

Rock Anchors for North American Dams: The Development of the National Recommendations (1974-2004)

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Abstract

This paper describes the third major goal of Phase 1 of a National Research Program dealing with rock anchors for North American dams. Since 1974, there have been 5 successive versions of the “Recommendations” for ground anchor practice which have each effectively acted as a national standard. An analysis is provided which illustrates the evolution of theory and practice with time, with particular reference to the philosophies and details of corrosion protection.

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 third research goal, with a particular focus on the evolution of corrosion protection concepts and details. The findings of the first two research goals are presented in the companion paper, “Rock Anchors for North American Dams: The National Research Program Bibliography and Database,” 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 co-operation of specialty contractors and specialist post-tensioning suppliers who provided access to historical records.

General Statement

Current research indicates that the first U.S. dam to be stabilized by high capacity prestressed rock anchors was the John Hollis Bankhead Lock and Dam, Alabama (first 6 test anchors and 16 production anchors installed from 1962). This project was completed for the U.S. Army Corps of Engineers who had sufficient confidence in the technology (and, presumably, a pressing need for it!) that they were the sponsor for most of the half dozen or so similar applications in the six years that immediately followed. The U.S. Bureau of Reclamation

began using anchors to stabilize appurtenant structures at dams in 1967. The Montana Power Company was also an early proponent. In those days, the technology was largely driven by the post tensioning specialists, employing the same principles and materials such as used in prestressed/post tensioned structural elements for new buildings and bridges. The “geotechnical” inputs, i.e., the drilling and grouting activities, were typically subcontracted to drilling contractors specializing in site investigation and dam grouting in the west, and to “tieback” contractors in the east.

Recognizing the need for some type of national guidance and uniformity, the Post Tensioning Division of the Prestressed Concrete Institute (PCI) formed an adhoc committee which published, in 1974, a 32-page document entitled “Tentative Recommendations for Prestressed Rock and Soil Anchors.” It is interesting to note (Table 1) that half of the document comprised an appendix of annotated project photographs intended to illustrate and presumably promote anchor applications, including dam anchors at Libby Dam, Montana, and Ocoee Dam, Tennessee.

After publication of its document, the Post Tensioning Division of PCI left to form the Post Tensioning Institute (PTI) in 1976. Successive editions of “recommendations” were issued in 1980, 1986, 1996 and 2004. As general perspective to the development of concepts, Table 1 provides an analysis of the relative and absolute sizes of the major sections in each successive edition. It is immediately obvious that the original documents stressed “applications” – in an attempt to promote usage – while the most recent edition provides very detailed guidance (and commentary) on the “big five” in particular (i.e., Materials, Design, Corrosion Protection, Construction, and Stressing/Testing).

Table 1. Number of Pages in Major Sections of Successive U.S. “Recommendations” Documents

ASPECT	1974	1980	1986	1996	2004
Materials	1	2	2	8	10
Site Investigation	0	1	1	1	2
Design	2	6 ½	6 ½	12+ Appendix on grout/strand bond,	14
Corrosion Protection	1	4	5	10	14
Construction	7	9	9	10	15
Stressing and Testing	1	6	8	17	18
Bibliography/References	0	1	1	1 ½	4
Applications	16	18	0	0	0
Recordkeeping	0	1	1	1 ½	1 ½
Specifications	0	1	1 ½	2	2
Epoxy-Coated Strand	0	0	Very minor reference,	Frequent reference but no separate section.	10 Separate sections.
TOTAL PAGES	32	57	41	70	98

Detailed Comparison by Technical Topic

The structure of each successive edition has changed in the same way that the content has, although there are comparatively few structural differences between the 1996 and 2004 versions. The following comparison therefore is based on the structure of the 2004 version.

Scope and Definitions (Chapters 1 and 2)

The scope has remained relatively constant, and focuses on the anchors themselves (as components) as opposed to the analysis and design of the overall anchored system. A total of 72 technical terms are now defined, which represents a major expansion even over the 1996 edition: the first edition has 24 definitions, most of which, incidentally, remain valid and little changed.

Specifications, Responsibilities and Submittals (Chapter 3)

Whereas 1974 provided no insight into specifications and responsibilities, certain records were required to be maintained on the grouting operations. By 1980, however, specifications had been addressed, reflecting the need to tailor procurement processes to “experienced” contractors, “thoroughly experienced” and match the innovation of the technique with alternative procurements methods. It is notable that the three types of specification outlined in 1980 (namely open, performance and closed) have endured, although “closed” is now referred to as “prescriptive.” Building on a 1996 innovation, the responsibilities to be discharged during a project — regardless of type of specification — were summarized in 2004 as shown in Table 2. Clear guidance is also provided on the content of preconstruction submittals and as-built records. The former also include the requirement for the contractor to prepare a Construction Quality Plan. Emphasis remains on the need for “specialized equipment, knowledge, techniques and expert workmanship” and for “thoroughly experienced” contractors. The obvious, but often ignored, benefit of “clear communication and close co-operation,” especially in the start up phase of a project, is underlined.

Table 2. Tasks and responsibilities to be allocated for anchor works (PTI, 2004)

1.	Site investigation, geotechnical investigation and interpretation, site survey and potential work restrictions.	6.	Anchor spacing and orientation, minimum total anchor length, free anchor length and anchor load.
2.	Decision to use an anchor system, requirements for a pre-contract testing program, type of specification and procurement method, and contractor prequalification.	7.	Anchor components and details.
3.	Obtaining easements, permits, permissions.	8.	Determination of bond length.
4.	Overall scope of the work, design of the anchored structure, and definition of safety factors.	9.	Details of water pressure testing, consolidation grouting and re-drilling of drill holes
5.	Definition of service life (temporary or permanent) and required degree of corrosion protection.	10.	Details of corrosion protection.
		11.	Type and number of tests.
		12.	Evaluation of test results.
		13.	Construction methods.
		14.	Requirements for QA/QC Program.
		15.	Supervision of the work.
		16.	Maintenance and long-term monitoring.

Anchor Materials (Chapter 4)

The 1974 document very briefly refers to wires, strand, and bars, and to protective sheathing. In stark contrast, the current version has built to 10 pages providing definitive detail on materials used in each of the 10 major anchor components, with particular emphasis placed on steel, corrosion-inhibiting compounds, sheathings and grouts (cementitious and polyester).

Strong cross-reference to relevant ASTM standards is provided as a direct guide to specification drafters.

Site Investigation (Included in Chapter 6 – Design)

Not referred to in 1974, recommended first in 1980 and completely revised and expanded in 1996 and 2004, this issue now provides clear guidance on the goals and details of a site investigation program. “Minimum requirements” are recommended. However, this remains an area where the anchor specialist often has less “leverage” to influence since the costs associated with such programs typically exercise strong control over the scope actually permitted by the owner.

Corrosion and Corrosion Protection (Chapter 5)

Given the significance and relevance of this topic to the current conference, this subject is discussed separately below (Section 4).

Design (Chapter 6)

Judging from the relatively short and simplistic coverage of this aspect in 1974, it is fair to say that not much was really then *known* of the subject. Core drilling was considered absolutely necessary and preproduction pullout tests were “strongly recommended.” However, two enduring issues were faced:

- The safety factor (on grout-rock bond) “should range from 1.5 to 2.5”, with grout/steel bond not normally governing.
- A table of “typical (ultimate) bond stresses” was issued as guidance to designers.

Today even despite superior and often demonstrated knowledge of load transfer mechanisms (i.e., the issue of bond stresses NOT being uniform), the same philosophy prevails:

- The safety factor (reflecting, of course, the criticality of the project, rock variability and installation procedures) is normally 2 or more.
- A table of “average ultimate” bond stresses presented, which is basically identical except for typographic errors, to the 1974 table.

However, the current edition does provide very detailed guidance on critical design aspects, including allowable tendon stresses; minimum free and bond lengths; factors influencing rock/grout bond stress development; anchor spacing; grout cover/strand spacing; and grout mix design.

Construction (Chapter 7)

As noted above, there was a strong bias in the 1974 document towards construction, largely, it may be assumed, because practice far led theory. Furthermore, much of what was described in 1974 remains valid, especially with respect to issues relating to grouts, grouting and tendon placement. Certain features, such as a reliance on core drilling, the use of a “fixed anchorage” (i.e., the use of a plate) at the lower end of multistrand tendons, and specific water take criteria to determine the need for “consolidation grouting” are, however, no longer valid.

The 2004 version expanded upon the 1996 guidance, itself a radical improvement over its two immediate predecessors, and is strongly permeated by an emphasis on quality control and assurance. For example, practical recommendations are provided on the fabrication of

tendons (including the pregrouting of encapsulations) and storage handling and insertion. Drilling methods are best “left to the discretion of the contractor, wherever possible,” although specifications should clearly spell out what is not acceptable or permissible. In rock, rotary percussion is favored, and the drilling tolerance for deviation of 2° is “routinely achievable,” while smaller tolerances may be difficult to achieve or to measure. Holes open for longer than 8 to 12 hours should be recleaned prior to tendon insertion and grouting.

The acceptance criterion for water pressure testing is adjusted to 10.3 liters in 10 minutes at 0.035 MPa for the entire hole. Technical background is provided on the selection of this threshold (based on fissure flow theory). Holes with artesian or flowing water are to be grouted and redrilled prior to water pressure testing. The pregrout (generally WCR = 0.5 to 1.0 by weight) is to be redrilled when it is weaker than the surrounding rock. When corrugated sheathing is preplaced, a water test should be conducted on it also, prior to any grouting of its annulus.

The treatment of grouting is considerably expanded and features a new decision tree to guide in the selection of appropriate levels of QC programs. Holes are to be grouted in a continuous operation not to exceed 1 hour, with grouts batched to within 5% component accuracy. The value of testing grout consistency by use of specific gravity measurements is illustrated. Special care is needed when grouting large corrugated sheaths; multiple stages may be required to avoid flotation or distortion. The cutting of “windows” in the plastic (to equalize pressures) is strictly prohibited.

Stressing, Load Testing and Acceptance (Chapter 8)

Given the professional experience and background of the drafting committee, it is surprising, in retrospect, to note the very simplistic contents of the 1974 document:

- “proof test” every anchor to $\geq 115\%$ “transfer” load (to maximum 80% GUTS),
- hold for up to 15 minutes (but no creep criterion is given),
- lock-off at 50 to 70% GUTS,
- alignment load = 10% of Test Load, with movement only apparently recorded at this Test Load (115 to 150% transfer load). “If measured and calculated elongations disagree by more than 10%, an investigation shall be made to determine the source of the discrepancy,”
- lift-off test may be instructed by the Engineer “as soon as 24 hours after stressing.”

Despite significant advances in the 1980 and 1986 documents, reflecting heavily on European practice and experience, significant technical flaws persisted until the completely rewritten 1996 version. The 2004 document was little changed in structure and content, the main highlights being as follows:

- Practical advice is provided on preparatory and set up operations and on equipment and instrumentation including calibration requirements.
- Alignment Load can vary from 5 to 25% of Design Load and 10% is common. This initial, or datum load, is the only preloading permitted prior to testing. On long, multistrand tendons, a monojack is often used to set the Alignment Load, to ensure uniform initial loading of the strands.
- Maximum tendon stress is 80% F_{pu} .
- Preproduction (“disposable,” test anchors, typically 1 to 3 in number), Performance and Proof Tests are defined, the latter two covering all production anchors.

- For Performance Testing, the first 2 or 3 anchors plus 2 to 5% of the remainder are selected. The test is a progressive cyclic loading sequence, typically to 1.33 times Working Load. A short (10 or 60 minute) creep test is run at Test Load.
- Proof Tests are simpler, requiring no cycling and are conducted to the same stress limits. The option is provided to return to Alignment Load prior to lock-off (in order to measure the permanent movement at Test Load), otherwise this movement can be estimated from measurements from representative Performance Tests.
- Supplementary Extended Creep Tests are not normally performed on rock anchors, except when installed in very decomposed or argillaceous rocks. A load cell is required and the load steps and reading frequencies are specified.
- Lock-off load shall not exceed 70% F_{pu} , and the wedges will be seated at 50% F_{pu} or more.
- The initial lift-off reading shall be accurate to 2%.
- There are three acceptance criteria for every anchor:
 - Creep: less than 1 mm in the period 1 to 10 minutes, or less than 2 mm in the period 6 to 60 minutes.
 - Movement: there is no criterion on residual movement, but clear criteria are set on the minimum elastic movement (equivalent to at least 80% free length plus jack length) and the maximum elastic movement (equivalent to 100% free length, plus 50% bond length plus jack length).
 - Lift-Off Reading: within 5% of the designed Lock-Off load.
- A decision tree guides practitioners in the event of a failure in any one criterion. The “enhanced” creep criterion is 1 mm in the period 1 to 60 minutes at Test Load.
- The monitoring of service behavior is also addressed. Typically 3 to 10% of the anchors are monitored (or more if desired), by load cells or lift-off tests. Initial monitoring is at 1 to 3-month intervals, stretching to 2 years later.

Epoxy-coated strand (Supplement)

This material and its use was first discussed systematically in 1996, although minor references had been made in 1986. The 2004 document contains a separate supplement dealing with specifications, materials, design, construction and testing, being a condensed and modified version of a document produced by the ADSC Epoxy-Coated Strand Task Force in November 2003. The Scope (Section 1) notes that anchors made from such strand “require experience and techniques beyond those for bare strand anchors.” The supplement is a condensed version of the “Supplement for Epoxy-Coated Strand” as prepared by the ADSC Epoxy-Coated Strand Task Force (November 2003). It supplements the recommendations provided in the general recommendations with respect to specifications/responsibilities/submittals; materials; design; construction; and stressing and testing.

The Issue of Corrosion Protection

1974. Figure 1 illustrates the very simple approach to tendon protection, i.e., cement 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 cement grout alone would be acceptable.

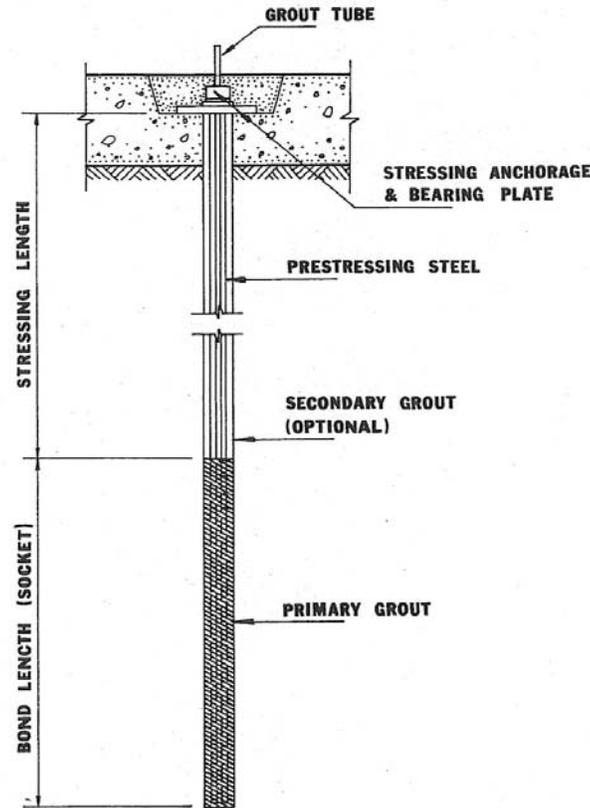


Figure 1. Rock Anchor Components (PCI, 1974) (Note the lack of protection to the steel other than cement grout)

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 cement 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, cement 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 cement 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 cement grout, depending on the results of laboratory tests on small samples. Encapsulation was not detailed.

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 3 and a “decision tree” was provided for the guidance of designers (Nierlich and Bruce, 1997).

Table 3. 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

2004. The 1996 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 3 was revised, as shown in Table 4, mainly to clarify the acceptable Class I status of epoxy protected steel in a “water proofed hole.” The sophistication of contemporary tendons is shown in Figure 2. A long supplement is devoted to epoxy protected strand.

Table 4. 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

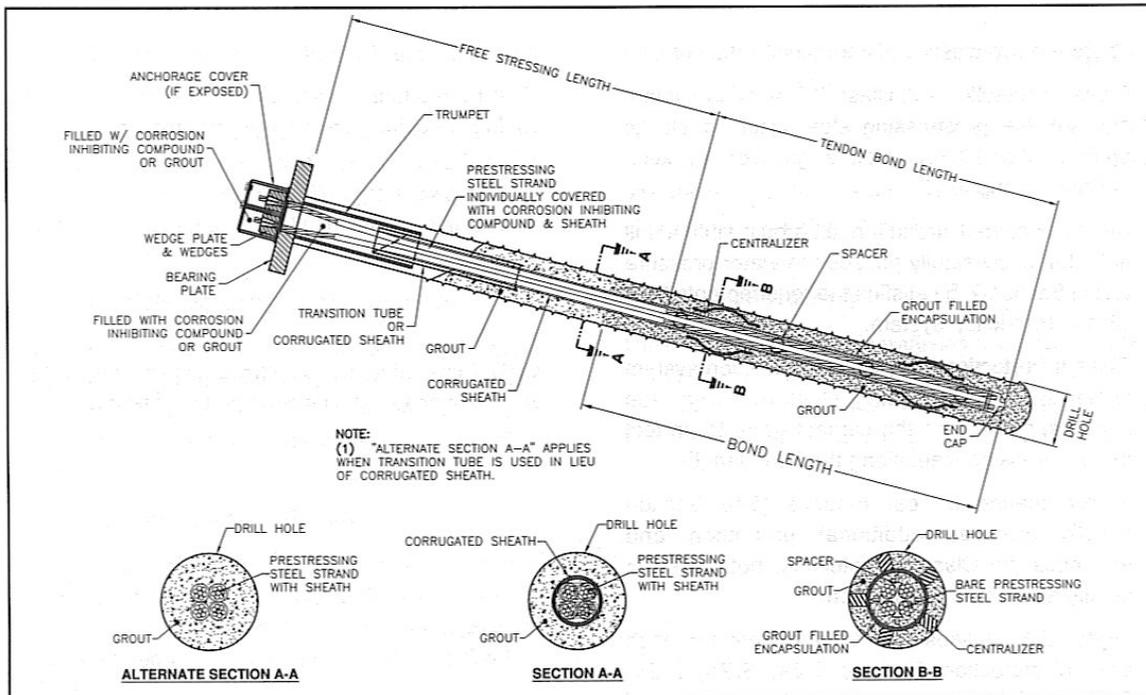


Figure 2. Class I Protection – Encapsulated Strand Anchor (PTI, 2004)

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 reaffirmed 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 drill hole “waterproofing” criterion under which they were constructed.

Final Observations

The Phase 1 research into the successive “Recommendations” provides a fascinating insight into the evolution of a specialist technology over thirty years of practice. The observations support and often explain the similar trends described in the companion paper dealing with the Program’s Bibliography and Database.

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