made in the last few years following the works of FIP (1986) and Littlejohn (1990) in particular. The major point of difference between U.S. and foreign practice is in the concept of double corrosion protection. Foreign engineers, following their national codes, do not regard cement grout as an acceptable barrier to corrosion, in that it carries the potential for microfissuring under load: the protective alkaline environment can then be depassivated quickly in the presence of aggressive anions, notably chloride. An acceptable barrier is one which can be inspected <u>prior to installation</u>. Therefore, a tendon incorporating a plastic sheath, and grouting in place with a normal cement grout is regarded as a singly protected tendon overseas, but a doubly protected tendon in the U.S. The least protected part of the tendon defines the class of protection, and joints or transitions are particularly vulnerable.

  American engineers may argue, with a certain justification, that most dams are founded on 'good', impermeable rock which is then further grouted, if necessary, prior to anchorage installation. In short, the real danger of water percolating through possible microfissures in both rock and grout – and then a flow through the plastic protection is generally regarded as a tolerable risk.

Within the last few years, attitudes toward long multistrand tendon protection have undergone the following chronological progression:

a) bare strand in bond zone, individual sheaths on the free length steel;
b) as a) except for a full length, outer 'group' sheath of corrugated plastic (polypropylene or polyethylene);
c) epoxy coated strand (and two phase grouting);
d) epoxy coated strand, with individual sheaths in the free length, permitting one phase of grouting.

In the current absence of a national policy towards corrosion protection, individual owners are responsible for specifying the degree of hole corrosion protection they want to pay for."

- Bogdan (2001) Review of Epoxy Protection. This is an excellent perspective of epoxy protected tendons, clearly listing the advantages and disadvantages of the technology.
- Bruce (2002) Review of Protection Evolution. "Although ground anchor practice in the United States has enjoyed a long, successful and internationally acclaimed reputation (Bruce, 1997) one area in which it differed from European concepts was in its somewhat more relaxed approach to corrosion protection. For example, what British practice (BS8081, 1989) regarded as single corrosion protection (i.e., the use of a protective corrugated sheath, grouted in situ) U.S. specialists typically referred to as double corrosion protection. The difference lay in the interpretation of the reliability of the grout in the bond zone as an acceptable layer of corrosion protection. Thus while the British tended not to count the grout as a reliable and permissible layer of corrosion protection since it could crack during stressing due to its strain differential with the far more elastic steel it encased, others disagreed. It was argued that any stress fractures would be of very small aperture, and that the highly alkaline environment of the grout would prevent corrosion of the steel – should it actually be exposed to direct contact with continually aggressive groundwater in any case. No case has been reported, nevertheless, of failure resulting from bond length corrosion in a properly grouted anchor.

  Around the same period in the late 1980s, U.S. contractors installing permanent ground anchors began to realize that the use of a corrugated plastic duct as corrosion protection over the bond length required special attention to construction detail during the grouting operation (e.g., tremie tubes inside and outside the sheath, grouted in careful sequence to avoid structural distress to the sheath due to differential fluid grout pressures); as well as demanding larger diameter drill holes to accommodate the tendon, the corrugated sheath, and the multiple tremie tubes.

  It was logical, therefore, that epoxy protected strand should become considered for strand tendons: it removed the necessity for a separate tendon protective encapsulating sheath, allowed hole diameters to be minimized, and simplified the grouting operation. Such construction efficiencies would have the potential to offset the far higher material costs of such strand."

## The Database

### General

Given that anchoring is conducted in dams other than earth embankments, Figure 2 presents a histogram of U.S. dam construction involving concrete and masonry structures.

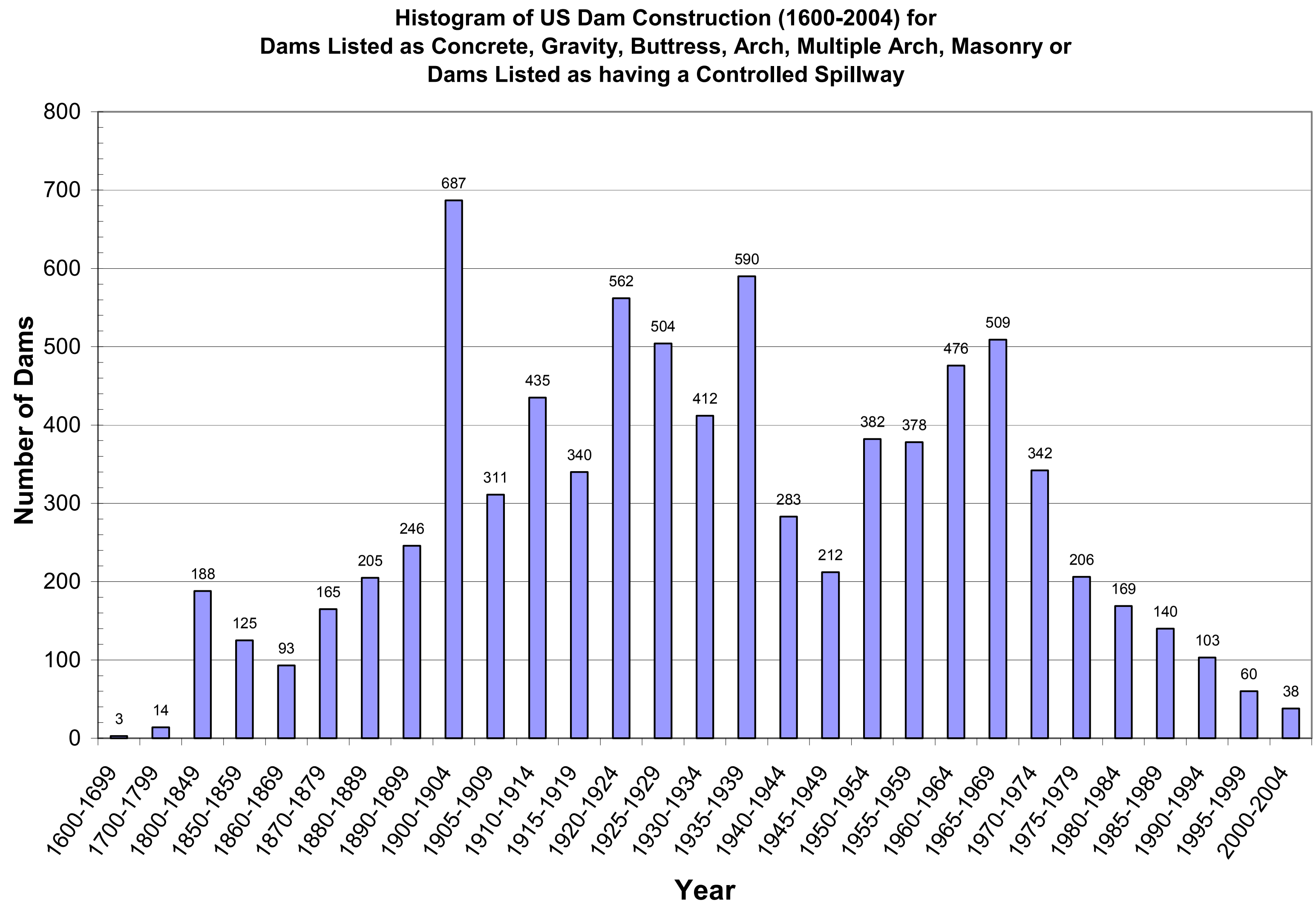
Phase 1 of the database preparation has revealed 239 projects whose anchor details are essentially "complete," a further 50 projects classified as "nearly complete," and a further

104 case histories regarded as "incomplete." (This will clearly drive the nature of the Phase 2 studies.) Nevertheless, a total of 318 anchor projects do have sufficient data to allow year of commencement to be plotted (Figure 3). Over the 40-year period, well in excess of 20,000 tendons were installed, with the peak years, driven by Federal Regulatory demands, being in the period 1988-2002. Further details of individual projects are provided in Bruce and Wolfhope (2006).

## Corrosion Protection

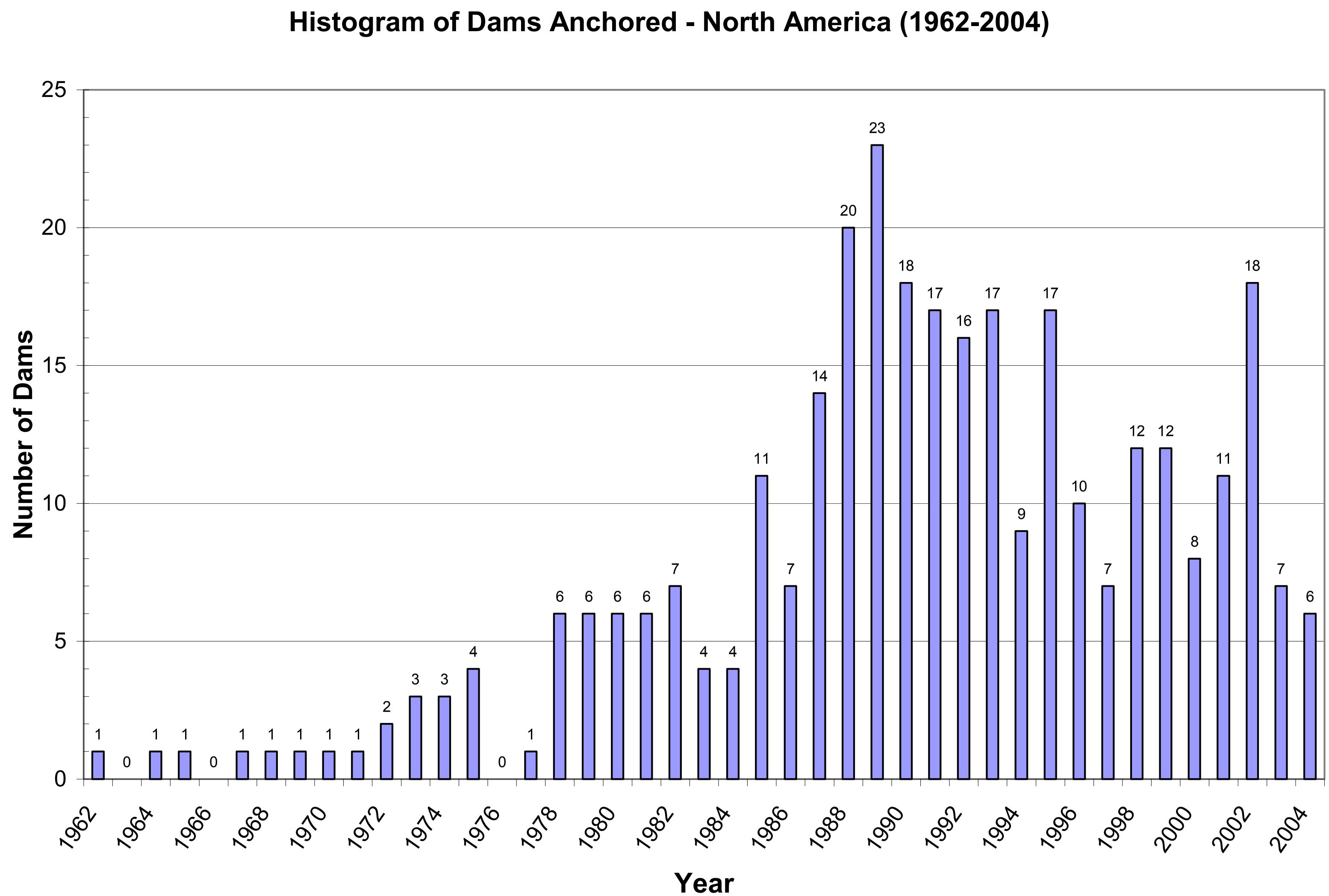
An analysis of the database provides the information upon which Figure 4 is based. The following comments pertain to the different types of tendons and protections used over the years.

- Wire tendons, comprising eventually up to 212 each 6 mm diameter wires, giving a Working Load of around 6,800 kN at 60% GUTS, were the original choice for dam remediation, but were used only very infrequently in subsequent years. Apparently, the last example was in 1982 at Bagnell Dam, MO. Such tendons had to be grouted in two stages, had no corrosion protection on the steel (other than cement grout) and were challenging and tedious to assemble, handle and stress. However, they were promoted to dam engineers by certain post-tensioning suppliers as being the state of practice in the wider world of post-tensioning and therefore would be appropriately suited to dam work also. According to Bogdan (2007), there were numerous examples of "improper" corrosion protection using wire tendons and he cites the case of Railroad Canyon Dam, California. Here, lift-off testing confirmed that the existing wire tendon anchors had to be replaced due to corrosion. This was accomplished in 1991 by using restressable anchors with epoxy coated strand.
- From the early days, post-tensioning suppliers also offered a variety of tendon types based on their standard 12.7 mm strand system which had been used for up to 55 strand tendons in nuclear facilities. A few strands in each tendon were omitted in favor of grout tubes and vents for rock anchor applications (Crigler, 2007). Early applications involved bare steel and two stage grouting, but by 1976 such tendons were typically used only where a "fully bonded" design was in fact to be implemented. By then, a plastic sheathing was used on individual strands, primarily as a bond breaker to thereby permit single stage grouting. This, itself, began to be superseded by the "Double Corrosion Protected Anchor" by 1978 where designers judged the conditions to be particularly aggressive, and an exterior "group sheath" (corrugated in the bond length and often smooth in the free length) was added. This was a Canadian-German concept which was first widely used for the Waldeck Cavern anchors in Germany in 1969, following work in Calgary, Alberta, in 1968.
- By the mid-1980s, 12.7 mm strand (190 kN GUTS) had been superseded by 15.2 mm strand (266 kN GUTS) which was by then more cost effective and readily available. Also, by this time, geotechnical contractors had become the prime movers in the dam remediation market and were pushing post-tensioning companies to provide dam specific solutions for tendon configurations. Tendons made from 15.2 mm strand were almost always greased and sheathed in the free length (Lang's extruded coating "polystrand" system, had been patented in 1972 but not widely used until 1982, except where full bonding was a design requirement). By 1986, full length secondary protection also became equally popular, partly as a result of marketing to DOTs, leading to the elimination of bare strand in the bond zone by 1998. One may note that in the early days of outer corrugated sheathing, only the bond zone was so covered. However, contractors found this an awkward detail to handle and to grout effectively in the field, and soon began to install the corrugated sheathing full length to facilitate constructability.




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 2. Histogram of U.S. Dam Construction by Type of Dam




Notes: 1) Total Number of Dams Shown = 323
2) Does not include 70 anchor case studies where year anchored not reported or as yet ascertained.

Figure 3. Histogram of Dams Anchored by Year (1962-2004)

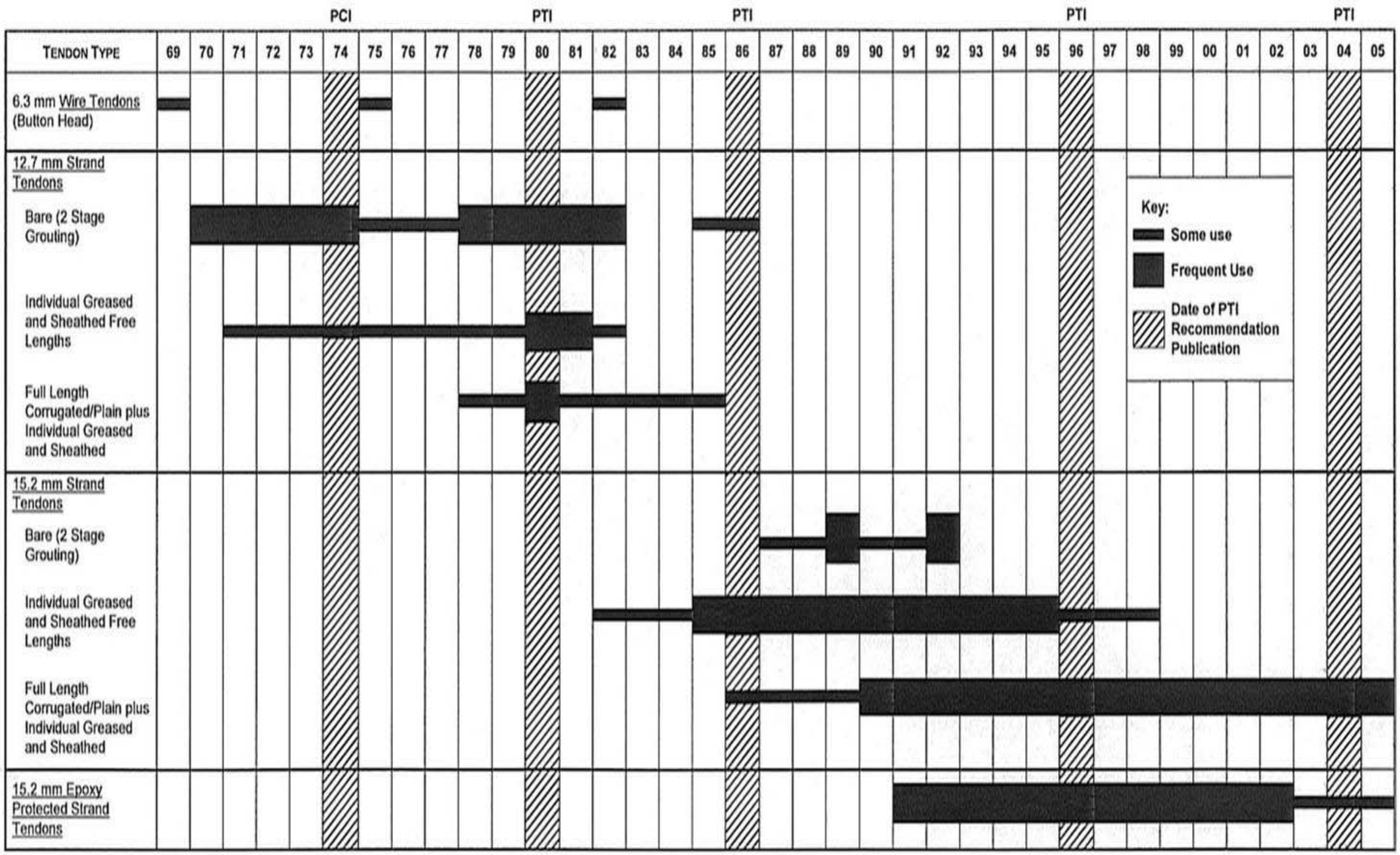



Figure 4. Illustrating how the Types of Corrosion Protection have Evolved (Data Drawn from the Authors' Research Database)

- On certain projects, the free length outer sheath is now plain and is joined very carefully to the bond zone corrugated sheath with heat-shrink bands and other defenses. In recent years, the outer protection has become so large (over 300 mm o.d.) that it has become common practice to grout the duct in place in the waterproofed drill hole before placing, grouting and stressing the tendon. This is a very intricate operation involving many water testing and grouting steps. It was first performed at Cross River Dam, NY in 1997. The method allows the acceptability of the corrosion protection to be verified at various stages prior to anchor completion (e.g., before placing, after placing, after exterior grouting and after tendon placement).
- According to Bogdan (2007) the current state of practice to provide individual strand sheaths is to have the plastic sheathing hot-melted and <u>extruded</u> in a controlled thickness over the greased strand. This method, imported from unbonded monostrand practice, assures that no air will be entrapped between sheathing and grease and that water will not penetrate inside. The traditional "stuffing" method, wherein a plastic tube is <u>forced</u> over a greased strand, is still acceptable for epoxy protected strand.
- A most interesting recent case history is the 2004 anchoring of Seven Mile Dam, a BC Hydro structure. Aschenbroich (2007) recounts that the owner researched corrosion protection systems in considerable detail since longevity for these tendons — at 92 strands the largest in the world with design working loads up to 14,000 kN – was critical. The decision was made to use petrolatum wax in lieu of the strand post-tensioning grease on the steel, inside the individual strand sheathing on the free length. This has now become standard practice in many quarters. Incidentally, these 130-m-long anchors had to be assembled on site and required a 20,000 kN jack with 1 m stroke since "stage stressing" was disallowed by Specification. The Seven Mile Dam achievement was indeed remarkable, but the massive size of the tendon verged on the impractical. It would seem that, in general, present practice is to limit individual tendon capacity to 61 strands (either bare in a pregrouted corrugated duct, or epoxy protected: each in a "waterproofed" hole).
- <u>Epoxy protected strand</u> made its dam debut in 1991 and, following an early surge of national popularity, has since accounted for less than 20% of dam projects and typically for one particular client. Of particular note is the "triple corrosion protection" selected by the designers for Pardee Dam, CA (Freitas et al., 1997) in 1995 when epoxy protected strand was encapsulated inside a full length corrugated pipe, while the free length strands also had individual greased and sheathed protection: "The California DSOD had concerns regarding long term corrosion resistance and performance of the anchors." Obviously!
- <u>Bars</u> have been used as relatively low capacity tendons (up to 800 kN) since the mid-1970s especially on smaller Canadian dams, and invariably were installed in a protective corrugated sheath, which gave rise to the term "Double Corrosion Protection," i.e., sheath plus grout, as noted above.
- As a final point of detail, it is widely believed that part of the tendon assembly at and just below the anchor head is most susceptible to corrosion. In accordance with PTI (2004), it is now common practice to provide a steel pipe trumpet that prevents water from penetrating behind the plate. The space inside the trumpet is usually filled with cementitious grout ("topping up"). Anchorages are placed inside blockouts and embedded in concrete. There are special cases when the owner requests some or all of the tendons to be retressable. In such cases, the trumpet will be filled with post-tensioning grease, and a restressable wedge plate and permanent load cell is added to the anchorage. This entire assembly is covered with a removable cover cap, also filled with grease. Such restressable systems are <u>not</u> recommended for anchors which may have to act in a

submerged condition, e.g., in an active spillway or plunge pool: the corrosion risk is simply too high.

### Prices and Costs

In compiling the anchor case study database of over 400 dam anchoring projects, meaningful construction cost information has to date been obtained for over 100 projects. The database captures the overall project construction cost and the more specific value of the anchoring aspects of the project. Graphs have been developed to identify a general relationship between the cost of the anchoring construction versus the overall length of drilled hole, and versus the overall length of pre-stressing steel installed in the project. All cost data were adjusted to a common baseline of 2007 construction costs using cost indices published by the U.S. Bureau of Reclamation (USBR) for concrete dam construction. Figure 5 provides a comparison of overall project drilling length to the adjusted cost of the anchoring construction. Figure 6 provides a similar graph based on the length of the pre-stressing steel: it only includes data for multi-strand tendon anchors, excluding wire and bar anchors, to reduce the variation in the data. Since the available historical information on projects ranges from a simple reference to project costs in a published journal to detailed bid sheets and final payment estimates identifying installed quantities, there is a large degree of variation in the data as to what is included (or not included) in the costs.

## Final Observations

The Phase 1 research has allowed a very detailed picture to emerge of the evolution of dam anchoring technology in North America over a 40-year period. Especially interesting points relate to developments in corrosion protection, costs, and to the overall size of the market. The authors hope that their colleagues in other countries which have also enjoyed a long history of dam anchoring will emulate the North American study.

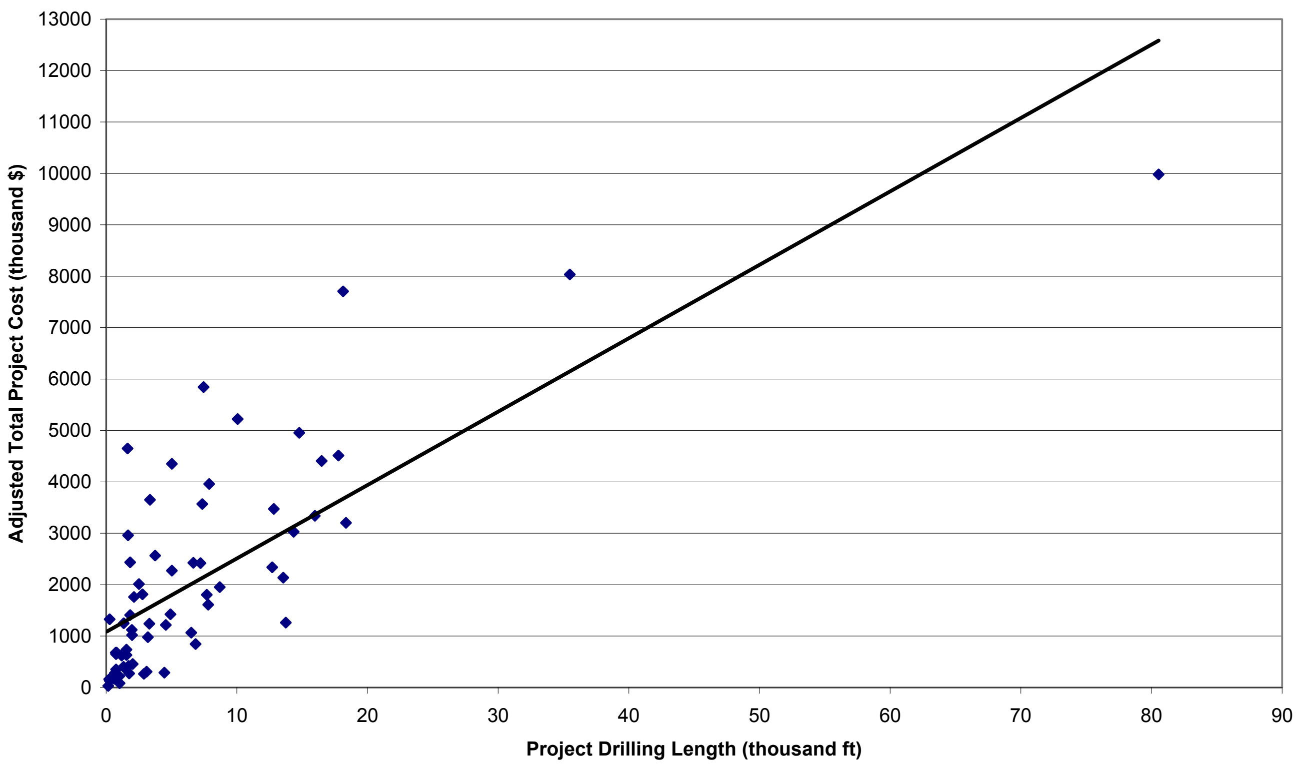



Figure 5. Drilling Length vs. Adjusted Cost

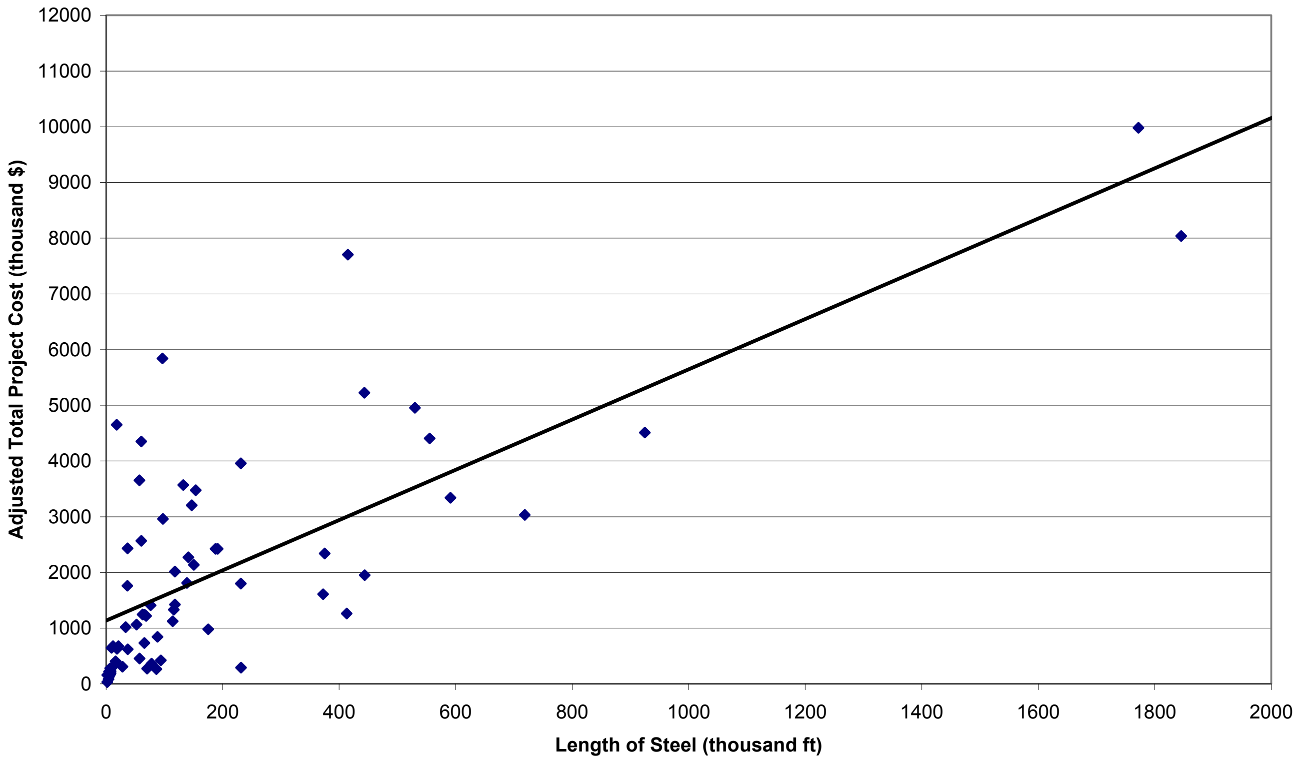



Figure 6. Length of Steel vs. Adjusted Cost

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## References

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