High Capacity Rock Anchors for Dams: Thirty Years of Recommendations for Practice

The National Rock Anchor Research Program[1]

Abstract

High capacity rock anchors have been used to stabilize dams in North America since 1968. In the absence of national standards governing design, construction and testing, practice has been directed by, and is reflected in, the successive versions of the "recommendation" documents prepared by the Post Tensioning Institute and, latterly, endorsed by ADSC. A National Research Program has recently been established, funded by industry (in the U.S. and Japan), and by ADSC. One of the goals of this program has been to trace the evolution of practice in the successive "recommendation" documents, the first issued in 1974, and the fifth and most recent in 2004. This paper provides a summary of the findings of this task.

1. Background

Current research indicates that the first U.S. dam project to be stabilized by high capacity prestressed rock anchors was Little Goose Locks and Dam, Washington in 1968. 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 followed. 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 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 the 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 a general perspective to the evolution of these documents, the following analyses are provided:

[1] The Program's Co-Principal Investigators are Donald A. Bruce and John S. Wolfhope. Further research has been conducted by Mary Ellen C. Bruce and Gary M. Weinstein.

- Table 1 indicates the composition (by employer) of the successive drafting committees. It will be noted that the chairman of the committee has always been from a post tensioning specialist company and that this position has been occupied by the same person (Heinz Nierlich) since 1980. His leadership has provided invaluable perspective and has been marked by infinite patience.
- Table 2 illustrates the way in which various themes have been addressed in the successive documents. Recent emphasis on corrosion protection, stressing and testing, and epoxy-coated strand is particularly notable, reflecting relative weaknesses in earlier versions.
- Table 3 provides a quick overview of the quality of the treatment given to major topics over the years, and so gives a most interesting insight into the evolution of practice over the years.

The full National Research Program task report on the evolution of the recommendations (2005) details the successive steps taken between each successive version. Given the space restrictions of this paper, the comparison between the 1974 and the 2004 recommendations is primarily pursued in the following.

2. Comparison Between 1974 and 2004 Documents

Scope and Definitions (Chapters 1 and 2 of the 2004 document)

The scope of 1974 was to "provide guidance in the application of permanent and temporary prestressed rock anchors utilizing high strength prestressing steel," and purported to represent "practical procedures for installation." The stated scope of the 2004 document is practically identical, although the current state of practice extends to design, installation and testing. The 2004 version was considerably expanded over 1996 to provide additional "educational" commentary and information. Consistently these documents have not dealt with the design of anchored structures in general, "but are limited to considerations specific to the prestressed anchors themselves." The 2004 version provides definitions on 72 technical terms, considerably expanded from 1996 by the incorporation of terms specific to grouts, grouting and epoxy-coated strand. A most telling illustration is provided in the comparison of the two corresponding drawings illustrating anchor terminology (Figures 1a and 1b).

The first anchor bibliography was provided in the 1980 version and contained 13 references, of which 2 were American. In contrast, the 2004 list (reduced in number from 1996) comprising 8 federally-sponsored reports or textbooks of U.S. origin, 8 foreign standard or textbooks, and 8 other technical papers (5 of U.S. origin).

Specifications, Responsibilities and Submittals (Chapter 3)

Whereas 1974 provided no insight into specifications and responsibilities, certain records were 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." It is notable that the three

Table 1. Number and Affiliations of Committee Members

ASPECT	1974	1980	1986	1996	2004
Post-Tensioning Suppliers	6†	4*	4*	2*	3*
Anchor Contractors	2	2	3	3	3
Consultants	2	None	1	2	2
Owners	1	2	1	3	3
Sponsor Organizations	1	None	0	1	11
TOTAL	12	8	9	11	12

* Including the same Chairman (Heinz Nierlich of DSI).
† Chairman from VSL

Table 2. Contents of the Various Editions

ASPECT	PCI 1974	PTI 1980	PTI 1986, 1989	PTI 1996	PTI 2004
Materials	Very light.	Somewhat expanded.	No change.	Greatly expanded.	Further enhanced.
Design	Light.	Significantly expanded.	No change.	Greatly expanded.	Slightly enhanced.
Site Investigation	Moderate.	Expanded.	No change.	Stronger.	Further enhanced.
Corrosion Protection	Very basic.	Expanded.	Improved.	Fundamentally and logically reassessed.	Further enhanced especially with respect to epoxy.
Construction	Strong.	Slightly expanded.	No change.	Revised and strengthened, emphasis on Contractor's skills.	Generally enhanced, new section on grout QA/QC.
Stressing and Testing	Very basic.	Expanded but flawed.	Expanded further but still flawed – introduces creep test.	Improved, rationalized.	Minor modification only.
Specifications	—	Strong.	No change.	Greatly strengthened.	Further enhanced.
Bibliography/References	—	Strong – international.	Strong – U.S. studies symposium.	Strong, increasing emphasis on U.S. papers and studies.	Strong, internationally balanced.
Applications	Strong and useful.	Strong and useful.	Omitted (obviously no need to "advertise").	Omitted.	Omitted.
Recordkeeping	Very light.	Little change.	No change.	Significantly improved	Further enhanced.
Epoxy-Coated Strand	—	—	Minor reference.	Strong references, especially in construction and stressing/testing.	Separate supplement devoted to material and its use.
General Comments	Tentative. Insular. Well meaning.	A quantum jump especially in the new section on corrosion protection. Much more confident and aware. Still flawed (unreal time). Emphasis on engineer/"foundation specialist."	Largely unchanged except for corrosion protection (much better) and stressing (still flawed).	Fundamental change in structure and content. Great improvement especially in corrosion protection and stressing.	Essentially same structure as 1996 but with considerable extra background information. Emphasis on epoxy-coated strand, corrosion protection, QA/QC, especially for grout.

Table 3. Number of Pages in Major Sections

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

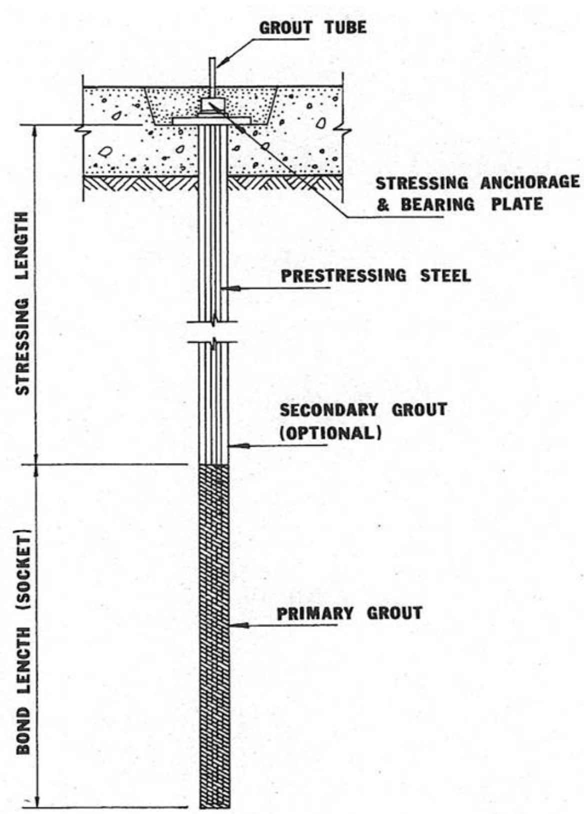

Figure 1a. Rock anchor terminology and components (PCI, 1974)

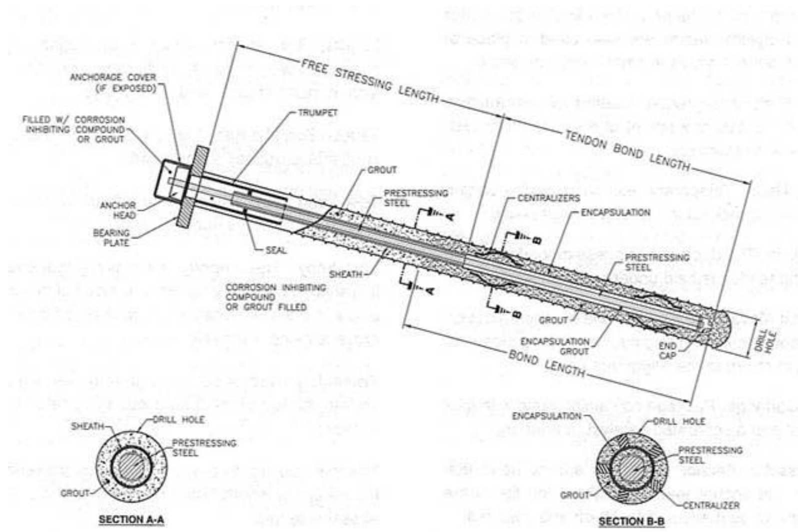

Figure 1b. Typical components of an anchor (PTI, 2004)

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 3.1. Clear guidance is also provided on the content of preconstruction submittals and as-built records. The former also include the requirement for 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 cooperation," especially in the start up phase, is underlined.

Specifications, Responsibilities and Submittals (Chapter 3)

Whereas 1974 provided no insight into specifications and responsibilities, certain records were 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." 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, responsibilities to be discharged during a project — regardless of type of specification — were summarized in 2004 as shown in Table 3.1. Clear guidance is also provided on the content of preconstruction submittals and as-built records. The former also include the requirement for 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 cooperation," especially in the start up phase, is underlined.

Table 3.1 Tasks and responsibilities to be allocated for anchor works (PTI, 2004).

1.	Site investigation, geotechnical investigation and interpretation, site survey and potential work restrictions.
2.	Decision to use an anchor system, requirements for a pre-contract testing program, type of specification and procurement method, and contractor prequalification.
3.	Obtaining easements, permits, permissions.
4.	Overall scope of the work, design of the anchored structure, and definition of safety factors.
5.	Definition of service life (temporary or permanent) and required degree of corrosion protection.
6.	Anchor spacing and orientation, minimum total anchor length, free anchor length and anchor load.
7.	Anchor components and details.
8.	Determination of bond length.
9.	Details of water pressure testing, consolidation grouting and re-drilling of drill holes
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 sheathing. In stark contrast, the current version contains 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)

Building on the 1980 recommendation that geologic studies be conducted (by a "competent foundations specialist"), and the completely revised 1996 version, the 2004 recommendations provide clear guidance as to the scope of a relevant prebid investigation. The following data are considered most useful for design purposes:

- Classification of mass and material (geometry and characteristics of discontinuities, degree of weathering, index test results, lithology).
- Rock quality designation and recovery percentage.
- Unconfined compressive strength of intact rock and shear strength of weaker rock.
- Unit weight.
- Groundwater level.
- Permeability.
- Aggressivity of rock and ground water.

The following information may also be useful on a site-specific basis:

- Modulus of elasticity of rock mass.

- Determination of stray currents present.

Typical spacing for investigative rock borings is in the range of 30 to 60 m depending on the uniformity of the ground.

Exploration of the site by core drilling is "a minimum requirement" and water pressure testing is advised. Notably, in light of certain early practices, core drilling in the bond zones of anchor holes is not advised on schedule, cost and technical (i.e., reduced grout/rock bond) grounds.

Corrosion and Corrosion Protection (Chapter 5)

Prior to 1996, European specialists found fault with the PTI recommendations insofar as they perceived U.S. practice to be somewhat lax — not to say deficient — with respect to attitudes towards corrosion and corrosion protection. However justified this criticism may have been when considering the entirety of anchor applications including relatively high capacity tiebacks in urban soil conditions, it was probably overstated when the particular issue of high capacity anchors for dam stabilization could be considered in isolation. For a variety of logical, historical reasons, by far the greatest percentage of U.S. dams had been founded on "good rock" foundations, typically on sites which had also been grouted to a certain intensity during initial construction. U.S. practitioners were therefore comfortable that the coincidence of rock masses with low permeabilities (natural or influenced) with appropriate standards of care and workmanship during construction would assure acceptable long-term performance with respect to corrosion resistance. The historical record supports this position, even if there has been a distinct element of "grace of God" in the supporting logic, and a marked degree of internal confusion as to what "single" and "double" corrosion protection really meant. In 1974, "permanent" was synonymous with a 3-year service life, this life varying to 18 months in 1980 (when a significant advance was made in the recommendations) to 24 months in 1996 and 2004. Permanent, it would seem, is subject to change.

There is no question that one of the main concerns frequently expressed by potential users of rock anchors in dams was (and still is) concern over corrosion protection. As illustrated in Tables 2 and 3, this concern was specifically addressed in the 1980 and 1996 recommendations in particular. By 2004 the PTI committee was in the comfortable position of simply having to install relatively minor modifications and enhancements to the structure radically introduced in 1996. The basic principles of our current practice are as follows:

- Selection of the corrosion protection "class" is to be based on the decision tree of Figure 5.1.
- The requirements of each class of protection are defined in Table 5.1.
- The aggressivity of the anchor environment is defined quantitatively, issue by issue, being influenced by:

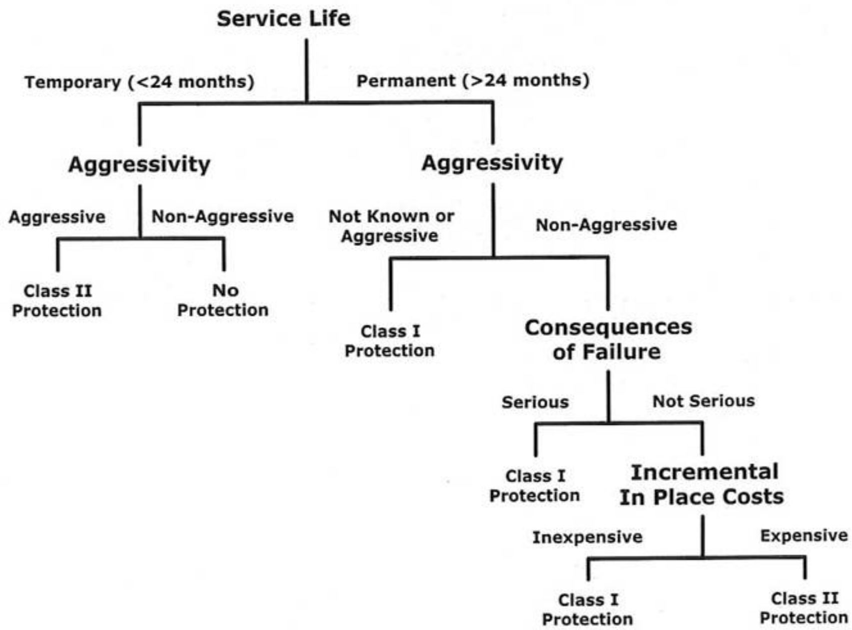

Figure 5.1 Corrosion Protection Decision Tree (PTI, 2004)

Table 5.1 Corrosion Protection Requirements (PTI, 2004)

CLASS	CORROSION PROTECTION REQUIREMENTS		
	ANCHORAGE	FREE STRESSING LENGTH	TENDON BOND LENGTH
I ENCAPSULATED TENDON	Trumpet Cover if exposed	• 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	• Grout-filled encapsulation, or • Epoxy-coated strand tendon in a successfully water-pressure tested drill hole
II GROUT PROTECTED TENDON	Trumpet Cover if exposed	• 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	• Grout • Polyester resin in sound rock with non-aggressive ground water

“1. Resistivity of the soil,
 2. pH value of the soil,
 3. Chemical composition of the ground water and the soil or rock,
 4. Water and air permeability of the ground,
 5. Groundwater elevation (stable or fluctuating) and
 6. External electrochemical and physical factors (long-line and stray-current corrosion systems).”

- Corrosion protection requirements are defined for Class I and Class II, respectively, as illustrated for a Class I Encapsulated Strand Anchor in Figure 5.2a.

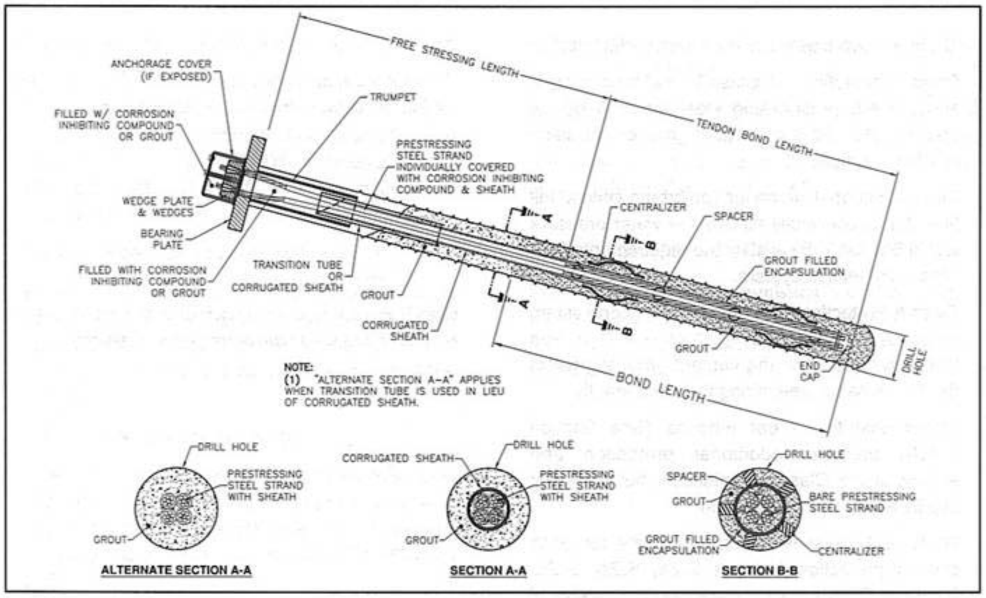

Figure 5.2a Class I Protection – Encapsulated Strand Anchor (PTI, 2004)

- Guidance is provided on the *details* of the protection in relation to anchorage, free length, bond length, and couplers (for bars). For example, at least 13 mm of grout cover must be provided over the encapsulation of bare strands, and a minimum of 50 mm of cover is required to the outside of steel trumpets.

The researches of the National Program so far confirm the following statement made in the 2004 Recommendations: "Permanent anchors have been routinely installed in North America since the mid 1960's. They continue to perform well in a variety of environments, applications and ground conditions."

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 *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:

Typical Bond Stresses for Rock Anchors (PCI, 1974)

Type	Ultimate Bond Stresses Between Rock and Anchor-Grout Plug Sound, Non-decayed
Granite & Basalt	250 PSI – 450 PSI
Dolomitic Limestone	200 PSI – 300 PSI
Soft Limestone*	150 PSI – 220 PSI
Slates & Hard Shales	120 PSI – 200 PSI
Soft Shales*	30 PSI – 120 PSI
Sandstone	120 PSI – 250 PSI
Concrete	200 PSI – 400 PSI

**Bond strength must be confirmed by pullout tests which include time creep tests.*

By 2004, 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 is produced (Table 6.1) — basically identical except for typos, to the 1974 table.

Table 6.1 Typical Average Ultimate Bond Stresses-Rock/Grout (PTI, 2004)

ROCK	AVERAGE ULTIMATE BOND STRESS-ROCK/GROUT	
	MPa	*PSI*
Granite & Basalt	1.7 - 3.1	250 - 450
Dolomite Limestone	1.4 - 2.1	200 - 300
Soft Limestone	1.0 - 1.4	150 - 200
Slates & Hard Shales	0.8 - 1.4	120 - 200
Soft Shales	0.2 - 0.8	30 - 120
Sandstones	0.8 - 1.7	120 - 250
Weathered Sandstones	0.7 - 0.8	100 - 120
Chalk	0.2 - 1.1	30 - 155
Weathered Marl	0.15 - 0.25	25 - 35
Concrete	1.4 - 2.8	200 - 400

However, strong guidance is provided in 2004, with appropriate back up, based on technical analyses and field experience, in the following fields:

- Factor of safety at design load for the tendon shall not be less than 1.67.
- Lock-off load shall not exceed 70% F_{pu}.
- Maximum test load shall not exceed 80% F_{pu}.

- For acceptable tendon/grout bond, the minimum tendon bond length shall not be less than 4.5 m for strand, and 3.0 m for bar. Most bond lengths in rock are less than 10.0 m, due to load transfer inefficiencies.
- Ultimate average rock/grout bond stresses depend on:
  1. Shear strength and modulus of elasticity of the rock.
  2. Discontinuities in the rock mass, including the spacing and orientation of bedding planes, joints and fractures.
  3. Minerals in the rock, which may "lubricate" the bond zone or reduce the grout strength.
  4. Method of drilling and cleaning of the drill hole.
  5. Drill hole wall roughness.
  6. Timing between drilling and grouting in soft rocks.
  7. In situ strength of the grout.
  8. Grouting methods and pressures, and mix designs.
  9. The bond length.
- Working bond stresses are to be established on a case-by-case basis.
- Ultimate rock/grout bond stresses can be initially approximated by using a value of 10% UCS rock to a maximum value of 4.2 MPa.
- Strand-to-grout bond shall be evaluated by tests for each strand manufacturer.
- Free lengths shall not be less than 4.5 m (strand) and 3.0 m (bar).
- Center-to-center bond length spacings shall be at least 4 times nominal diameter, and not less than 1.2 m. Staggering may be necessary.
- Drill hole diameter shall provide at least 13 mm grout cover over tendons and its corrosion protection. Also, the area of steel in the hole shall not exceed 15% of the total hole area.
- For an encapsulated multi-unit tendon, the encapsulation shall be sized to limit tendon area to 30% area of encapsulation (inner dimension). For bars, a minimum of 10 mm cover to be provided.
- Grout mix design shall provide at least 21 MPa at time of stressing, and have less than 2% bleed.

<u>Construction</u> (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" 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 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 2º is "routinely achievable," while smaller tolerances may be difficult to achieve 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) is to be redrilled when it is weaker than the surrounding rock. When corrugated sheathing is preplaced, the water test should be conducted on it, prior to any grouting.

The treatment of grouting is considerably expanded and features a new decision tree (Figure 7.1) 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, and the cutting of "windows" (to equalize pressures) is strictly prohibited.

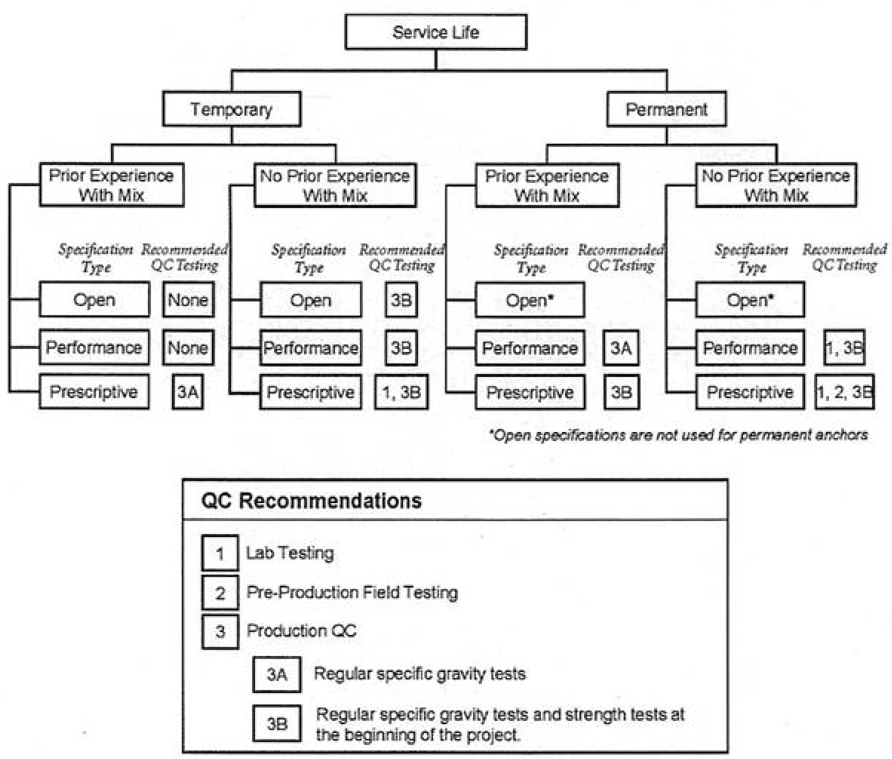

Figure 7.1 Minimum Recommended Levels of Grout QC Programs (PTI, 2004)

Stressing, Load Testing and Acceptance

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 ≥ 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, 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. Otherwise, no preloading is 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. Data are plotted as in Figure 8.1a and 8.1b.

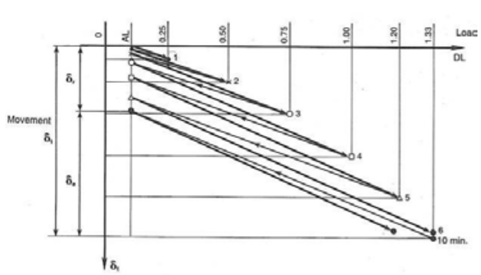

Figure 8.1a Plotting of Performance Test Data, (PTI, 2004)

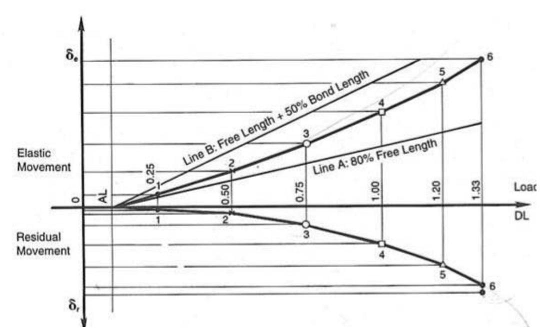

Figure 8.1b Graphical Analysis of Performance Test Data, (PTI, 2004)

- Proof Tests are simpler, requiring no cycling and are conducted to the same stress limits (Figures 8.3a and 8.3b). 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.

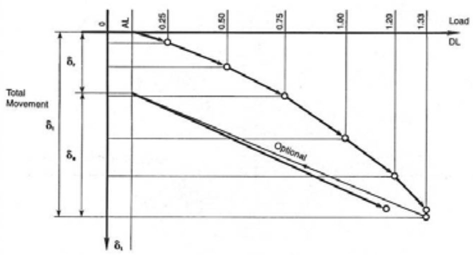

Figure 8.3a Plotting of Proof Test Data (PTI, 2004)

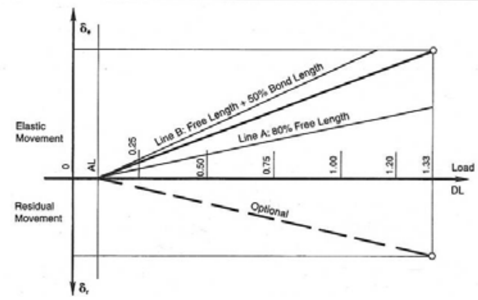

Figure 8.3b Graphical Analysis of Proof Test Data (PTI, 2004)

- 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 are shown in Table 8.3. Readings — as appropriate to each step — are taken at 1, 2, 3, 4, 5, 6, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120, 150, 180, 210, 240, 270 and 300 minutes. The family of curves is to be plotted as in Figure 8.4.

Table 8.3 Supplementary Extended Creep Test (PTI, 2004)

Load	Observation Period (min)
AL	
0.25 DL	10
0.50 DL	30
0.75 DL	30
1.00 DL	45
1.20 DL	60
1.33 DL	300

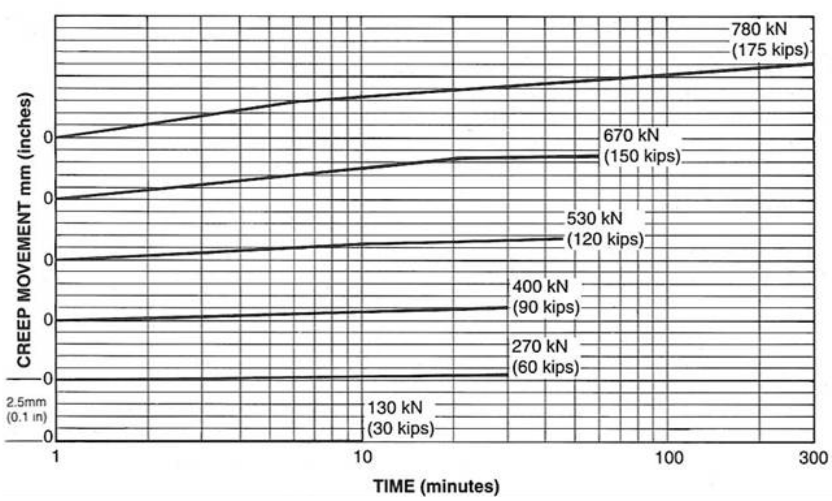

Figure 8.4 Typical Creep Movement Plot (PTI, 2004)

- 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 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 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 (Figure 8.5) 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 (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

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 2003 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.

Section 3 notes special attention is to be paid to handling and storage, insertion, repair, stressing and testing. "These submittals and procedures shall be developed in conjunction with the tendon manufacturer." Emphasis is placed on "thoughtful procedures and quality control measures" "prepared in advance."

Section 4 (Materials) notes that ASTM 882 – 02a allows the minimum coating thickness to be reduced from 25 to 15 mils. A suitable test for epoxy-steel bonding is still being developed. Significantly, recommendations additional to ASTM 882 are provided regarding:

- uniformity of coating
- presence of "craters," and holidays
- reel size (minimum i.d. 0.9 m)
- creep testing (one per 15,000 lin m per project)

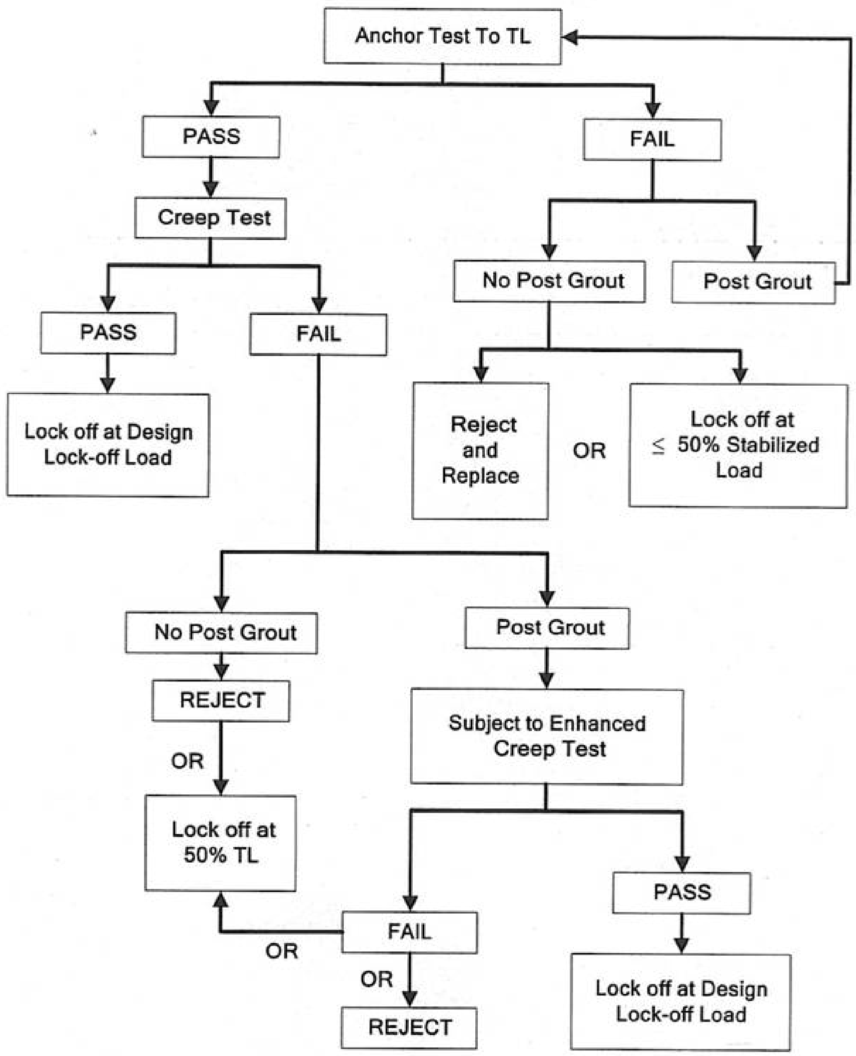

Figure 8.5 Decision diagram for acceptability testing of anchors (PTI, 2004)

Anchorages will be special 3-part types, capable of engaging the steel. Stripping is not allowed.

Section 6 (Design) notes that when sufficient data on creep have been submitted to predict its creep rate, the anchor can be tested to 80% GUTS. If this degree of confidence cannot be established, then the maximum test load shall be 70% GUTS. (There is significantly less creep in the strand at 70%.) Also, the relaxation can be as high as 6.5% in 1,000 hours compared to 2.5% for bare strand.

A minimum free length of 11.5 m recommended "unless special details are employed," to compensate for wedge seating losses (15 to 28 mm as opposed to 3 to 12 mm) with bare strand. This upper 11.5 m shall not be grouted *prior* to stressing even if greased and sheathed, and other measures shall be taken to avoid deviations.

Section 7 (Construction) provides practical guidance on tendon fabrication, storage, handling and installation, including the care and placing of the 3-part wedges. The focus is on component cleanliness, care during handling, steel repair, component alignment, and avoidance of sharp edges and bends.

In Section 8 (Stressing and Testing) the practical flavor is maintained, although a higher degree of quality control and understanding of the wedge seating mechanism is required. Special care is needed during creep testing: "since the creep behavior of epoxy-coated strand cannot be predicted with a sufficient degree of accuracy and consistency, creep acceptance criteria based on the use of correction values shall not be used." The variability in the creep characteristics of the strand from different manufacturers is noted: this range would "swamp" the sensitivity of the corrected value. Instead, three "acceptable options" are tabulated in order of preference (Table S8.1).

Options		Creep Criteria	Test Load as % of F_{pu}	Comments
1	Test to 1.5 *DL*	None	80	No Creep Test is conducted
2	Test to 1.33 *DL*	Same as bare strand	70	Limited test data suggest creep for epoxy-coated strand at this stress level is similar to bare strand
3	Test to 1.33 *DL* and conduct subsequent Lift-off Tests	None	80	Lift-off must be at least the original load minus the predicted tendon relaxation

Table S8.1 Creep Test Options (PTI, 2004)

The Engineer is to specify the option most applicable for the project, i.e., as related to the interpreted creep susceptibility of the ground. Options 1 and 2 will result in a lower permissible tendon stress level at DL, and therefore a greater number of strands.

Option 1 only applies to rock or coarse-grained soil anchors, (design working stress ≤ 53% F_{pu}), as does Option 2.

Option 3 applies for non-creep susceptible rocks and replaces the creep test with subsequent lift-off tests (t = 0, 24 hours and later, depending on the Engineer, with unsatisfactory behavior requiring tests to 30 days). Only experienced personnel should be used.

Note that since these supplementary recommendations were published, at least one supplier have learned to manufacture epoxy-coated strand with creep characteristics very close to those of bare steel. This development may already have rendered this part of the supplement obsolete.

Concluding Remarks

This paper has focused only on the application of permanent rock anchor technology for dam stabilization. The successive sets of recommendations provide an equally clear and interesting picture of soil anchor evolution of the same 30 years, and the interested reader is referred to the documents themselves in this regard. Even with the relatively narrow perspective of this paper, the development of anchor technology provides a long and fascinating story, which is not yet fully refined. By the time the next document is due for publication —2014? — the authors of this paper have no doubt that significant advances will exist to be described.

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