

ROCK ANCHORS FOR DAMS: EVOLUTION AND ANALYSIS OF CORROSION PROTECTION SYSTEMS AND CONSTRUCTION COSTS

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Abstract

In recent ASDSO conferences, the authors have presented the results of Phase 1 of the National Research Program into prestressed rock anchors for dams. This paper specially addresses two key issues which the authors observe are of prime interest to engineers considering dam remediation using prestressed anchors, namely corrosion protection (and, hence, anticipated longevity) and project costs. The conclusions are drawn from a study of over 400 case histories and 230 technical papers which have been collected on North American practice in the course of the Phase 1 studies.

1. Introduction

Two of the most commonly asked questions when contemplating a dam anchoring project are:

- How long will the anchors last? and
- How much do they cost?

As is well known to members of the Association of State Dam Safety Officials through previous related papers (e.g., Bruce and Wolfhope 2005, and 2006), the authors have compiled a database of over 400 dam anchor projects completed in North America from 1968 to 2004. They have also reviewed the five successive phases of “Recommendations” provided as quasi-industry standards by the Post Tensioning Institute (PTI), and its predecessor, between 1974 and 2004, and have further compiled a collection of 230 technical papers authored on North American dam anchor projects to date.

The purpose of this paper is to help answer the two key questions posed above.

2. Corrosion Protection and Anchor Longevity

2.1 *What the Recommendations Said*

Ground anchors had been used in the U.S. since the early 1960’s primarily as temporary “tie backs” and as permanent installations for dams since 1968. With the rapid growth of the market at that time, there was a clear need to establish some type of nationally

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acknowledged, unifying, guidance document, especially since the drivers of the industry (principally post tensioning specialists) each promoted his own proprietary philosophies and systems: these often merely parroted the mantra of the European country of their corporate headquarters. Such systems were also primarily “off the shelf” having been developed for post-tensioning applications other than geotechnical, or dam remediation.

The first such American document was published in 1974 by the Post Tensioning Division of the Prestressed Concrete Institute. This Division soon thereafter broke away to form the Post Tensioning Institute, and later published successive sets of *Recommendations* documents in 1980, 1986, 1996 and 2004. Although certain states, agencies and, indeed even consultants, have traditionally issued their own “anchor specifications,” there is no doubt that the PTI documents are the national reference point and, as such, have been embraced and/or endorsed by the Federal Highways Administration (FHWA), the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation (USBR) and The International Association of Foundation Drilling (ADSC), amongst numerous others.

A most telling observation is the amount of attention paid to “Corrosion and Corrosion Protection” in the successive Recommendations:

1974 Edition	1 page
1980 Edition	4 pages
1986 Edition	5 pages
1996 Edition	10 pages
2004 Edition	14 pages (plus a 10-page supplement on epoxy protected strand)

Key features from these successive Recommendations can be summarized as follows:

1974. Figure 1 illustrates the very simple approach to tendon protection, i.e., grout or nothing. “Permanent” is defined as “generally more than a 3-year service life.” Sheathing is only discussed as a debonding medium, not a corrosion protection barrier. For permanent anchors “protective corrosion seals over their entire length” are to be provided (but are not defined). For two stage grouted tendons, *sheathing can be omitted*, the implication being that grout alone would be acceptable.

1980. The same Figure 1 is reproduced (as it was also in 1986). The term “permanent” is now reduced to 18 months or more, and growing attention is drawn to the requirements of permanent anchors: sheathing is for debonding “and/or to provide corrosion protection,” as is secondary grout. Corrugated protection, and epoxy coating for bars are discussed.

The type and details of corrosion protection are to be based on longevity, anchor environment, consequences of future and in-hole conditions/length of time before grouting. For the bond length, grout is considered “the first level of corrosion protection,” and plastic corrugated sheathing (“for multiple corrosion protection schemes”) or epoxy are permitted. Such protection is to extend at least 2 feet into the free length.

The free length is to have, as a minimum, a sheath with grout or grease infill. A full length outer sheath is regarded as “good practice.”

1986. The emphasis is placed on first investigating the chemical aggressiveness of the soil and ground water: “Permanent anchors placed in environments where any one of these tests indicate critical values must be encapsulated over their full length.” Thus, even up until the next set of Recommendations (1996), it was considered acceptable to allow anchors for dams to be installed without any protection for the bond length other than grout, depending on the results of laboratory tests on small samples. Encapsulation was not detailed.

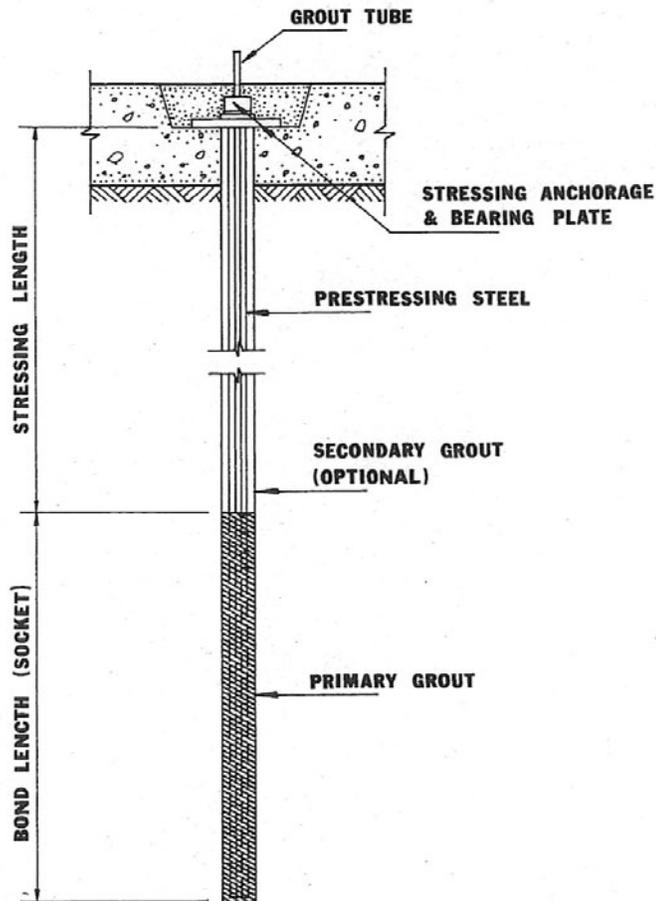


Figure 1. Rock Anchor Components (PCI, 1974).
 (Note the lack of protection to the steel other than grout.)

1996. Permanence is now defined as a minimum of 24 months in a completely revised set of Recommendations. A wider spectrum of issues than simple chemistry now have to be considered when selecting corrosion protection principles. A major breakthrough was to identify two classes of protection (Class I and II) for permanent anchors to replace the poorly defined and loosely used “double” and “single” corrosion protection systems offered by various tendon manufacturers. The details are summarized in Table 1 and a “decision tree” (Figure 2) was provided for the guidance of designers.

Table 1. Corrosion Protection Requirements (PTI, 1996).

CLASS	PROTECTION REQUIREMENTS		
	ANCHORAGE	UNBONDED LENGTH	TENDON BOND LENGTH
I ENCAPSULATED TENDON	1. TRUMPET 2. COVER IF EXPOSED	1. GREASE-FILLED SHEATH, OR 2. GROUT-FILLED SHEATH, OR 3. EPOXY FOR FULLY BONDED ANCHORS	1. GROUT-FILLED ENCAPSULATION, OR 2. EPOXY
II GROUT PROTECTED TENDON	1. TRUMPET 2. COVER IF EXPOSED	1. GREASE-FILLED SHEATH, OR 2. HEAT SHRINK SLEEVE	GROUT

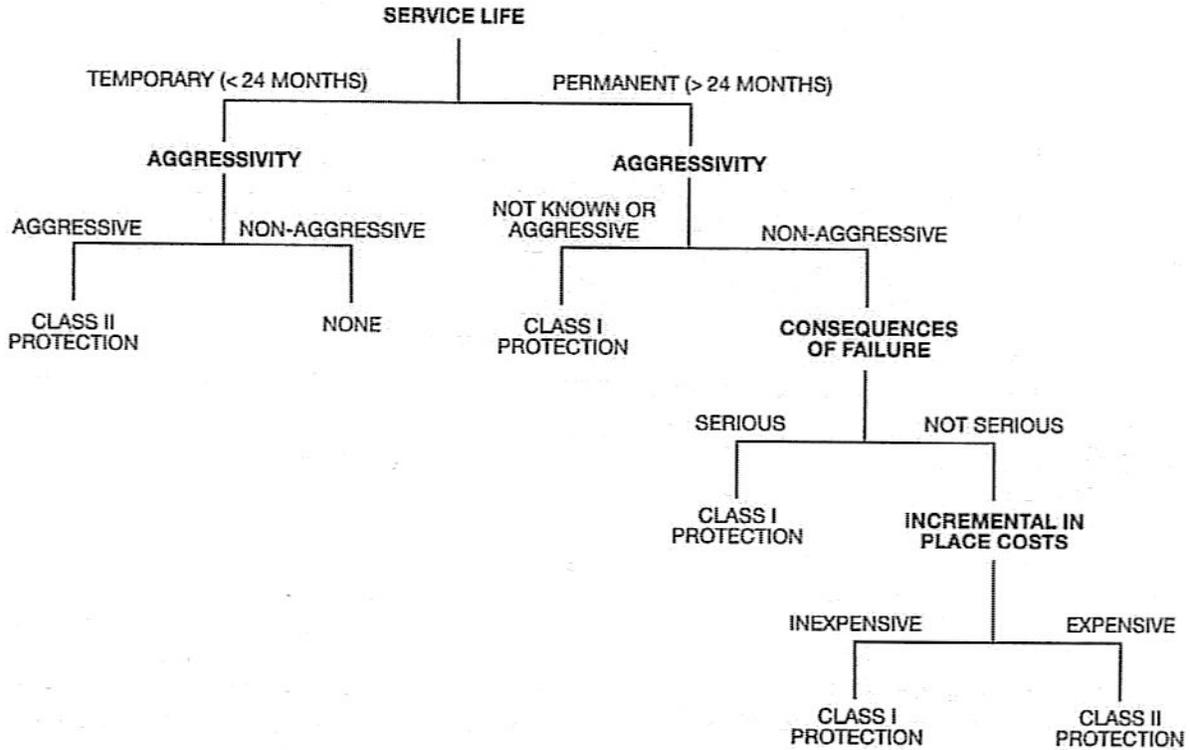


Figure 2. Corrosion Protection Decision Tree (PTI, 1996).

2004. The existing Recommendations were revalidated while it is stated that, for permanent anchors, “aggressive conditions shall be assumed if the aggressivity of the ground has not been quantified by testing.” Table 1 was revised, as shown in Table 1R, mainly to clarify the Class I status of epoxy protected steel in a “water proofed hole.” The sophistication of contemporary tendons is shown in Figure 3 and 4. A long supplement is devoted to epoxy protected strand.

Table 1R. Corrosion Protection Requirements (PTI, 2004).

CLASS	CORROSION PROTECTION REQUIREMENTS		
	ANCHORAGE	FREE STRESSING LENGTH	TENDON BOND LENGTH
I ENCAPSULATED TENDON	Trumpet Cover if exposed	<ul style="list-style-type: none"> Corrosion inhibiting compound-filled sheath encased in grout, or Grout-filled sheath, or Grout-encased epoxy-coated strand in a successfully water-pressure tested drill hole 	<ul style="list-style-type: none"> Grout-filled encapsulation, or Epoxy-coated strand tendon in a successfully water-pressure tested drill hole
II GROUT PROTECTED TENDON	Trumpet Cover if exposed	<ul style="list-style-type: none"> Corrosion inhibiting compound-filled sheath encased in grout, or Heat shrink sleeve, or Grout-encased epoxy-coated bar tendon, or Polyester resin for fully bonded bar tendons in sound rock with non-aggressive ground water 	<ul style="list-style-type: none"> Grout Polyester resin in sound rock with non-aggressive ground water

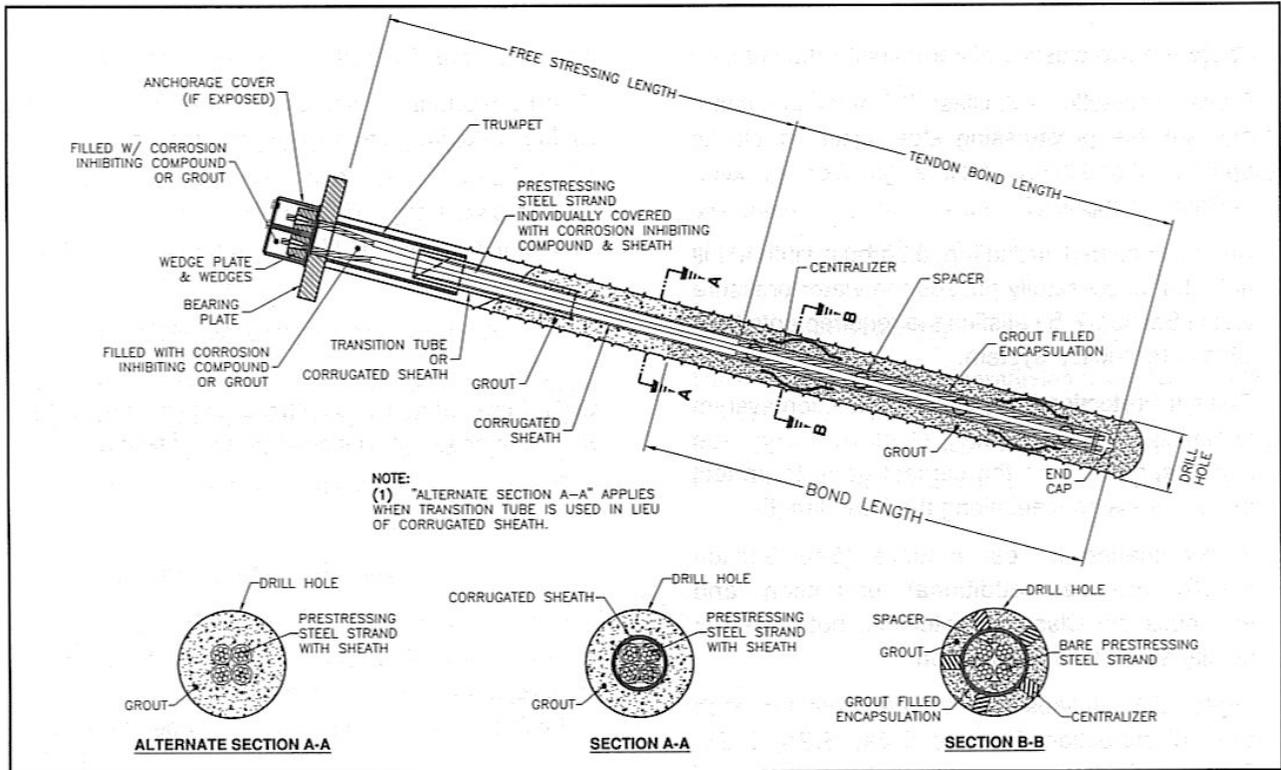


Figure 3. Class I Protection – Encapsulated Strand Anchor (PTI, 2004).

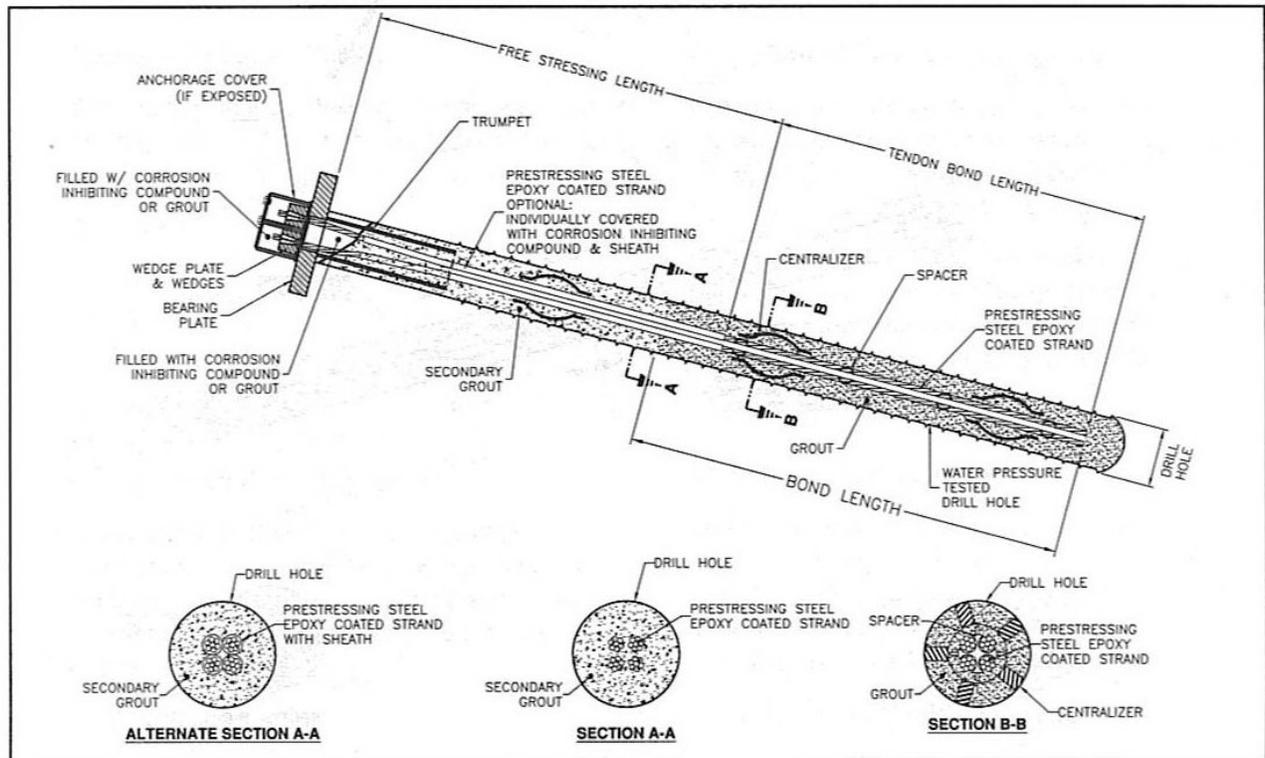


Figure 4. Class I Protection – Epoxy Coated Strand Anchor (PTI, 2004).

Overall, therefore, one is impressed that between 1974 and 2006 (i) extremely sophisticated corrosion protection systems were developed and (ii) the latitude offered to designers relative to choice of corrosion protection intensity and details was severely restricted: to install a permanent anchor in a dam without Class I protection is now not only impermissible, but unthinkable.

It must also be noted that the philosophy of pregrouting and redrilling the hole (“waterproofing”) if it were to fail a permeability test was restated from 1974 onwards: indeed the early “pass-fail” acceptance criteria were, in fact, very rigorous and led to most anchors on most projects having to be pregrouted and redrilled several times. Although laudable, this was often, in fact, “extra work” since the criterion to achieve grout tightness is really much more lax than the criterion needed to provide the specified degree of water tightness. The saving grace of many of the early anchors was doubtless, therefore, the somewhat erroneous waterproofing criterion under which they were constructed.

2.2 What the Technical Press Said

When analyzing the 230 technical papers devoted to dam anchoring in North America to date, one occasionally wins fascinating insights into contemporary thinking regarding corrosion protection issues. The following is provided by way of illustration: no commentary is necessary. No claim is made that this is anything other than a sampling of the whole.

Thompson (1969) (John Hollis Bankhead Dam, AL, 1969). 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) (Rocky Ridge 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. This information would hopefully be illustrative of the performance of the other wires in the other tendons also. (Performance to date has, in fact, been excellent.)

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.”

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, with grout being placed by the tremie method up from the bottom of the hole, around the strands 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. A contemporary VSL “Project Sheet” indicates that the tendon cost of Delta Dam was \$284,000 compared to a total contract value of \$4,355,000.

Corns (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 et al. (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 the (underline added) corrosion protection for the bare strand.”

ENR (1977) Conowingo Dam, VA (1977-1978). “To finish the job, each hole receives a lean grout mixture to prevent corrosion of the tendon...”

Bruce (1988) General Commentary on Anchors for Dams. Notes Graber’s (1981) report detailing cracks (radial and longitudinal) of up to 0.1" aperture at 4" centers in the grout of a Tarbela Dam test anchor installed in 1980. Plastic sheathing was found to be effective in arresting crack development 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 et al. (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.”

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 prior to installation. 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 acid 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 with appropriate thicknesses of grout cover.

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.”

2.3 What the Database Says

An analysis of the National Research Program database provides the information upon which [Figure 5](#) 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 ¼-inch diameter wires, giving a Working Load of around 1,500 kips 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 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 0.5" 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 (as in [Figure 1](#)), 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 ([Figure 6](#)). 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, 0.5" strand (41.3 kips GUTS) had been superseded by 0.6" strand (58.6 kips 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 0.6" 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 ([Figure 7](#)). One may note that in the early days of outer corrugated sheathing, only the bond zone was so covered ([Figure 8](#)). 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.
- 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 12" 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

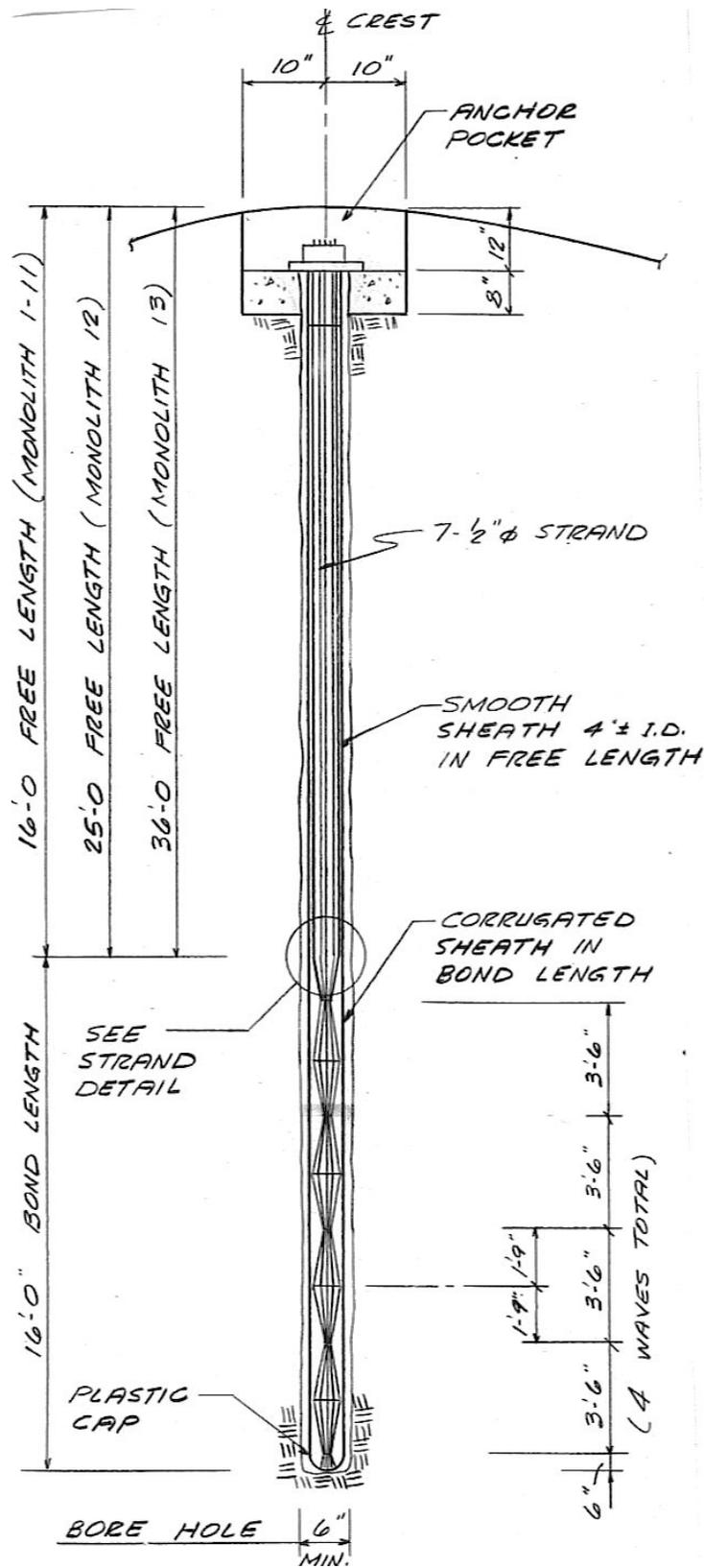


Figure 6. Full Length (Corrugated and Smooth) Encapsulation
 (Franklin Falls Dam, NH, 1980).

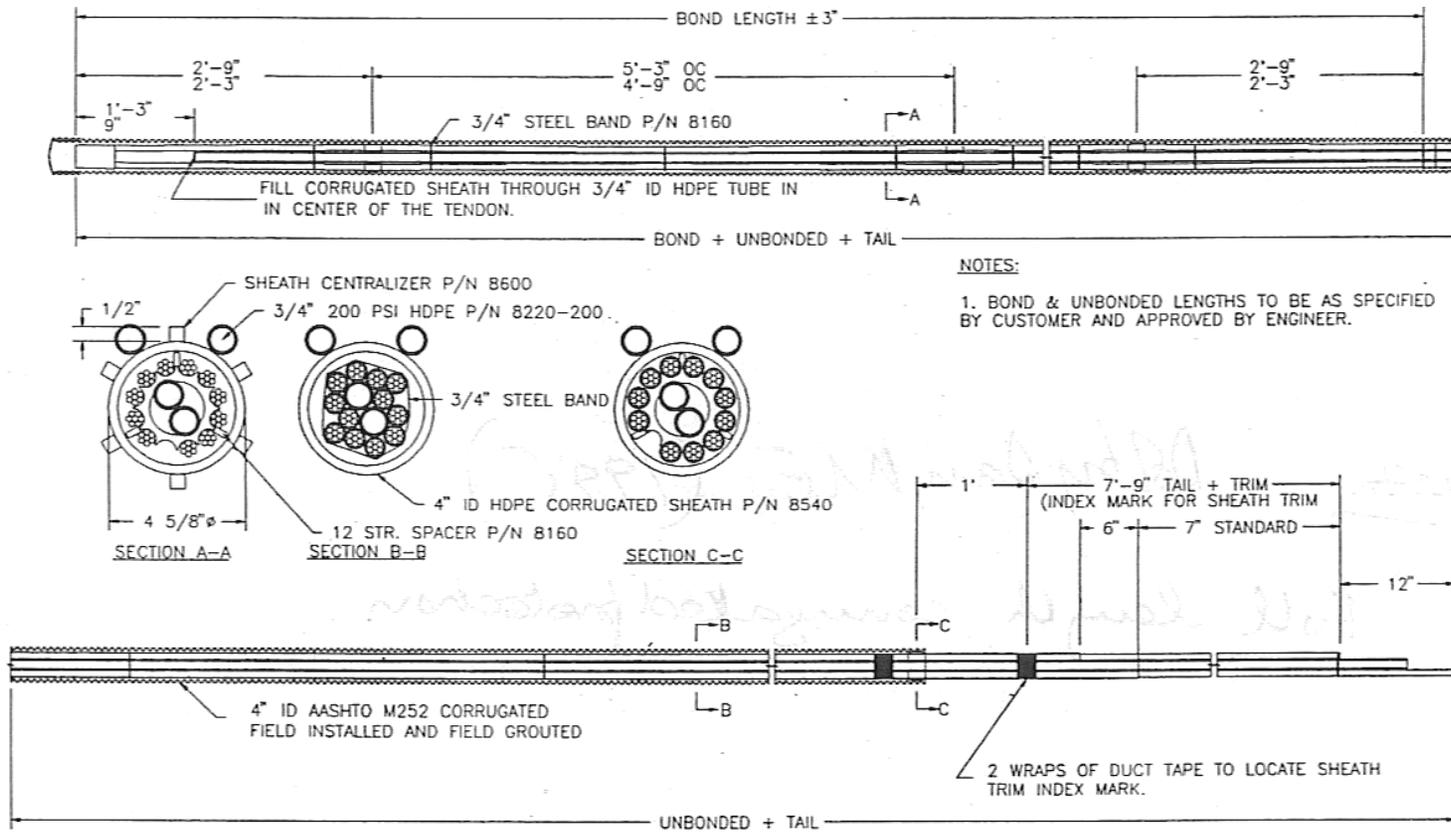


Figure 7. Full Length Corrugated Protection (Dolby Dam, ME, 1995).

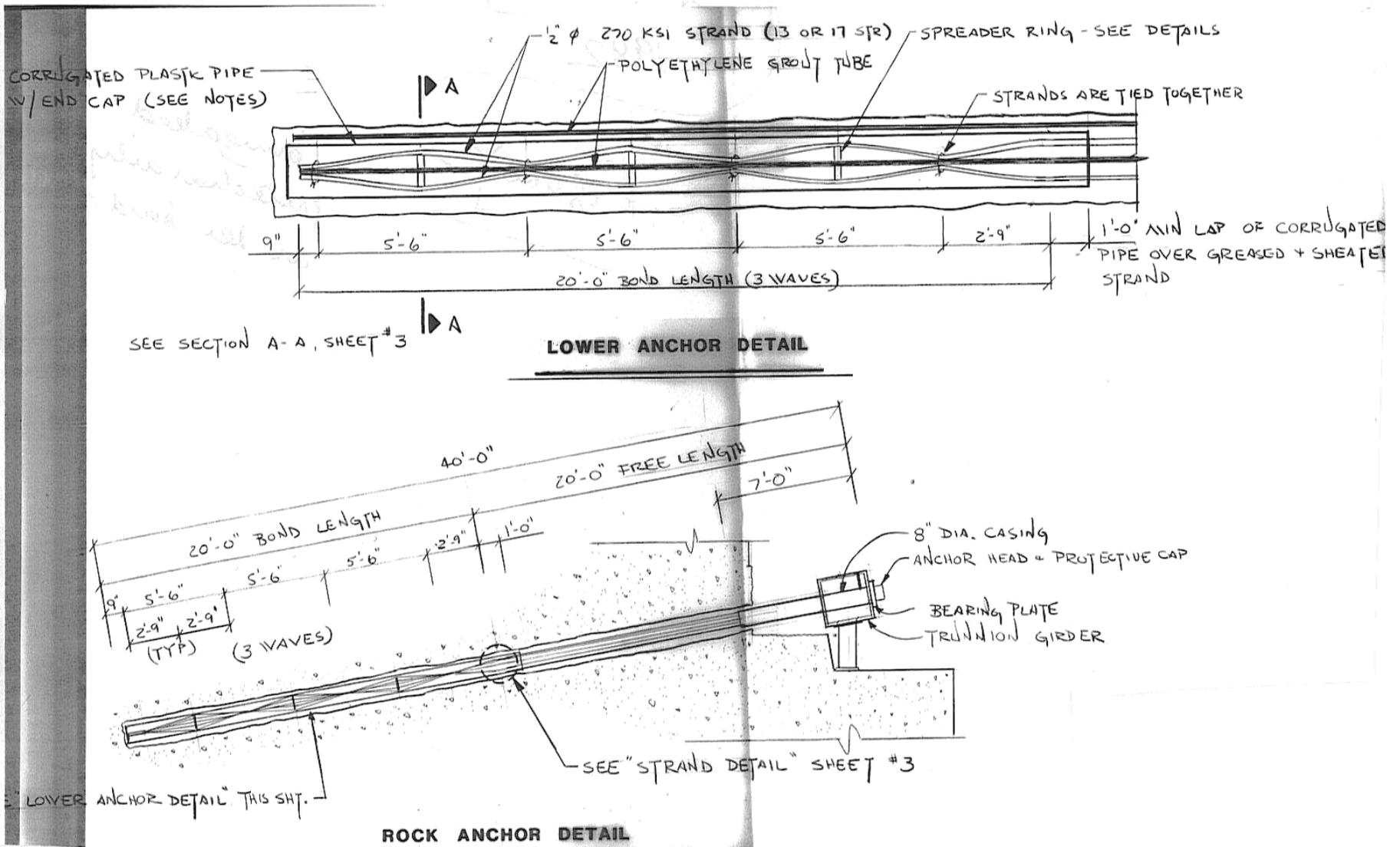


Figure 8. Corrugated Protection Only on the Bond Zone (St. Anthony Falls Locks and Dam, MN, 1982).

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 extruded 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 forced 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 — 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 430-foot-long anchors had to be assembled on site and required a 2,200-ton jack with 35-inch stroke since “stage stressing” was disallowed by Specification. Hence, this is now the largest jack in the world! 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).
- Epoxy protected strand 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!
- Bars have been used as low capacity tendons 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 restressable. 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 not 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.

3. Prices and Costs

3.1 General Observations

The price to construct an anchor project is highly variable and job specific, since it is controlled by a large number of very strong influences. The selling price of a tendon and associated hardware, by the post tensioning specialist to the contractor submitting the overall anchor price, tends to be a more regular and predictable figure, driven simply by the amount of steel to be provided, the cost of ancillary components (grout tubes, corrosion protection, spacers, etc.) and his estimated assembly and transportation costs. However, and greatly dependent on the overall *nature* of the project, this element of the contractor's selling price is always a minor portion (i.e., less than 40%) and often an even smaller component (less than 10%).

The selling price of a project depends on the impact on productivity, resources, materials and consumables of the following factors in particular:

- Geological conditions, for example, the “drillability” of the rock mass (and the dam), and the needs imposed by water pressure testing, pregrouting and re-drilling.
- Design requirements, for example, the number of anchors, their length, their capacity, their orientation and location, their corrosion protection and QA/QC requirements, and the stressing and testing procedures (including any preconstruction testing to be conducted).
- Logistical issues, such as how and where the drilling rigs, grout plants, tendon uncoilers, and stressing gear must be – or can be – located. Thus, for dam crest anchors, Contractor A may elect to build a work platform along the entire length, whereas Contractor B may decide to float in equipment on a barge. Contractor C may decide to install face anchors from a scaffold work platform, while Contractor D may choose large leads suspended from a crane located in the forebay.
- Schedule and interim milestones, which will dictate the number of drill rigs and their sequencing.
- Miscellaneous issues such as the Contractor's bidding strategy (e.g., Is he busy and does he need the work? How strong is the competition?); the geographic location of the work (just outside New York City or in Central Idaho?); union or non-union; the reputation of the Owner/Engineer as a business Partner [or otherwise]; climatic/environmental challenges, and so on.

A clear message is, therefore, that anyone contemplating providing an estimate for an anchoring project to the Owner as the basis of a project budget must be extremely careful to consider the relative accuracy of the estimate. Standard means of preparing such a budget include:

- Analysis of previous anchor costs on projects in which the designer has been personally involved.
- Obtaining “quotes” from one or more specialty contractor known to be experienced in this field, to assess constructability and site specific aspects.

Although the process is laudable and logical, such estimates are of limited accuracy and are not precise: in fact, if the final constructed cost of the project is within 20% of the

Engineer’s estimate, then, frankly, this success may be as much due to fortune as to engineering logic. Analysis of previous projects is always risky – so many intangibles which create subtle differences with major consequences can be easily overlooked, especially by a design engineer who has limited field experience. Equally, “budget quotes” from contractors are typically hurried, and not based on full awareness of the project details and challenges, as detailed above. Also, contractors will often be careful not to divulge the details of their proposed construction approach to important aspects such as site access and temporary facilities as these aspects are often the secret to their ability to be competitive and win the project. As a consequence, such “quotes” tend to be either deceptively low or discouragingly high, depending on the degree of optimism in the “marketing/sales” engineer who has picked up the owner’s telephone enquiry.

3.2 Information from the Database

In compiling the anchor case study database of over 400 dam anchoring projects, meaningful construction cost information has 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 USBR for concrete dam construction. Figure 9 provides a comparison of overall project drilling length to the adjusted cost of the anchoring construction.

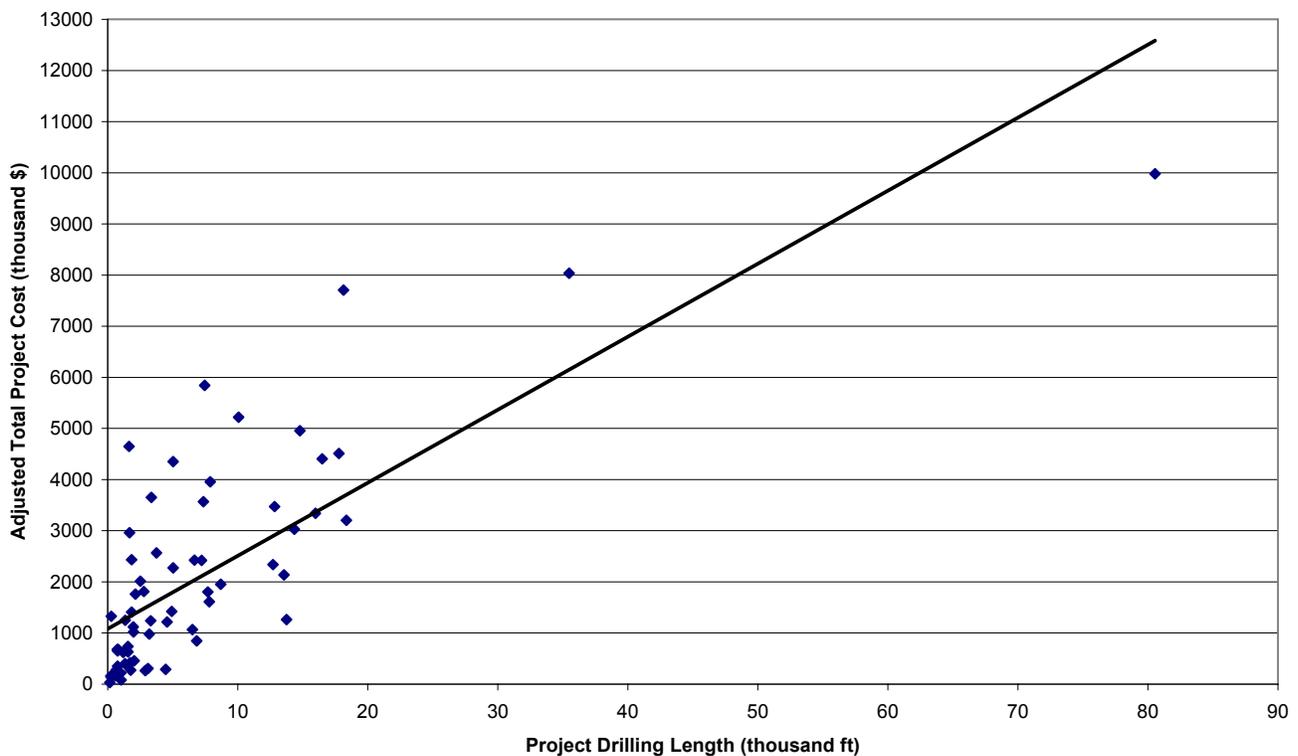


Figure 9. Drilling Length vs. Adjusted Cost

Figure 10 provides a similar graph based on the length of the pre-stressing steel. Figure 10 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 tabs 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. Statistics are presented in Table 2 summarizing the data from the 100 projects reporting cost information.

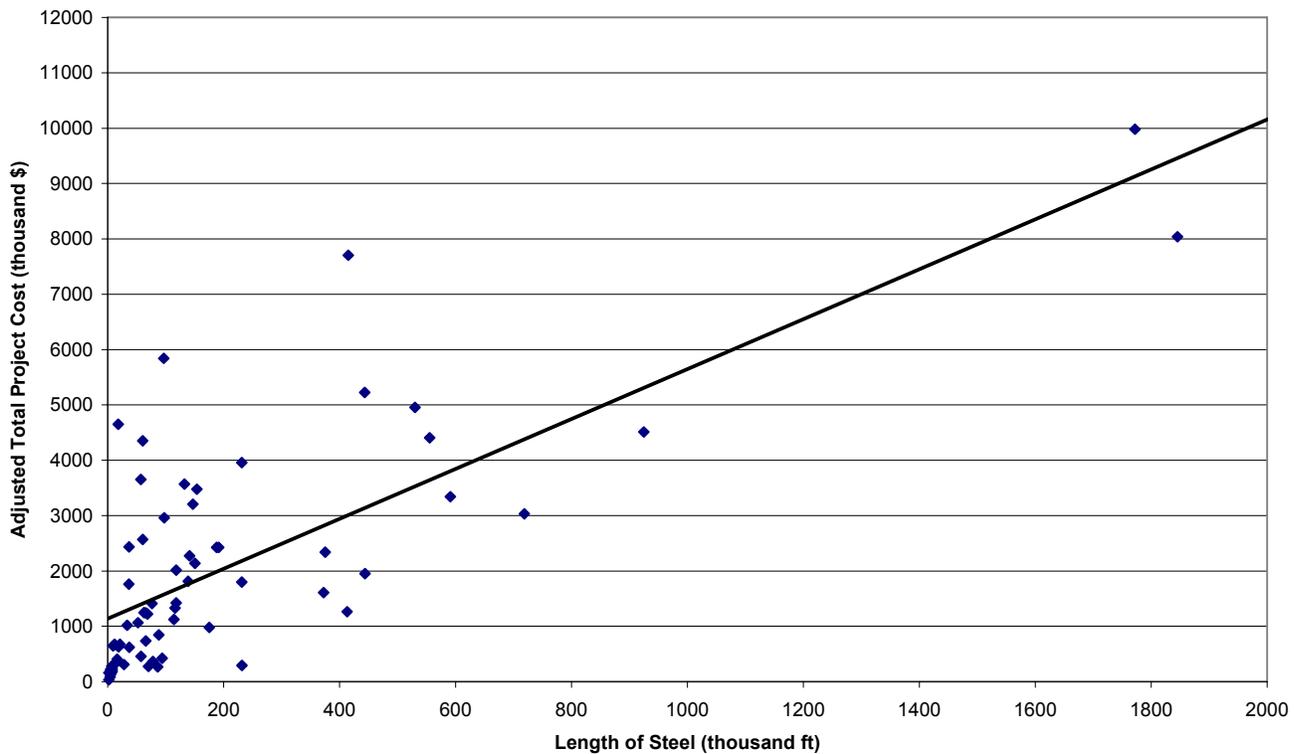


Figure 10. Length of Steel vs. Adjusted Cost

Table 2. Summary of Anchoring Construction Costs

Statistic	Cost / Drilling Length (Figure 9)	Cost / Total Steel Length in Tendon (Figure 10)
# Projects	100	92
Average	\$450	\$22
Minimum	\$65	\$1.25
Maximum	\$1760	\$83
Std Deviation	\$340	\$19

4. Conclusions

The authors have no doubt that the grout in the bond zone of a high capacity prestressed rock anchor, and just above it, cracks and crushes locally during stressing and testing. Therefore, tendons installed without Class I corrosion protection will have potential problems with long-term corrosion protection. It is fortunate indeed that the pregrouting of rock anchor boreholes was traditionally conducted to an extraordinarily tight criterion: this is doubtless the reason that no anchor failures due to corrosion in the bond zone have been reported – so far. Conversely, tendons designed and installed in accordance with the 2004 PTI Recommendations have every reason to be regarded as permanent: it is not unreasonable to think of service lives of at least 100 years, assuming appropriate accommodations for creep or relaxation. One may also note that there is currently no way to judge the present acceptability of the hundreds of anchors installed with bare steel (wire or strand) up until the early 1990s. This is a dilemma facing dam safety engineers worldwide. The logical, conservative view is to assume the anchors have no value and to therefore reprise the anchoring, using Class I protection.

The price to construct an anchor project is highly variable and job specific. Preparing cost estimates for dam anchoring projects is complicated by the many project specific aspects including geologic conditions, site access, site logistics, project location, schedule limitations, and design requirements. It is critical to evaluate the project specific aspects and constructability issues in developing project budgets. Using the database of over 400 anchoring projects completed in North America, a preliminary analysis of historical anchoring costs was completed. The analysis of cost data from 100 projects provides a general guideline to probable costs. Further studies of the cost data are planned for the second phase of the National Research Program, where additional information will be collected on the engineering aspects of the projects. By further refining the data to account for project specific aspects, an effort can be made to attribute variations in project costs to identifiable cost influences. One of the continuing goals of the National Research Program is to provide dam owners, engineers, and contractors resources to assist in planning, designing, and constructing prestressed anchor systems with confidence.

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