

## 2. Prestressed Rock Anchors for Dams: U.S. Experience and Practice

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Growing Fundamentals & Current Practice

April 24 - 27, 2023  
Bundeswehr University Munich

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## Agenda

- History of Anchor Usage in North American Dams
- Evolution of Best Practices:
  - Design
  - Construction
  - Stressing and Testing
- Notable Influential Case Histories
- Long Term Performance Assessment and Portfolio Risk Assessment of "Legacy Anchors"

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## 1. History of Anchor Usage in North American Dams

Histogram of US Dam Construction (1950-2004)

Interim Release Work in Progress

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## Table 1. Number and affiliations of Post-Tensioning Institute's Anchor Committee members.

| ASPECT                    | 1974      | 1980     | 1986      | 1996      | 2004      | 2014      |
|---------------------------|-----------|----------|-----------|-----------|-----------|-----------|
| Post-Tensioning Suppliers | 2*        | 4*       | 4*        | 2*        | 3*        | 1         |
| 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         |
| <b>TOTAL</b>              | <b>12</b> | <b>9</b> | <b>10</b> | <b>11</b> | <b>12</b> | <b>11</b> |

\* Including the same Chairman from PDI (Post-Tensioning Suppliers)  
 \* Chairman from NAD (Post-Tensioning Suppliers)  
 \* Chairman from National Foundations (Specialty Contractors)

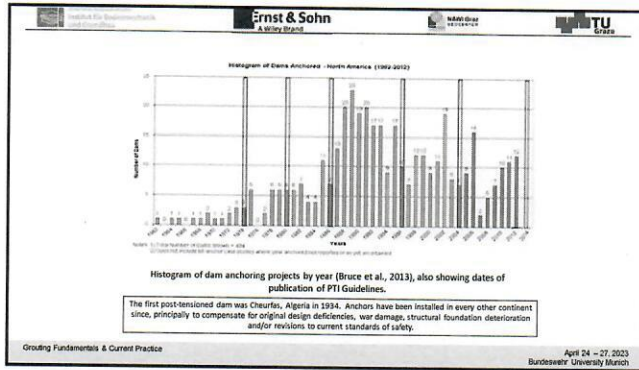
## Table 2. Number of pages of major sections of the Recommendations.

| ASPECT                           | 1974      | 1980      | 1986      | 1996      | 2004      | 2014      |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Investigations                   | 2         | 1         | 1         | 2         | 1         | 1         |
| Design                           | 2         | 40        | 40        | 12        | 13        | 13        |
| Construction                     | 1         | 3         | 4         | 11        | 14        | 15        |
| Stressing and Testing            | 1         | 1         | 1         | 1         | 1         | 1         |
| Performance References           | 1         | 1         | 1         | 1         | 1         | 1         |
| Appendices                       | 1         | 1         | 1         | 1         | 1         | 1         |
| Recommendations                  | 1         | 1         | 1         | 1         | 1         | 1         |
| Recommendations and Supplemental | 1         | 1         | 1         | 1         | 1         | 1         |
| <b>Grand Total</b>               | <b>11</b> | <b>58</b> | <b>59</b> | <b>39</b> | <b>42</b> | <b>43</b> |
| <b>TOTAL PAGES</b>               | <b>12</b> | <b>63</b> | <b>61</b> | <b>50</b> | <b>58</b> | <b>60</b> |

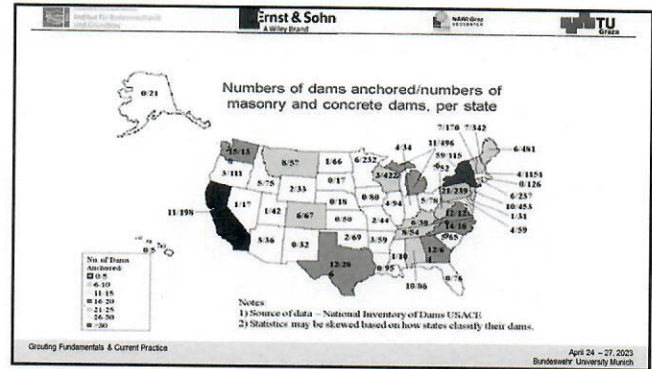
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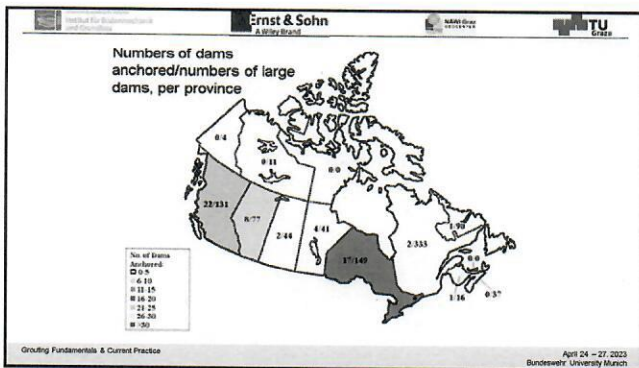
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## 2. Evolution of Best Practices

### 2.1 Design

General Note: All aspects, except overall stability and system design, are covered best in the Recommendations of the Post Tensioning Institute (2014), and are little changed from Littlejohn & Bruce (1977).

#### 2.1.1 Overall Stability (i.e., Resistance to pull out)

- Conventional – and very conservative – to assume submerged “weight of rock” in a cone. The apex of the cone is typically assumed to be at the mid point of the bond length, with a 90° included angle. Individual cones transform into slabs in closely spaced anchors.
- Few designs consider the rock mass structure in dictating failure volumes, or friction across the assumed surface.
- See Hobst & Zajic (1977): no one else has!

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2.1.2 Bond Length

Approach:  
Uniform bond distribution  
0.9 MPa



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- Permissible geotechnical bond values are selected from
  - PTI, and other published sources
  - Prior experience
  - Site specific testing
- Geotechnical bond invariably governs design of bond length (not grout/tendon bond for clean steel)
- Bond lengths over about 10m are progressively less load efficient (bond is not uniformly distributed in all except the strongest rock masses: controlled by E rock to E grout ratio)



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2.1.3 Tendon Design

- Stress at Test Load must never exceed 80% GUTS.
- Stress at Working Load typically 50 – 66% GUTS, thereby allowing test factors of safety of  $\geq 1.33$ .
- Lock-off Loads are typically 60 – 70% GUTS but can be much lower in certain conditions (e.g., AAR structures).
- Bar v strand selection depends on site logistics, load, and length. Typically multistrand tendons are required for dam anchors.
- Details provided in PTI (2014).



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2.1.4 Corrosion Protection Design

- For permanent anchors (i.e., service life over 2 years), Class I Protection is required, per PTI (2014).
- Components may include corrugated ducting, greasing and sheathing and/or epoxy coating/epoxy filling.
- Design must always be the task of the Engineer of Record.
- Historically ineffective/unreliable corrosion protection has given rise to the "legacy anchor" problem, discussed in Part 4 of this Presentation.



Courtesy of N.C.C.

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## 2.2 Construction Processes

### 2.2.1 Drilling

1970's:

- Diamond drilling in concrete and occasionally in rock
- Rotary or rotary percussive in rock
- Deviation monitoring ( $< 1$  in 100)
- Pressure grouting and redrilling if watertest failed
- Maintain full manual logs

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Now:

- Diamond drilling only used for reinforced concrete or very weak structures
- Use of down-the-hole hammer prevalent
  - Deviation control
  - Speed
  - Vibrations/pneumatic fracture
- MWD common

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### 2.2.2 Water Pressure Testing

1970's:

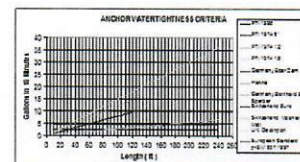
- Full length test
- 2 l/min at 0.4 Mpa
- Very conservative criterion: most holes had multiple regouts and redrills

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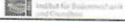
Now:

- Knowledge of fissure control on permeability
- 10.3  $\ell$  at 0.04 Mpa over 10 minute period
- Testing of corrugated protection also



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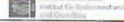



### 2.2.3 Tendon Placement

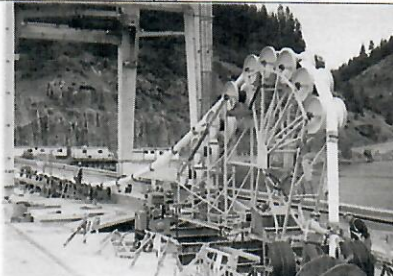
- Method is project-specific.
- Goal is to install in a controlled and safe fashion to minimize potential for damage to the tendon and its corrosion protection.
- The following slides were provided by Mr. Paul Krumm of Nicholson Construction Company.

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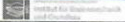




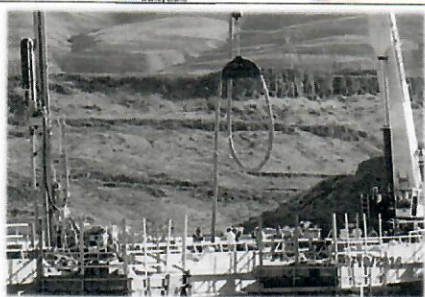



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### 2.2.4 Grouting

1970's:

- Proprietary non-shrink grout for first stage
- Water:cement ratio  $\leq 0.45$
- Pre-construction testing of mixes
- High speed, high shear mixer
- Tremie grout



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Now: Same except:

- No use of preblend cements
- Focus on fluid property testing, as opposed to cubes
- Often single stage grouting
- Preproduction testing



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### 2.3 Stressing and Testing

1970's:

- Progressive simple loading to 115% Design Working Load (to maximum 80% GUTS)
- Alignment Load of 10% Test Load
- No cycling
- Very little data recording required or analysis described (Read extension only at Test Load)
- Lock off at 50 to 70% GUTS
- Lift off test
- No creep test



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VDI 2230  
STEEL DESIGN



TU  
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Now:

- Proof and Performance Tests
- Analysis of elastic movement data
- Creep testing: short and extended
- Lift off testing
- Lock off  $\geq 60\%$  GUTS
- Special provisions for epoxy coated strand
- Clear acceptance criteria and “rework” guidance

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graph TD
    Start([Anchor Pass To T1]) --> P1{PASS}
    Start --> F1{FAIL}
    P1 --> C[Concrete Test]
    F1 --> NP[Non-Pass Concrete]
    F1 --> PC[Point Cloud]
    C --> P2{PASS}
    C --> F2{FAIL}
    P2 --> L1[Lock off at Design  
Lock off Loose]
    F2 --> NP2[No Point Cloud]
    F2 --> R1[Rejected]
    NP --> R2[Rejection measure]
    NP --> L2[Lock off at Design  
Lock off Loose]
    PC --> D[Design/Enhanced  
Control Time]
    PC --> L3[Lock off at Design  
Lock off Loose]
    D --> L4[Lock off at T2, T1]
    D --> L5[Lock off at Design  
Lock off Loose]
    L4 --> O1{OK}
    L4 --> R3[REJECT]
  
```

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## 3. Influential Anchor Projects

### 3.1 PhD Thesis (1973 – 1976)




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3.2 Tarbela Dam, Pakistan (1979 – 1980)



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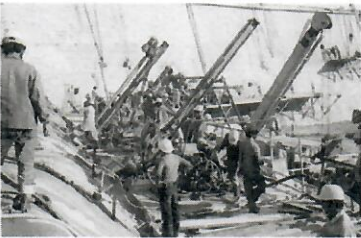
Sevice Spillway, protected by RCC and 1200 (invisible) high capacity anchors.

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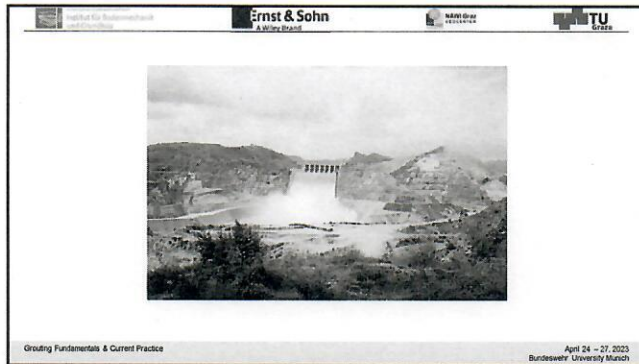
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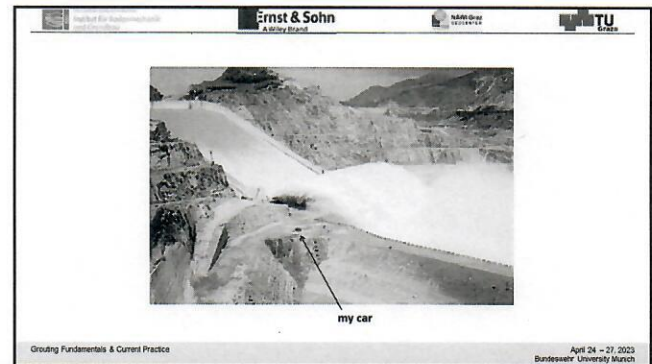
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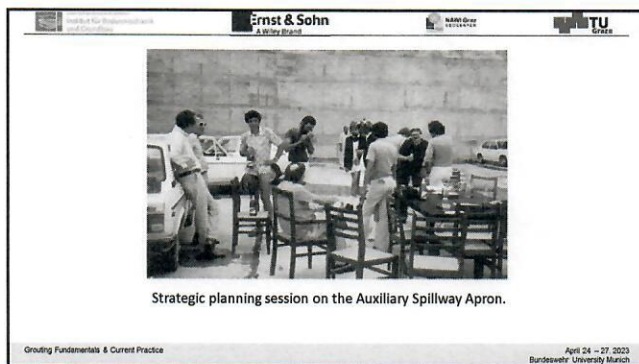
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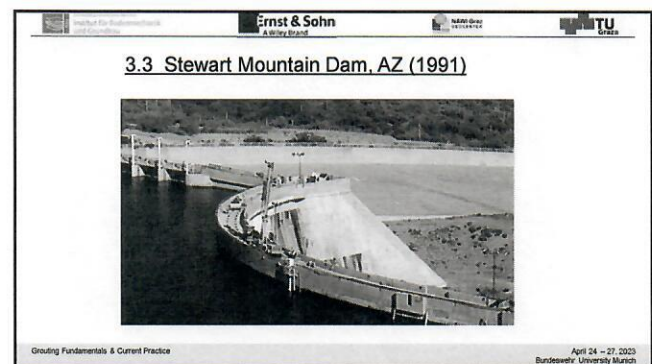
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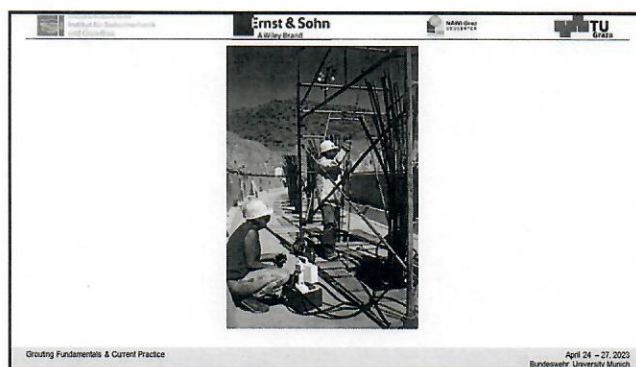
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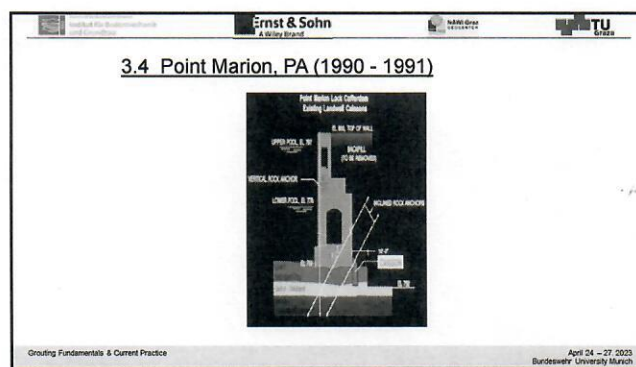
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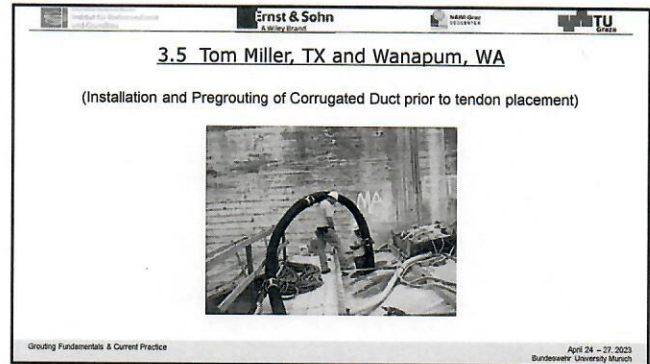
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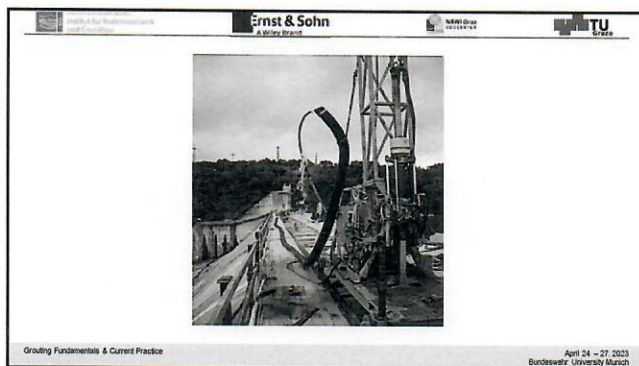
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4. Long Term Performance Testing and Portfolio Risk Assessment of "Legacy Anchors"

4.1 Evolution of Corrosion Protection Concepts

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1960s – 1970s  
Bare Strand/Wire Throughout

- Tendon proposed/selected by Contractor/PT Supplier (wire, strand, bar).
- Grout conceived to be the only protection: 2 stages essential.
- Fully bonded, and so no long-term load monitoring capability.

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1970s – 1980s  
Greased and sheathed free lengths, bare strand on bond length.

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1990's Onwards

Epoxy-coated and filled strand with or without grease sheathed free length. Typically require special handling and installation methods.

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Photo 5-26

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### Corrosion Protection Requirements

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

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Figure 5.2a - Class I protection: encapsulated strand anchor (PTI 2034)

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Figure 5.2b - Class II protection: encapsulated strand anchor (PTI 2034)

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Based on the results of our database of dam anchor projects, we conclude:

- About 60% of the existing anchors in N. American dams were installed prior to Class I protection becoming mandatory in 1996. This defines "legacy" anchors.
- Early anchor technology was driven by post-tensioning suppliers and specialists, and not geotechnical contractors, as now.
- The problem is worldwide.
- There is no single, easy, technical answer, and different owners have different risk tolerance levels. Therefore owner attitudes range from total replacement to "turn a blind eye."

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#### 4.2 Challenges to Evaluating Legacy Anchors

1. Most owners and consultants simply did not contemplate at time of design and installation that long-term monitoring would be advantageous, let alone fundamental. Therefore, no provisions for installing restressable or retestable anchor heads.



2. Fully grouted tendons without a sheath around the free length cannot be lift-off tested to measure residual load.

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3. Anchors heads are usually concreted in, and/or are physically inaccessible.
4. Reliable and accurate strain gages and load cells were not available for incorporation into legacy anchors.
5. Contemporary construction records are not always available, or do not include vital information on construction techniques or materials (e.g., static and dynamic stability properties of the grout).
6. Exhumation of legacy anchors is technically very difficult and is costly. However, there is recent promising information from U.S. exposures, and Australian extractions.
7. Design lives of 25-30 years were originally foreseen; many legacy anchors are over 50 years old, and current longevities are up to 100 years.
8. No reliable NDT method has yet to be brought to a level where it can be used routinely or economically. Three show promise: Dispersive Wave Technology; Ultrasonic Testing; and "Performance-Based Evaluation" Techniques.

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#### 4.3 Key Factors in Risk Evaluation During the Portfolio Risk Assessment Process

- Dam owners typically have a portfolio of several dams. Each dam cannot, for financial reasons, be remediated at the same time. However, all anchored dams can be evaluated to the same standard of care in a brisk risk assessment process.
- Risk-based priority screening is the first step – the model being the USACE's Screening Portfolio Risk Assessment (SPRA) Program of 2005-2006. The outcome is to prioritize a "worst-first" risk list of projects.
- This must be accomplished by a consistent, multi-skilled team ("cadre") who will apply a common standard of care across all project assessments.
- This SPRA is primarily implemented as a series of desk studies. The outcome of such studies will determine the next strategic steps, such as field observation, some type of field residual load/corrosion condition testing (may be impossible), or NDT Testing (may not be reliable).

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Therefore, the desk study (Screening Portfolio Risk Assessment) process is fundamental, the goal being to prioritize projects which have an unacceptable likelihood of having been compromised by corrosion of the anchor system.

The successive, key factors for evaluation in this Assessment are:

- Factor 1:** Date of anchoring, and so the controlling PTI Recommendations (being the Referenceable Standard of Care).
- Factor 2:** Review of construction records to identify the details of corrosion protection (including the intensity and standard of borehole pregrouting).
- Factor 3:** Review of original anchor system design and prestress demands to establish the degree of dependency on the anchor system.
- Factor 4:** Making then an informed decision about the risk to the project of inferior legacy anchors.

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This can be illustrated in the following flow diagram. Highest risk anchored dams will fall in the "5 high" limb. After these projects have been dealt with (typically by re-anchoring the dam), then the "high-high-high-moderate" category is assessed.

Figure: Flow chart for Screening Portfolio Risk Assessment. (Only the high risk branch is shown for clarity.)

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#### 4.4 Ongoing & Future Study Research

- Current CEATI Study (2017 – 2022) with John Wolfhope
  - Review of past case histories
  - Review of past research projects
  - Interviews with key owners
  - Update database of projects
  - Development of "path forward" / "best practice" guidelines
- Future Research Opportunities
  - Exhumation upon dam decommissioning
  - Overcoring and extraction
  - Optimization of NDT testing potentials
  - Sharing of national and international concepts and information
- Challenge
  - Finding a platform to fund and publish new findings

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### What's Wrong with this Picture?

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