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HOW TO DEAL WITH AGING PRESTRESSED ANCHORS IN DAMS: A NORTH AMERICAN PERSPECTIVE *

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1. INTRODUCTION

Prestressed rock anchors have been installed in dams throughout the world since 1934. In the U.S., the first installation was in 1964. Since then, well over 400 case histories have been recorded by the authors [1] [2] [3]. Practice has evolved over the years, governed by, and reflected in, successive editions of the Post-Tensioning Institute's "Recommendations" documents. Since 1996, virtually all projects have been completed using what may reliably be referred to as "Permanent" anchor systems (i.e., with PTI Class I Protection) and responsive drilling, water testing, and grouting methodologies. However, older-vintage anchorage systems did not generally include corrosion protection systems which would be acceptable today, and did not generally provide the means to measure residual load or the state of corrosion in-situ. This is a challenge facing dam owners throughout the world, since early anchor technology was largely driven by a limited number of European post-tensioning suppliers operating internationally.

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2. THE EVOLUTION OF CONTEMPORARY PRACTICE

2.1 REFERENCEABLE STANDARD OF CARE

There is no standard, per se, for rock anchoring in the U.S. However, the current governing document is "Recommendations for Prestressed Rock and Soil Anchors," Fifth Edition, 2014, published by the Post-Tensioning Institute [4]. This document, like its predecessors, was developed by a Committee of industry specialists and practitioners, an equal blend of consultants, contractors, suppliers, and regulators/ clients (Table1). The previous four editions (1980, 1986, 1996 and 2004) were in fact preceded in 1974 by the "Tentative Recommendations" document for the Prestressed Concrete Institute which, as the breakdown of Table 2 clearly illustrates, was principally a marketing and sales tool whose goal was to present illustrated applications to expand sales volumes of prestressing steel.

Table 1
Number and affiliations of ACI/PTI Prestressed Rock
and Soil Anchor Committee members.

ASPECT	1974	1980	1986	1996	2004	2014
Post-Tensioning Suppliers	6 [†]	4*	4*	2*	3*	4
Anchor Contractors	2	2	3	3	3	3*
Consultants	2	None	1	2	2	2
Owners/Regulators	1	2	1	3	3	3
Sponsor Organizations	1	None	0	1	1	2
TOTAL	12	8	9	11	12	14

- * Including the same Chairman from DSI (Post-Tensioning Supplier).
- † Chairman from VSL (Post-Tensioning Supplier).
- Chairman from Schnabel Foundations (Specialty Contractor).

Table 2
Number of pages of major sections of the PTI Recommendations.

ASPECT	1974	1980	1986	1996	2004	2014
Materials	1	2	2	8	10	10
Site Investigation	0	1	1	1	2	2
Design	2	6 ½	6 ½	12+ Appendix on grout/ strand bond	13	13
Corrosion Protection	1	4	5	10	14	15
Construction	7	9	9	10	15	17
Stressing and Testing	1	6	8	17	18	19
Bibliography/References	0	1	1	1 ½	4	3

(continues)

ASPECT	1974	1980	1986	1996	2004	2014
Applications	16	18	0	0	0	0
Recordkeeping	0	1	1	1 ½	1 ½	2
Specifications, Responsibilities and Submittals	0	1	1 ½	2	2	2
Epoxy-Coated Strand	0	0	0	No separate section	10	10
TOTAL PAGES	32	57	41	70	98	109

In this regard, it may be noted that, in the earlier days of practice in the U.S., anchoring was a technique pioneered by the post-tensioning suppliers themselves, subcontracting out to specialty geotechnical contractors the "dirty bits," i.e., the actual drilling, water testing, tendon placement and grouting processes. This tendency was reversed by the early 1980's: in the U.S. the geotechnical contractors win the projects, buy the steel and frequently rent the prestressing equipment.

Again it is reiterated that industry operates under a set of "Recommendations" provided by an ad hoc committee of a Trade Association, i.e., the Post-Tensioning Institute. However, for liability reasons, industry treats the Recommendations virtually as a standard, and it is very rare for any significant deviation to be found in Specifications or associated Method Statements. In the authors' experience, the "Recommendations" constitute excellent, comprehensive and practical guidance, and stand in very favorable comparison with more rigorous European standards and guidelines.

The Recommendations do not provide guidance on the analysis or overall design of an anchored structure (e.g., selection of number and capacity of anchors, their length, spacing and inclination), for that is the responsibility of the Engineer-of-Record, using well established methods of rock mechanics and structural engineering. The Recommendations address the design, construction, testing and performance of individual anchors.

2.2 EVOLUTION OF PRACTICE

This is covered in detail in the papers contained in the References, and only a very brief summary is provided hereunder, insofar as the points have relevance to the assessment of aging anchors.

2.2.1 Design

Excluding, for the moment, the critical issue of corrosion protection, it may be concluded that most key elements of design have been little changed over the years, and so remain as described in Littlejohn and Bruce's State of the Art Study [5]. It is tacitly assumed that load transfer mechanisms in and around the bond

length are based on uniform bond distribution. Although inaccurate, this is a conservative assumption.

2.2.2 Construction Practices

While most drilling was done in early projects by coring (for fear of somehow damaging the dam, and to extract samples of bedrock in the bond zone), current drilling practice features rotary percussive methods, and especially Down-the-Hole Hammers (DTHH). Grout mix designs, grout blending (in a high speed, colloidal mixer) and placement (always via tremie) have changed only insofar as equipment has improved. Water pressure testing (and pregrouting if necessary) has always been of a high and conscientious standard, and this is of great importance when trying to evaluate the reliability of legacy anchors.

Equally important are the changes to the grouting/stressing sequence:

- (i) Prior to the use of sheathing on the free length of the tendon components, the sequence was:
 - drill, water test (and pregrout and redrill if necessary),
 - place the tendon,
 - grout the bond zone,
 - stress, test and lock-off,
 - grout the free length.
- (ii) After the use of sheathing on the free length of the tendon components, the sequence was:
 - drill, water test (and pregrout and redrill if necessary),
 - place the tendon,
 - grout the tendon completely,
 - stress, test and lock-off,
 - complete underhead grouting.

Most of the early anchors had tendons comprising a multitude (“bundle”) of 6 mm diameter wires (Figure 1). These wires were typically fully bonded to the concrete of the dam by the free length (secondary) grouting after prestressing and lock-off. Thus, such anchors have only grout for corrosion protection and cannot be lift-off tested to establish residual load in the tendon.

2.2.3 Stressing and Testing

Early stressing and testing procedures were surprisingly simple (given the sophistication of the original European post-tensioning specialists), and remained so in the U.S. until the 1996 Recommendations. Thus, it is typical that legacy anchors were quickly stressed to the Test Load in progressive steps, held there for a short period (but without a quantified creep criterion) and then destressed to the lock-off (or “transfer”) load. The benefits of progressive cycle loading, with well-defined criteria for creep and elastic analyses, cannot be exploited when evaluating contemporary records of legacy anchors, while Lift-Off Testing was optional and, in any case, of quite short-term duration (say 48 hours).



The use of different tendon and corrosion protection types with time in N. American dams.

Note: Bar tendons have also been used in lower capacity anchors since the 1970's, with varying degrees of corrosion protection.

2.2.4 Corrosion and Corrosion Protection

References [1] and [2] provide an analysis of the PTI Recommendations to that point (i.e., including the 2004 version) and a summary of over 400 individual case histories. Note that the provisions of the PTI 2014 edition are sensibly the same as in 2004, while the database has recently been further updated [3]. It is extremely important in the context of legacy anchors to gain perspective of contemporary attitudes, and the development of these attitudes with time.

In summary, the anchor grout itself was regarded, during the early decades of practice, as an acceptable barrier to corrosion, for both the bond and free lengths. It was only with the 1996 version of the PTI Recommendations that full-length protection by at least one plastic sheath was required for permanent anchors, i.e., Class I protection, so matching contemporary standards of care in Europe (Figure 1).

3. CHALLENGES TO EVALUATING LEGACY ANCHORS

There are many challenges relating to the design and the construction of such anchors, and to practical/logistical aspects of condition assessment. These challenges are common to dam Owners and Regulators throughout the dam anchor world.

Firstly, it is clear that the majority of dam Owners and their consultants simply did not contemplate at the time of design and construction that long-term monitoring would be advantageous, let alone fundamental to risk management. The general philosophy was that anchors designed and constructed to the standards of the day would not corrode since the steel would be encased in grout, and placed into boreholes whose immediate proximity was pregrouted (to prevent water ingress and to prevent anchor grout loss). The anchor head itself was generally encased in concrete. Further, in acknowledgement that the tendon would naturally suffer long-term stress loss (principally due to relaxation), the post-tensioning specialists selected Lock-Off/Transfer Loads, which included an allowance for these losses, the magnitude and rate of which were well known from structural post-tensioning projects. Such elevated tendon stress levels, while (usually) still within the elastic response range (i.e., $\leq 80\%$ fpu), would however increase the tendency for stress-induced corrosion to be initiated or accelerated under certain conditions. No provisions were made for installing restressable anchor heads.

Secondly, it was exactly these old methods which have now rendered lift-off testing unfeasible: without a developed free length, it is impossible to directly measure the residual load in the tendon, or to determine its distribution within the free length or, of course, the bond length.

Thirdly, it is often the case that the anchor heads are, for all practical purposes, inaccessible for any type of inspection or testing. In some cases, the functional anchor heads could be rendered accessible, but there would be a natural reticence to "probe too deeply" for fear of disturbing the anchor head – not so much from a load holding viewpoint, as the tendon is fully bonded below, but from the corrosion protection viewpoint. This is particularly the case with legacy anchors which do feature a greased and sheathed coating as a bond

breaker to preserve the true free length even when surrounded by grout. In this case, the load is still maintained by the gripping wedges in the head (in the case of strands), or by the lock nut (in the case of bars), and attempts to expose such heads, or indeed to attempt, somehow, a lift-off test, would be inviting trouble.

Fourthly, strain gages or load cells of adequate reliability were simply not available to provide long-term monitoring capability, and indeed are still not available today. Compounding this issue is the stark fact that there is still no completely reliable, calibrated NDT Method that can be used to check the residual load, or the integrity, of wire or strand tendons, fully grouted or otherwise. It may be noted, however, that some recent methods are showing promise for bar tendon assessments.

Fifthly, contemporary construction records may not always be available for review and, even if they are, they may not contain vital pieces of information, the clues to the likely adequacy of the construction details to preventing long-term corrosion. A case in point here would be the static (bleed) and dynamic (pressure filtration coefficient) stability properties of the grouts: if either property were deficient, then bleed pockets would develop, especially in the tightly arranged "bundles" of wires so common in early legacy anchors.

Sixthly, it is not uncommon for Owners to consider somehow exhuming production anchors and then closely examining the tendon for signs of corrosion. Exhumation is feasible if the dam is being deconstructed for decommissioning. This is a relatively rare occurrence and of course is not an option for evaluating legacy anchors in dams required for extended, long-term service. Alternatively, it is technically feasible – if sufficient access exists to allow for the mobilization of a major piece of drilling equipment – to overcore the entire anchor and remove it for inspection. However, this is a very difficult and typically costly option since the drilling method must be precisely colinear with the anchor, and the tendon will not permit the anchor to be removed in convenient "runs," for example, of 1.5 or 3.0 m. Furthermore, the grout is typically damaged or lost in the drilling process, and the concern will remain if the particular anchor removed is actually representative in its condition of the others, or if any localized corrosion-induced damage will indeed be recognized.

As a final point, it is easy to be critical of the contemporary standards used in the design and construction of legacy anchors. However, at the time of their installation, design lives of 25-30 years were considered satisfactory, whereas some of these installations are now over 50 years old. "Modern" anchors (with Type I Corrosion Protection) are children of the late 1990's, and a great deal of knowledge has been accumulated since then fuelled, in part, by our current attitudes to risk assessment such as inherent in the Potential Failure Modes Analysis process.

4. KEY FACTORS IN RISK EVALUATION DURING A PORTFOLIO RISK ASSESSMENT PROCESS

In the case where an Owner is responsible for a number of projects dependent for stability on prestressed rock anchors, it is logical and essential to conduct a preliminary screening process to identify and prioritize the most worrisome projects. This is akin to the process first adopted by the U.S. Army

Corps of Engineers in 2005-2006 to allocate a Dam Safety Action Category (DSAC) number (I to VI) to each of its portfolio of over 600 structures. This categorization process then allowed attention to be paid to the "worst first" dams (i.e., DSAC I) in terms of the need for Interim Risk Reduction Measures (IRRM's) to be emplaced pending the design and construction of Permanent Risk Reduction Measures in the form of Dam Safety Modifications (DSM's). For the typical dam Owner, the number of dams to be evaluated can be reasonably covered by the same dedicated team, so assuring a very even-handed, and uniform quality of assessment of the portfolio. Such an approach has recently been adopted widely, including as an important example, by the Tennessee Valley Authority.

The Portfolio Risk Assessment process for aging anchors in N. America is a desk study in which the following steps should be taken, in sequence:

Step 1. Determine the date of anchoring, and the edition of the PTI (or ACI) Recommendations under which the anchors were installed. The following risks can be allocated as a "first cut":

- All anchors installed prior to PTI (1986): High Risk
- Anchors installed 1986-1996 prior to PTI (1996): Moderate Risk
- Anchors installed post-1996 after PTI (1996): Low Risk

It should be noted that practitioners often continue to use an "old" edition of PTI for say 2 years after the "new" edition has been issued. So it would be prudent to amend the "High" category limit from 1986 to 1988, and the "Moderate" category from 1988 to 1998.

Step 2. Beginning with the oldest anchor project in the High Risk Group, very carefully examine all historical records for that project. In particular, the type of tendon (wire, bar, or strand) and the type of corrosion protection (if any, other than cement grout) should be identified. In addition, whether or not a free length actually remains or whether the free length steel is fully bonded to the concrete should be established, together with an understanding of the anchor head protection detail.

Anchors installed with no corrosion protection other than the grout are highest risk, together with anchors whose heads were encased in material other than grout or concrete (e.g., grease, or indeed without any protection). Anchors with no remnant free length, as typified by the multiwire "button head" tendons, cannot have their integrity or residual load measured, even if the heads are accessible.

The source details include the project specifications, the contractor's method statement and construction records, construction photographs, and any information or observations on post-construction testing or performance.

For High Risk anchors, without sheathing or coating on the free length, a consideration of the intensity and quality of the pregrouting should be conducted. If none were conducted, the risk of long-term corrosion occurring is greater than if intensive pregrouting had been conducted.

Step 3. Beginning with the prioritized list created by Steps 1 and 2, review the original overall anchor design to judge exactly how vital the anchors are to overall stability, and how much overall prestress can be lost (to corrosion, relaxation and creep) before the structure does not meet contemporary standards of care, for sliding and/or overturning, or other loading conditions.

Step 4. Focusing, then, on the "High Risk" list created by Steps 1-3, the Owner/ Regulator must then make a risk-based decision regarding actions to be taken on these projects. Owners with a very low risk tolerance will elect to ignore the legacy anchors and replace them entirely (if space and access permit).

Owners who can tolerate a higher risk may elect for either partial replacement, or indeed for no further post-tensioning at all, and some type of "observation" strategy.

Step 5. Once the "High Risk" projects have been evaluated thus, then the same process can be applied to the "Moderate Risk" projects. Such projects may also afford the possibility of conducting lift-off tests provided the free length is sheathed, the anchor head is accessible, and the field testing will not adversely affect the structural performance of the locking assembly (especially for wedges for strands) or its corrosion integrity.

This process is summarized in the flow diagram (Figure 2) which focuses on high risk legacy anchors. Thus, a project which scores "high-high-high-high-high" in each risk category will have a more urgent need of further action/evaluation, than one which scores, for example, "high-high-high-moderate-low." This figure only shows the flow path for the highest risk anchors.

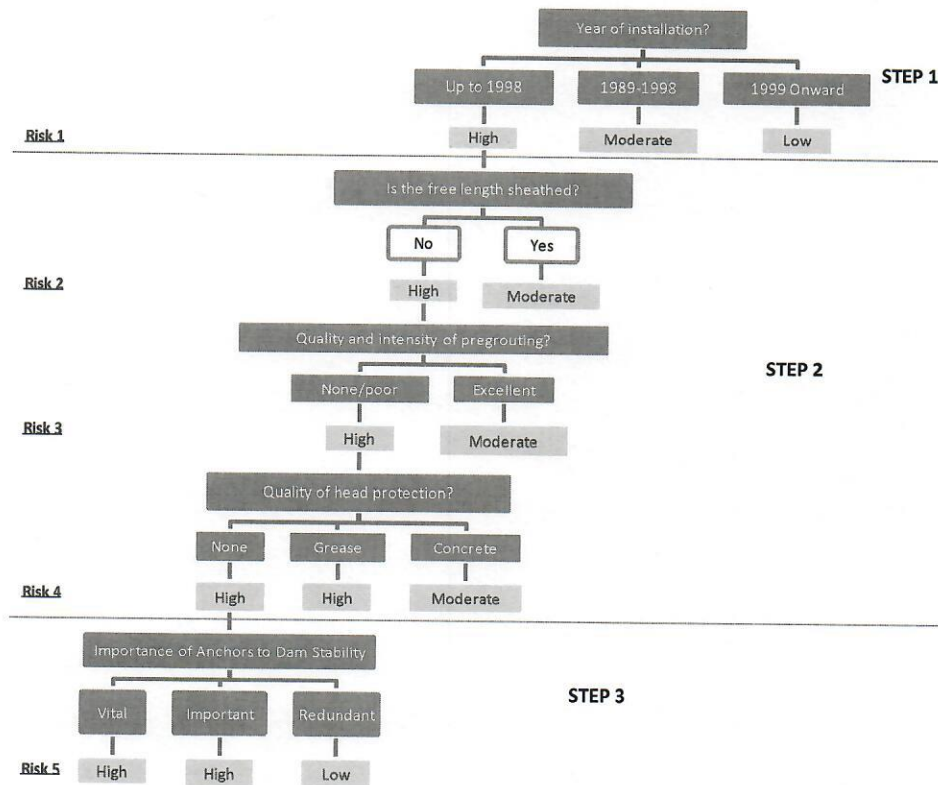


Fig. 2
Flow chart for screening portfolio risk assessment of aging anchors.

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SUMMARY

The evolution of practice in the design and construction of prestressed rock anchors for North American dams is described. This provides background to the problem of assessing the reliability of aging anchors, principally those installed prior to 1996. This review is based on the results of a study of over 400 case histories of projects completed since 1964.

L'évolution de la pratique courante en conception et construction avec ancrages précontraints dans le roc pour les barrages nord-américains est décrite dans cet article. Il fournit le contexte du problème d'évaluation de la fiabilité des ancrages en service, majoritairement ceux installés avant 1996. Cette revue s'appuie sur plus de 400 études des cas des projets achevés depuis 1964.

KEYWORDS

Aging, anchorage, concrete dam, inspection, prestressing, risk assessment.

Vieillessement, ancrage, barrage en béton, visite, précontrainte, analyse de risque.