ROCK ANCHORS – THEN AND NOW

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GEOSYSTEMS, L.P
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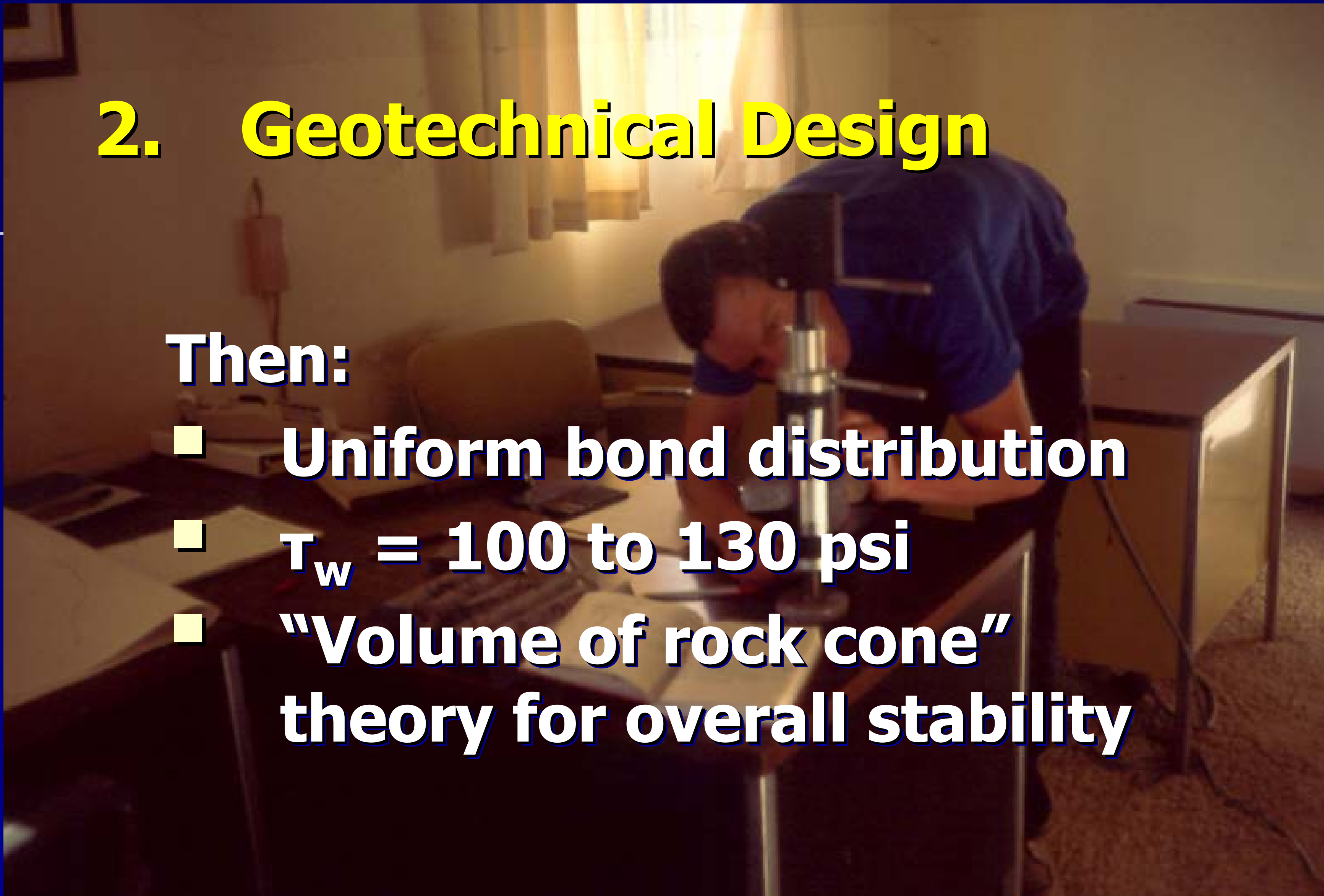
6. Overview

1. Background

- Large dam, Pacific Northwest
- 142 vertical anchors installed in 1975, to resist sliding
- "Button head" wire tendons, total length 55 to 168 feet.
- Design Working Load 205 to 1490 kips
- Long term performance monitored via 4-wire "minitendons"
- Original records available, permitting comparison with current PTI (1996) Recommendations

2. Geotechnical Design



Then:

- Uniform bond distribution
- τ_w = 100 to 130 psi
- "Volume of rock cone" theory for overall stability

Now:

Exactly the Same!

However…

Anchor Design Approach from Piling

Ultimate load = Ultimate bond stress x Bond area

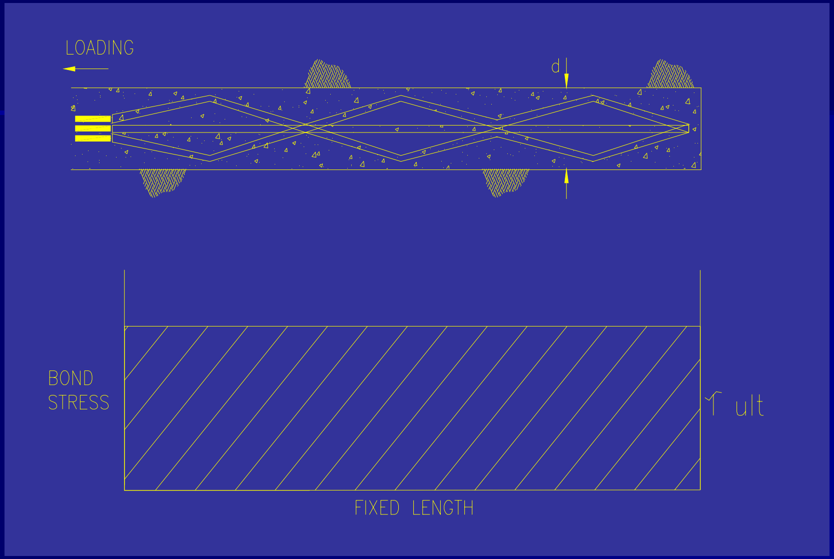
Bond area = π x Diameter x Bond length

therefore

Ultimate load ∝ Bond length

Normal Anchor Design

ASSUMPTION

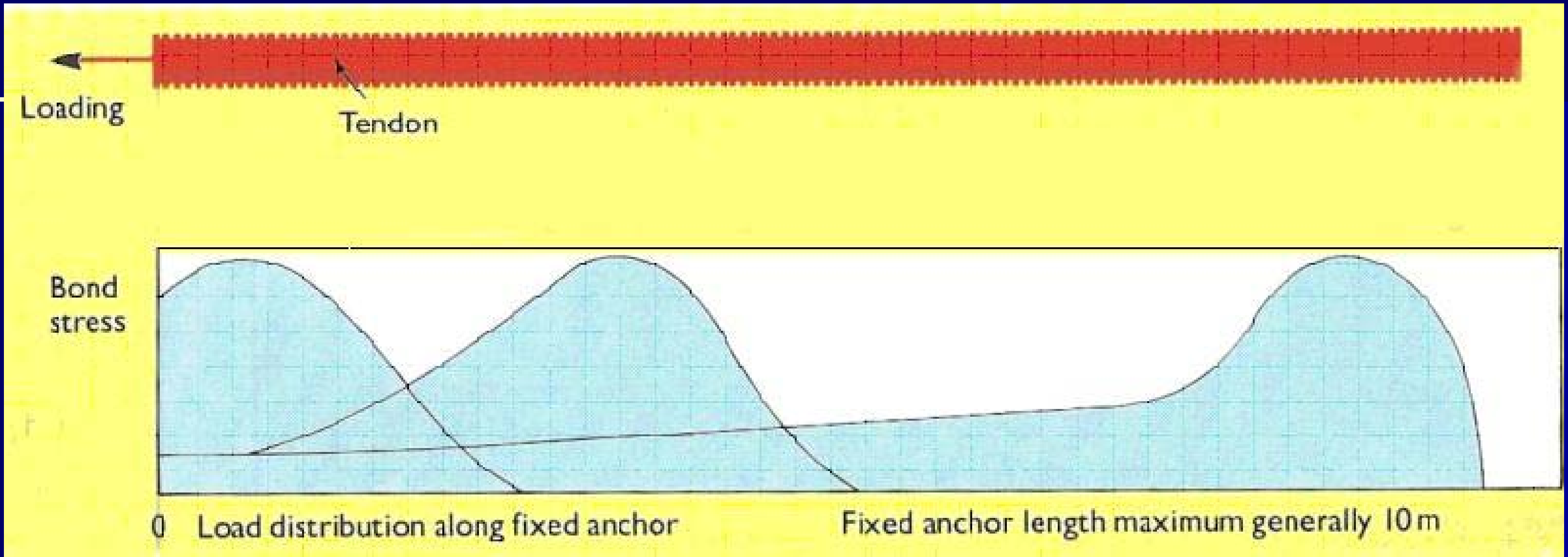


Stress distribution of a simple design approach

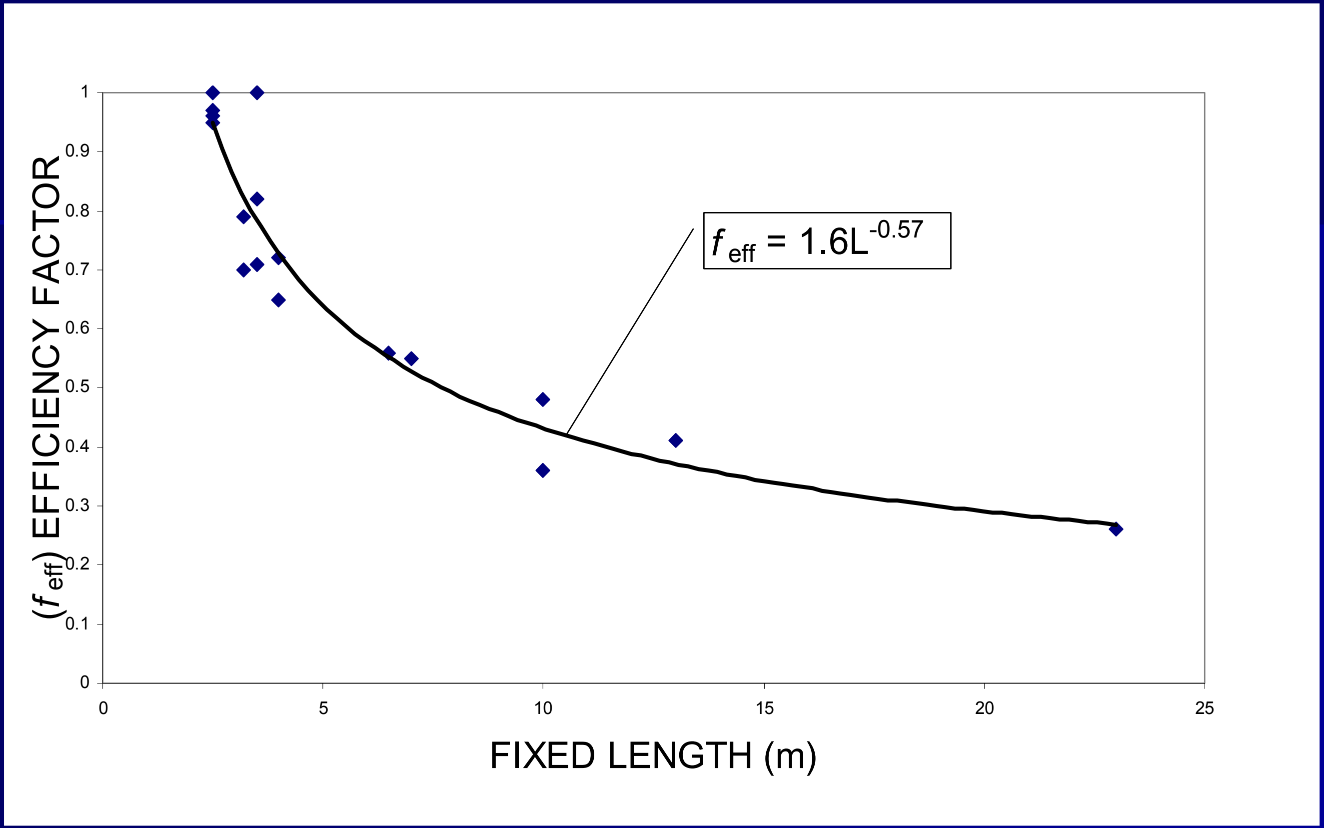
Ultimate load = $\pi \times d \times L \times \tau_{ult}$

This means load ∝ fixed length

This is <u>not</u> a true statement.



Actual normal anchor load distribution during loading



Distribution of anchor efficiency with fixed length showing best fit curve (Barley, 1995)

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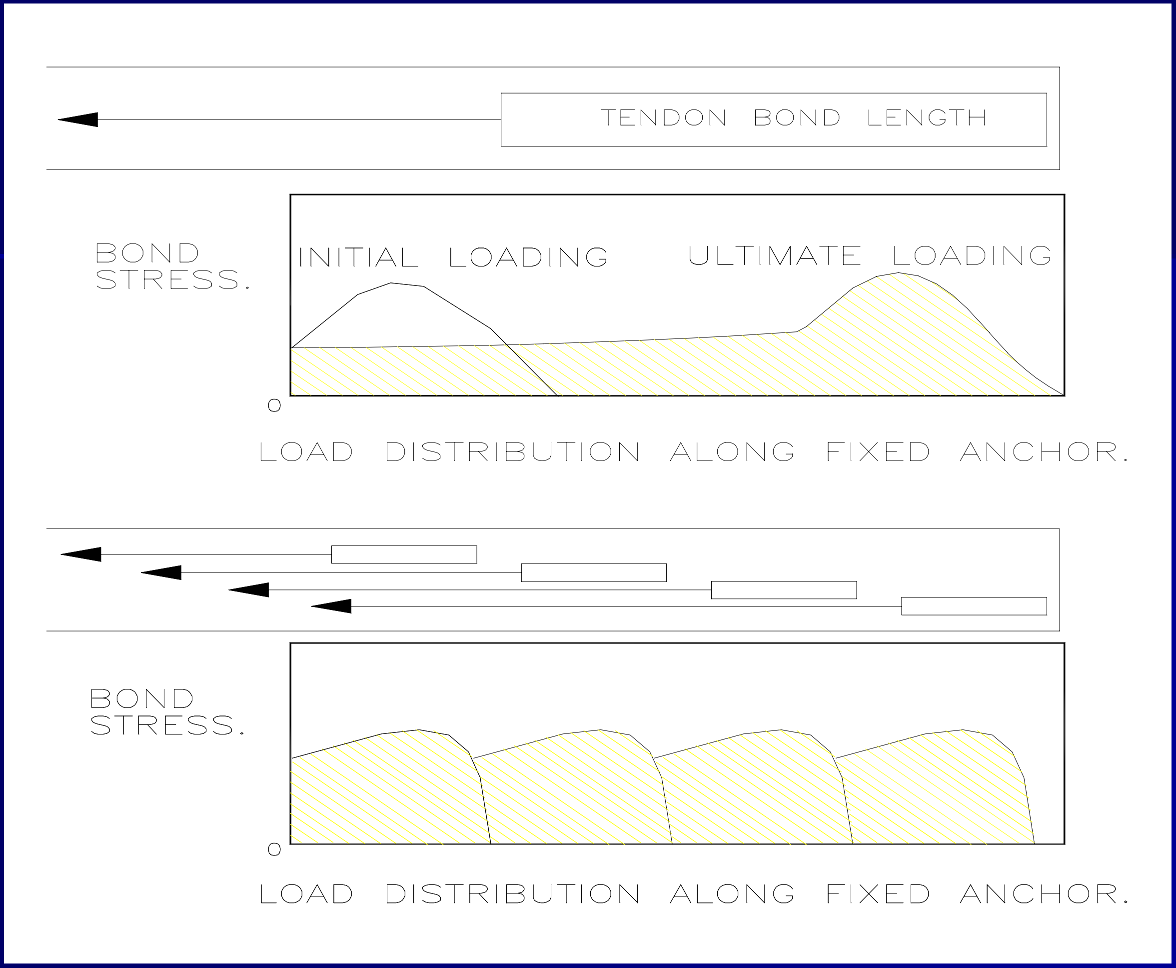


Comparison of the load distribution of a normal anchor with that of an early single bore multiple anchor

Normal 10 m anchor capacity vs. 10 m Multiple anchor capacity comprising four 2.5 m units

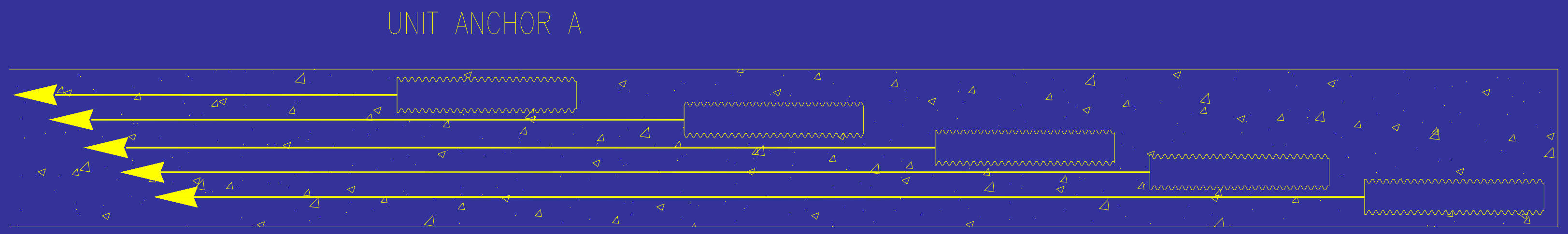
10-m Efficiency factor = 0.43

2.5-m Efficiency factor = 0.95

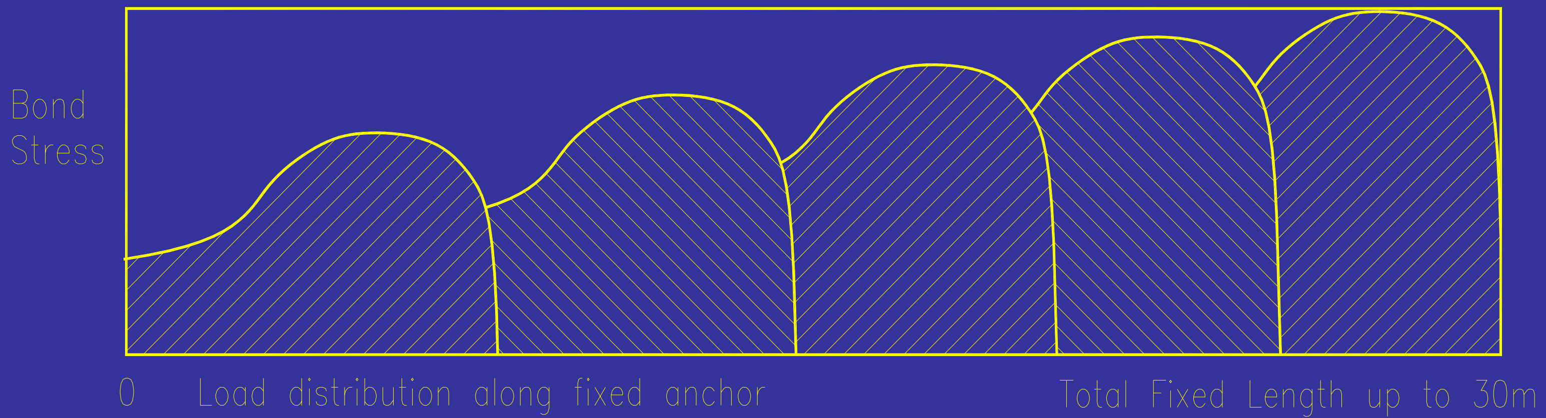
Therefore, SBMA has

0.95/0.43 = 2.2 x normal anchor capacity in same borehole

Load distribution developed in a SBMA



Where ground Strength improves with depth



Realistic consideration from circa 1992

3.1 Drilling

Then:

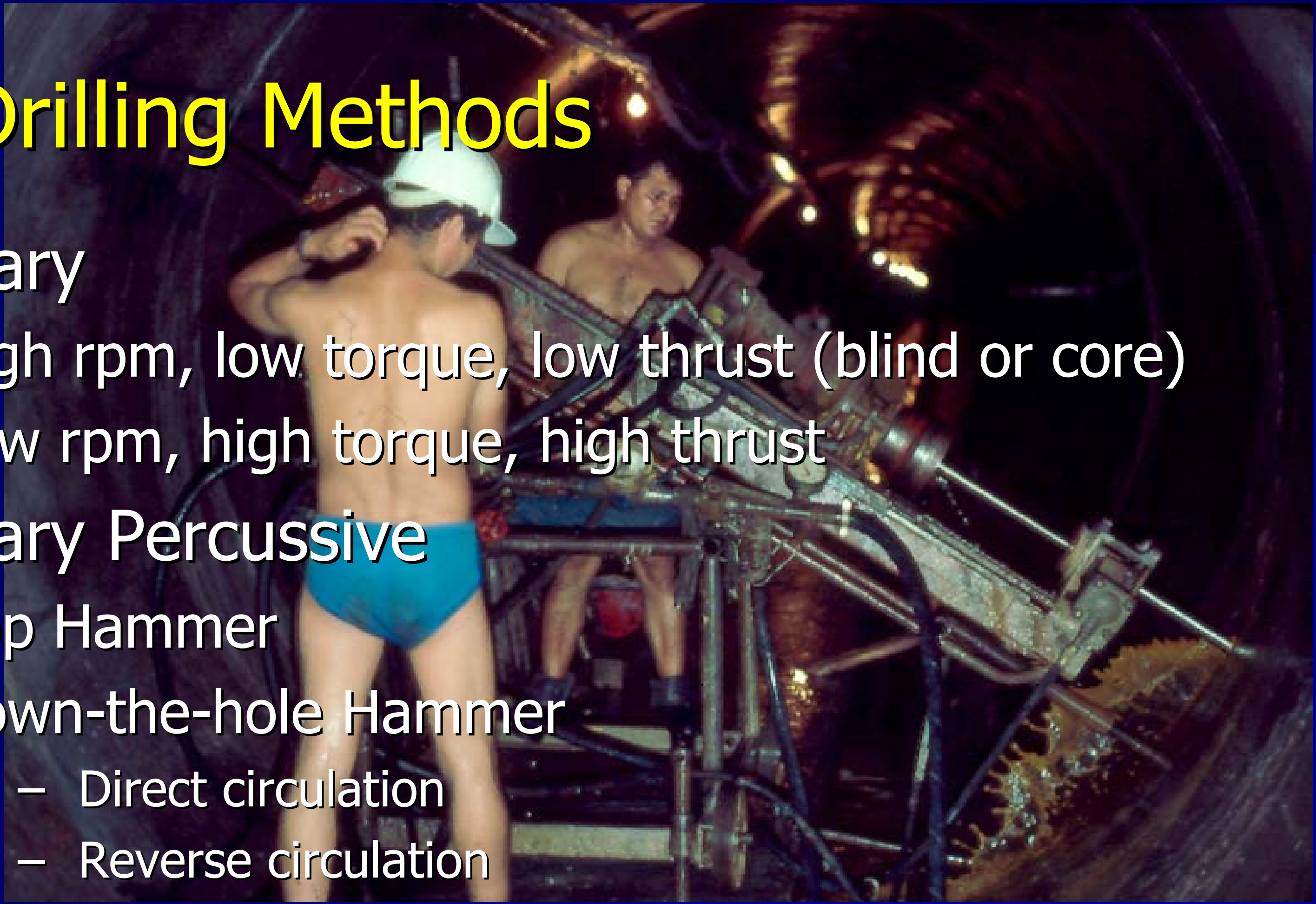
- Diamond drilling in concrete
- Rotary or rotary percussive in rock
- Deviation monitoring (< 1 in 100)
- Pressure grouting
- Maintain full logs

3.1 Drilling

Now:

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

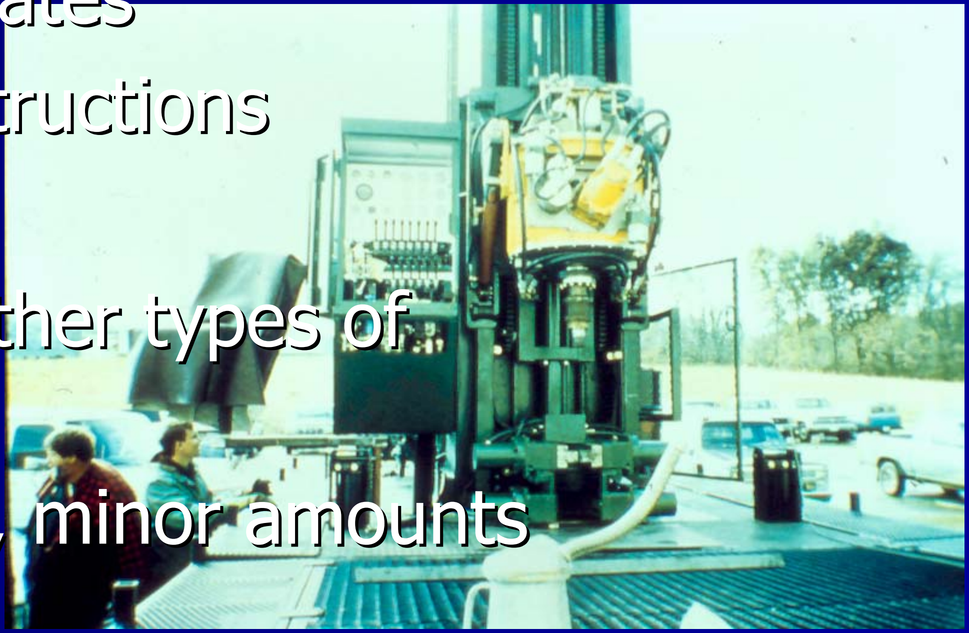
Rock Drilling Methods



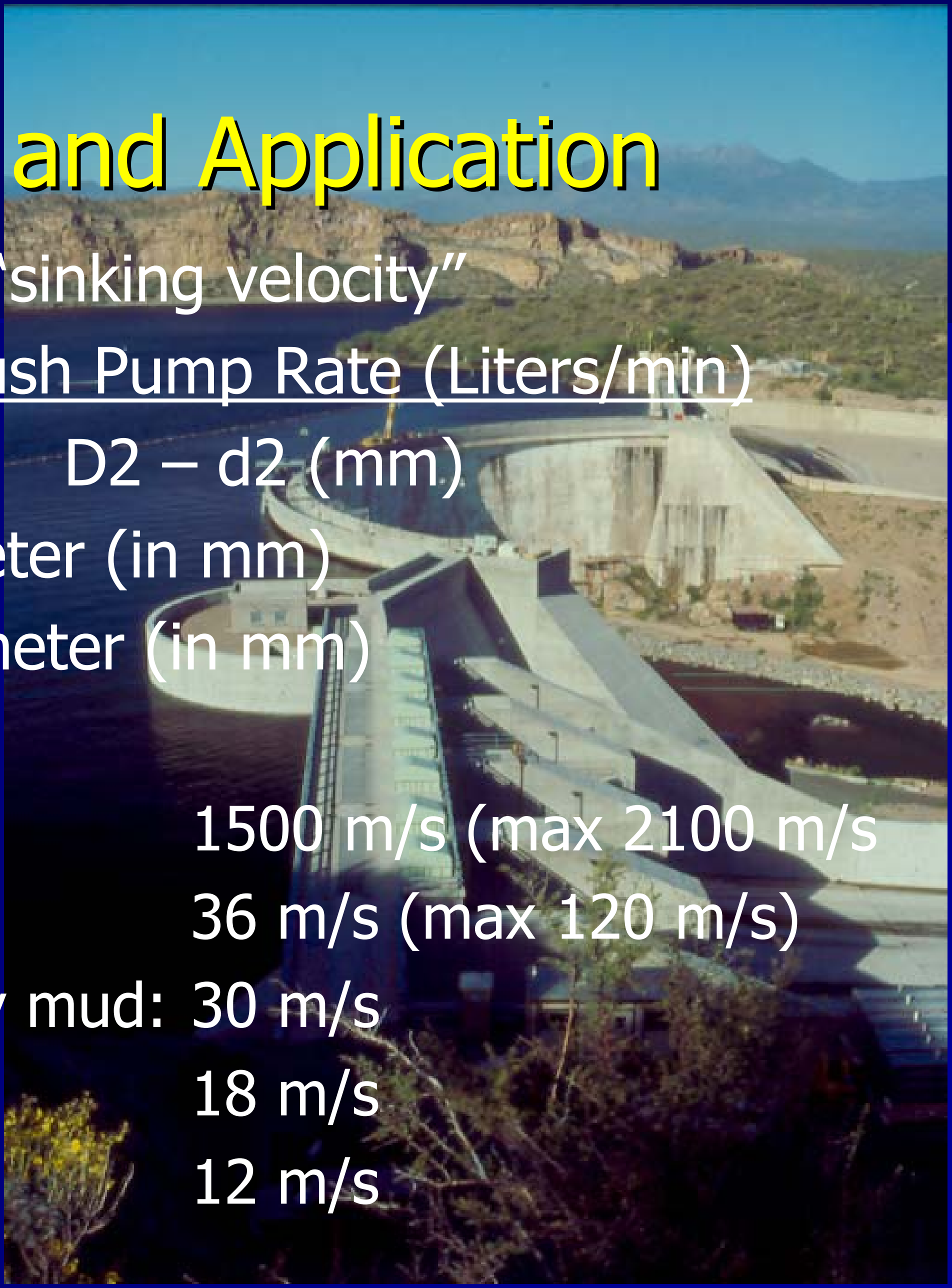
1. Rotary
   - High rpm, low torque, low thrust (blind or core)
   - Low rpm, high torque, high thrust
2. Rotary Percussive
   - Top Hammer
   - Down-the-hole Hammer
     - Direct circulation
     - Reverse circulation
     - Dual fluid drilling
     - Water hammers
3. Rotary Vibratory (Sonic)

Sonic Drilling: Advantages

- Can provide continuous, relatively undisturbed cores in soil (75-250 mm diameter) and rock
- Very high penetration rates
- Readily penetrates obstructions
- Depths to 150 m
- Can easily convert to other types of drilling
- No flush in overburden, minor amounts in rock



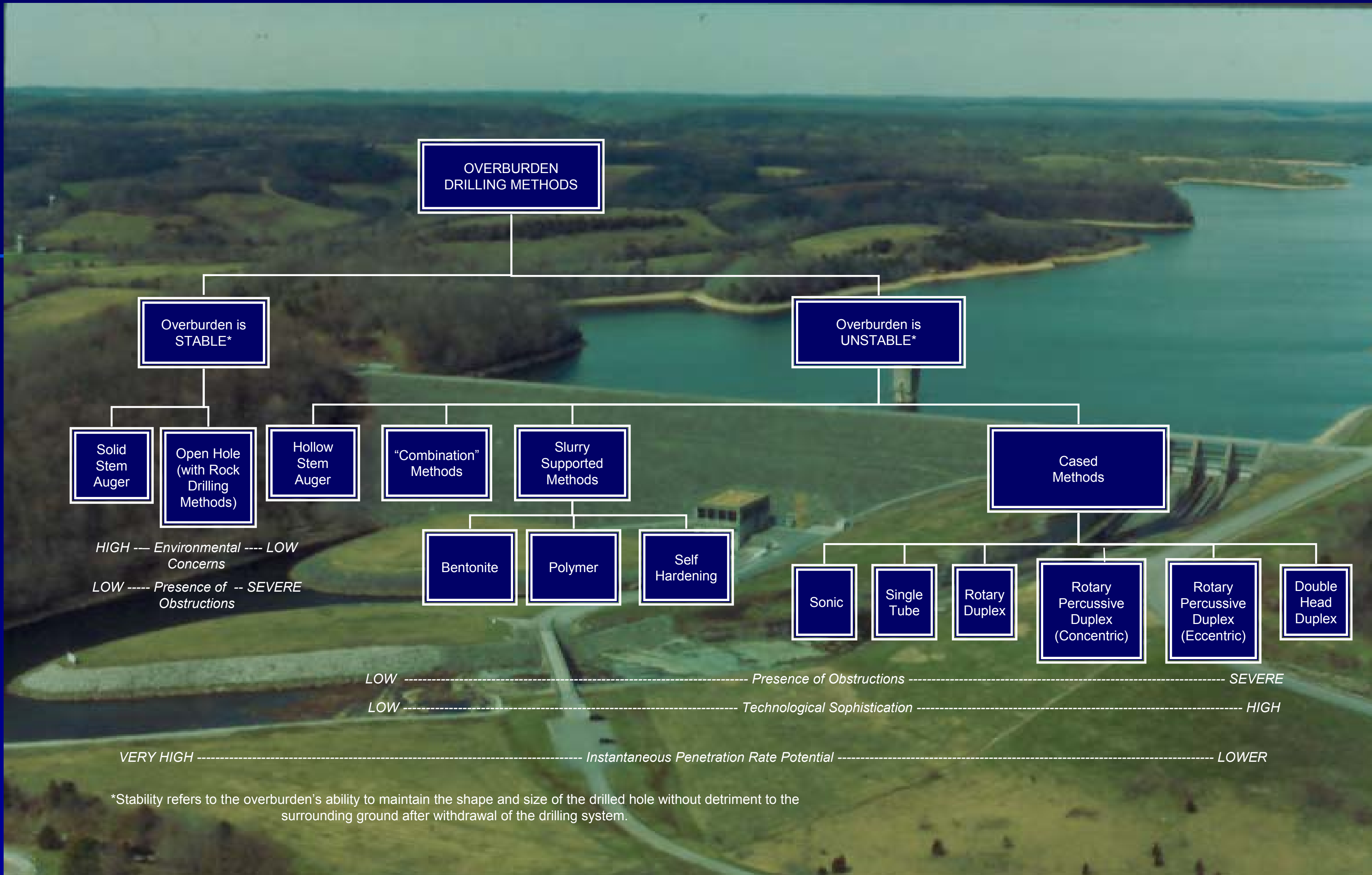
Circulation Type and Application



- Up-hole velocity (UHV) > "sinking velocity"
- UHV (m/min) = $\frac{\text{1274 x Flush Pump Rate (Liters/min)}}{\text{D2 – d2 (mm)}}$

  where D = drill hole diameter (in mm)

  d = drill string diameter (in mm)
- Typical UHV
  - Air, or air/water "mist": 1500 m/s (max 2100 m/s
  - Water: 36 m/s (max 120 m/s)
  - Low to medium viscosity mud: 30 m/s
  - Very thick mud: 18 m/s
  - Foam: 12 m/s


OVERBURDEN DRILLING METHODS
Overburden is STABLE*
Overburden is UNSTABLE*
Solid Stem Auger
Open Hole (with Rock Drilling Methods)
Hollow Stem Auger
"Combination" Methods
Slurry Supported Methods
Cased Methods
Bentonite
Polymer
Self Hardening
Sonic
Single Tube
Rotary Duplex
Rotary Percussive Duplex (Concentric)
Rotary Percussive Duplex (Eccentric)
Double Head Duplex
HIGH — Environmental ---- LOW Concerns
LOW ----- Presence of -- SEVERE Obstructions
LOW ---------- Presence of Obstructions ---------- SEVERE
LOW ---------- Technological Sophistication ---------- HIGH
VERY HIGH ---------- Instantaneous Penetration Rate Potential ---------- LOWER
*Stability refers to the overburden's ability to maintain the shape and size of the drilled hole without detriment to the surrounding ground after withdrawal of the drilling system.

Circulation Type and Application (Continued)

- Air vs. Water – Rotary vs. Rotary Percussion
- Guideline for selection
  - Provide clean hole
  - Enhance penetration rate
  - Minimize tool wear
  - Consistent with purpose of hole
  - Minimal damage to formation and/or structures
  - Environmentally compatible
  - Reconsider options if "lost flush" occurs

Borehole Deviation

Potential for deviation depends on

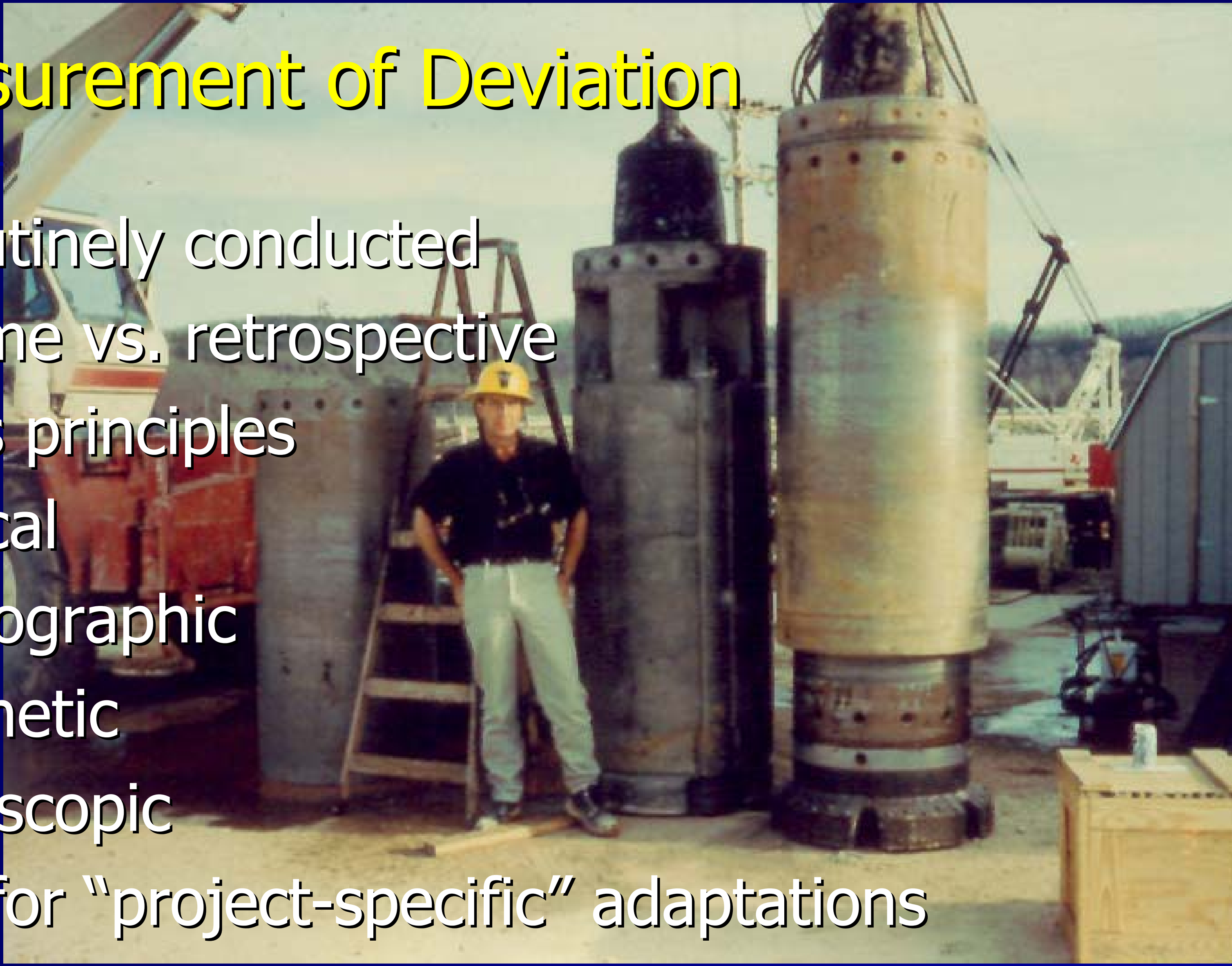
- Nature of subsurface conditions
- Nature of surface conditions ("drill platform")
- Nature of drilling method and tooling
- Accuracy of initial drill set up
- Inclination and length of hole
- Expertise and technique of driller
- Nature and length of guide casing
- Use of special stabilizing devices

Note: Different deviations are acceptable depending on project requirements and technique.

Table 2. Summary of recorded drill hole deviations from more recently published data

<table>
<tr><th>SOURCE</th><th>APPLICATION</th><th>METHOD</th><th colspan="2">RECORDED DEVIATION</th></tr>
<tr><td>Bruce (1989)</td><td>Dam anchors in rock and concrete</td><td>Down-the-hole hammer and rotary</td><td colspan="2">Target 1 in 60 to 1 in 240
Mainly 1 in 100 or better achieved</td></tr>
<tr><td>Bruce and Croxall (1989)</td><td>Deep grout holes in fill</td><td>Double head
Duplex</td><td colspan="2">Achieved 1 in 50 to 1 in 1000 (average 1 in 80)</td></tr>
<tr><td>BS 8081 (1989)</td><td>Ground anchors</td><td>General</td><td colspan="2">1 in 30 “should be anticipated”</td></tr>
<tr><td>Houlsby (1990)</td><td>Grout holes in rock</td><td>Percussion</td><td colspan="2">Up to 1 in 10 at 60 m</td></tr>
<tr><td rowspan="2">Weaver (1991)</td><td rowspan="2">Grout holes in rock</td><td>Down-the-hole hammer</td><td colspan="2">1 in 100 increasing to 1 in 20 with increasing depth (70 m)</td></tr>
<tr><td>“Dry Drilled Percussion”</td><td colspan="2">1 in 6</td></tr>
<tr><td>Bruce et al. (1993)</td><td>Dam anchors in rock and concrete</td><td>Down-the-hole hammer</td><td colspan="2">Target 1 in 125: consistently achieved as little as 1 in 400</td></tr>
<tr><td>Xanthakos et al. (1994)</td><td>General in soil</td><td>Drive Drilling</td><td colspan="2">Up to 1 in 14</td></tr>
<tr><td rowspan="6">Kutzner (1996)</td><td rowspan="5">Grout holes in rock</td><td>Percussion</td><td>Up to 1 in 20</td><td rowspan="5">“Unavoidable”</td></tr>
<tr><td>Down-the-hole</td><td>Up to 1 in 50</td></tr>
<tr><td>Rotary Blind</td><td>Up to 1 in 33</td></tr>
<tr><td>Rotary Core</td><td>Up to 1 in 100</td></tr>
<tr><td>Wireline Core</td><td>Up to 1 in 200</td></tr>
<tr><td>Horizontal holes in soil</td><td>Percussive Duplex</td><td colspan="2">Less than 1 in 100</td></tr>
<tr><td>PTI (1996)</td><td>Tiebacks</td><td>General statement</td><td colspan="2">Up to 1 in 30 normally acceptable</td></tr>
<tr><td rowspan="3">FHWA (1999)</td><td rowspan="3">General</td><td>High Speed Rotary</td><td colspan="2">2 to 5 in 100</td></tr>
<tr><td>Top Drive Percussion</td><td colspan="2">< 5 to 20 in 100 depending on depth</td></tr>
<tr><td>Down-the-hole hammer</td><td colspan="2">Typically 1 to 2 in 100</td></tr>
</table>

Measurement of Deviation



- Not routinely conducted
- Real time vs. retrospective
- Various principles
  - Optical
  - Photographic
  - Magnetic
  - Gyroscopic
- Scope for "project-specific" adaptations

Recording of Drilling Progress and Parameters

- Value of real time continuous monitoring for design purposes (manual vs. automatic)
- Look for "exceptions and unexpecteds" [Weaver, 1991]
- Indication of progressive improvement (e.g., denser, less permeable conditions)
- Concept of specific energy
- Several generations/evolutions

Calculation of Specific Energy

$$e = \frac{F}{A} + \frac{2 \pi N T}{AR}$$

where

e = specific energy (kJ/m3)

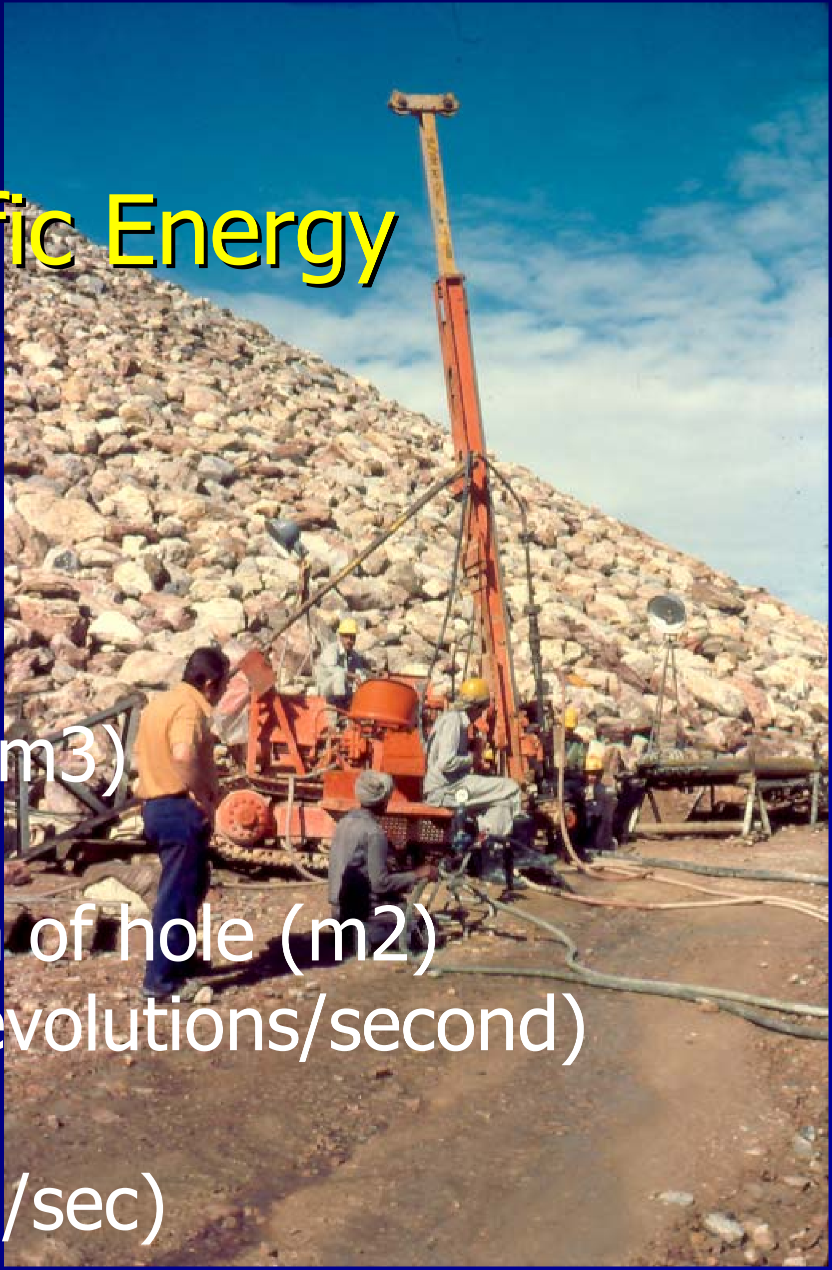
F = thrust (kN)

A = cross sectional area of hole (m2)

N = rotational speed (revolutions/second)

T = torque (kN-m)

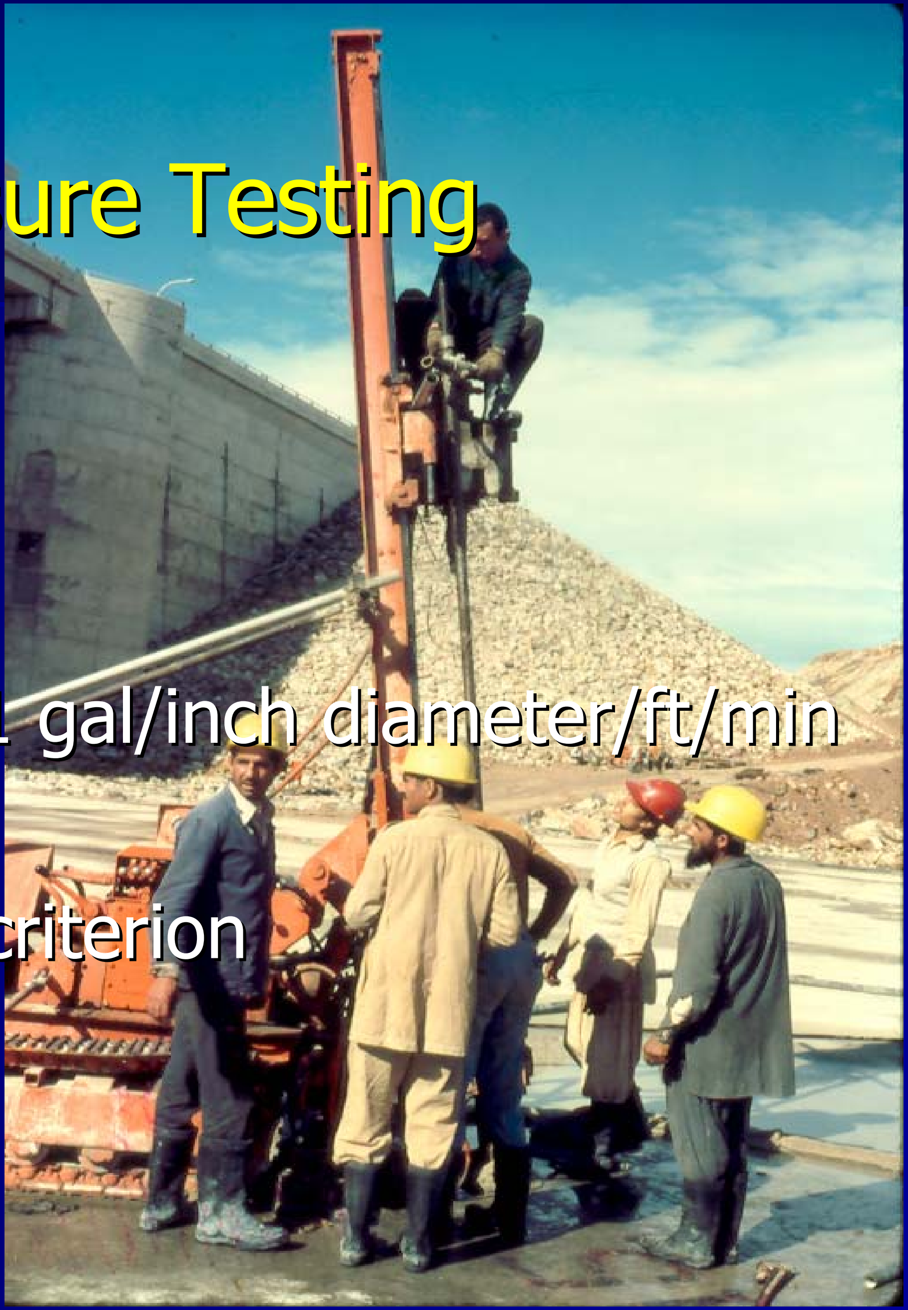
R = penetration rate (m/sec)



3.2 Water Pressure Testing

Then:

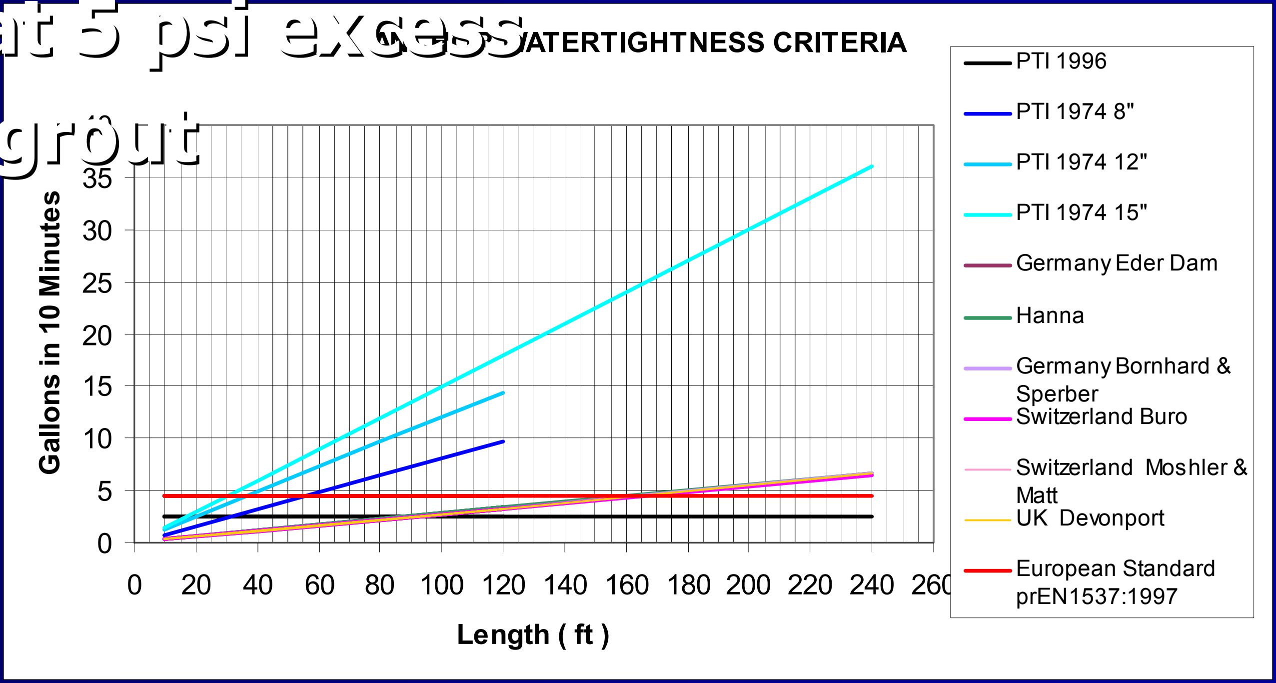
- Full length
- 0.5 gpm at 60 psi
  (more typical 0.001 gal/inch diameter/ft/min at 5 psi)
- Very conservative criterion



3.2 Water Pressure Testing

Now:

- **Knowledge of fissure control on permeability**
- **2.5 gal at 5 psi excess**
- **Gravity grout**



3.3 Grouting

Then:

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

3.3 Grouting

Now: <u>Same</u> except:

- **No use of preblend cements**
- **Focus on fluid property testing**
- **Often single stage grouting**

Trial Mixes

- Cement selection
- Compatibility with admixtures
- Minimize bleed
- Water:cement ratio
- Stability

Trial Batches

- Workability
  - Flow
  - Stability
- Measure Performance
  - Bleed
  - Density
  - Strength
- Mixing Time
  - Manufacturer's Recommendations
  - ≅ 4-5 Minutes
  - Mixer Optimization Process

3.4 Tendon

Then:

- **Contractor selection**
- **Use of wire/button head**
- **No corrosion protection other than grout**

3.4 Tendon

Now:

- **Tendon specified**
- **No use of wire tendons**
- **Class 1 – Class 2 Corrosion Protection**
- **Use of epoxy coated strand**

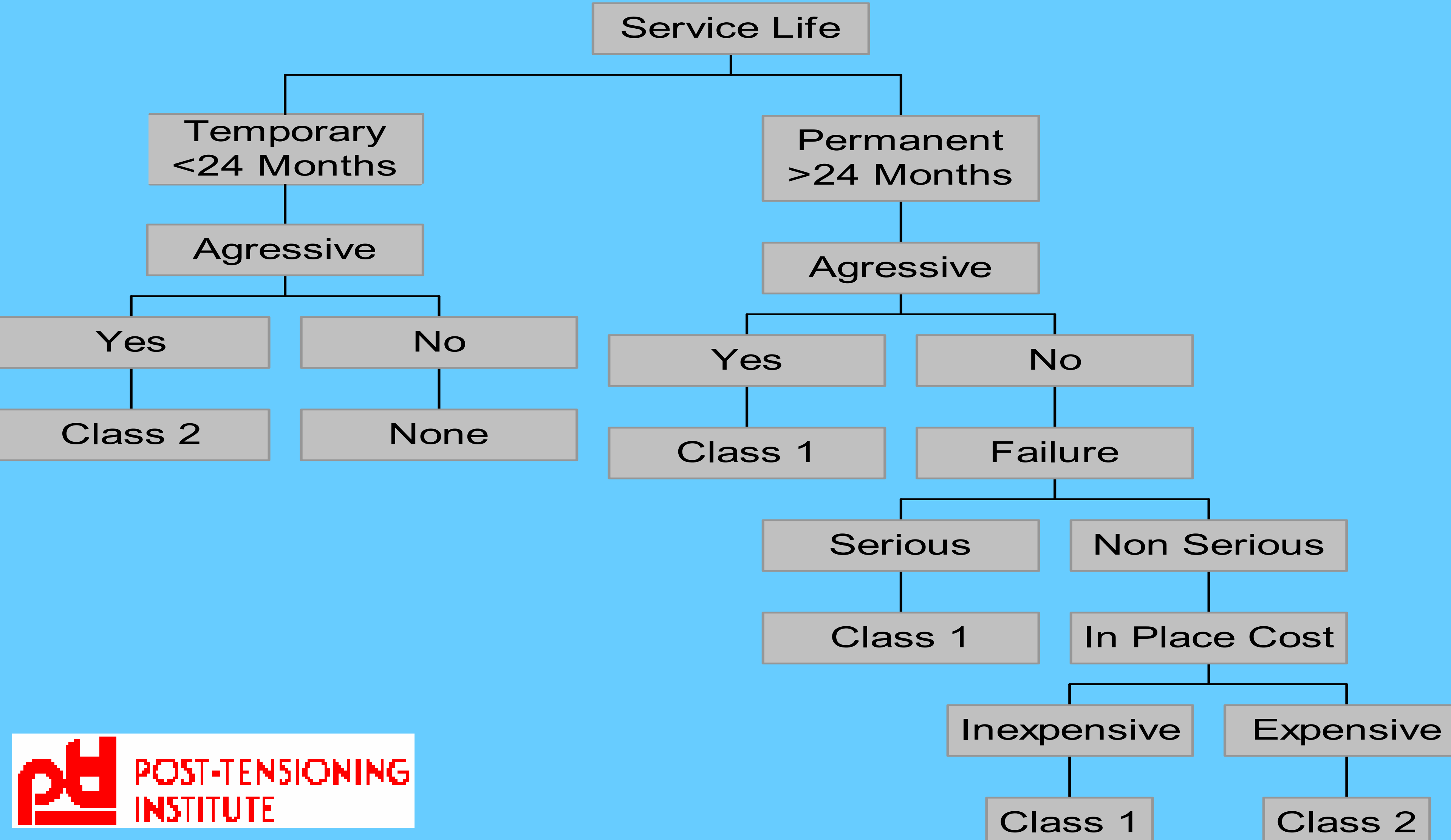
How to provide the needed Corrosion Protection?

- Extrusion Sheathed Strand
  - Complete filling of all Interstices with Corrosion Inhibitor – No Voids
- Epoxy Coated Strand
  - ASTM A-882, revised 2002
  - Coating is a barrier to corrosion,
  - If damaged, Local Galvanic Cell may occur
- Corrugated Outer Duct
  - Barrier to corrosion elements
  - Larger dia. duct is job site installed.
  - Larger dia. drill hole may be required.

How to provide the unbonded length?

- Sheath Extruded onto the Strand
  - Assured Corrosion Protection
  - High Force Transmission Efficiency
- Slipped on Tube Sheath
  - Larger accumulated diameter of anchor tendon bundle
- Two stage grouting – no sheath
  - Additional step of grouting after stressing

Corrosion Protection Decision Tree



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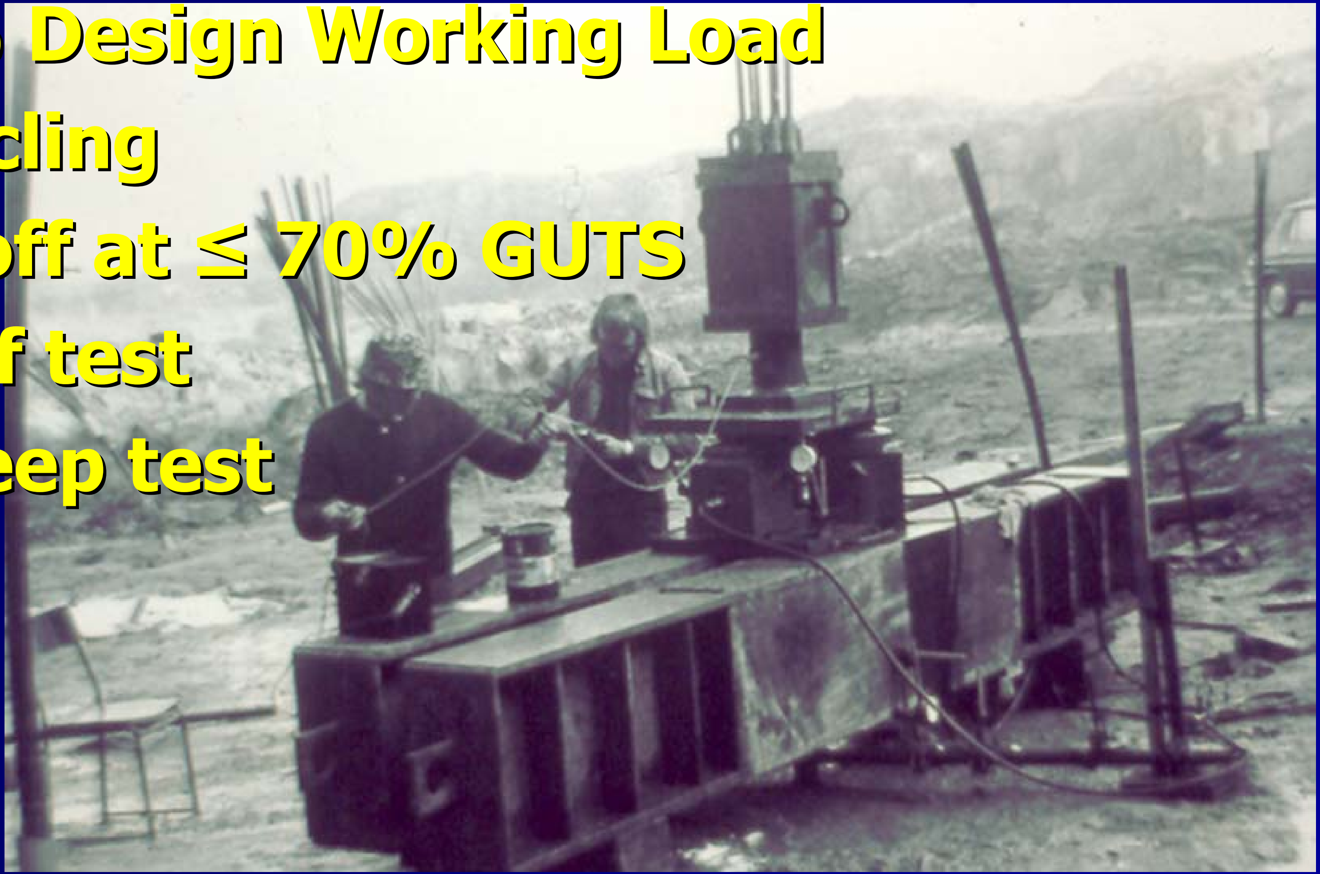
Corrosion Protection Requirements

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

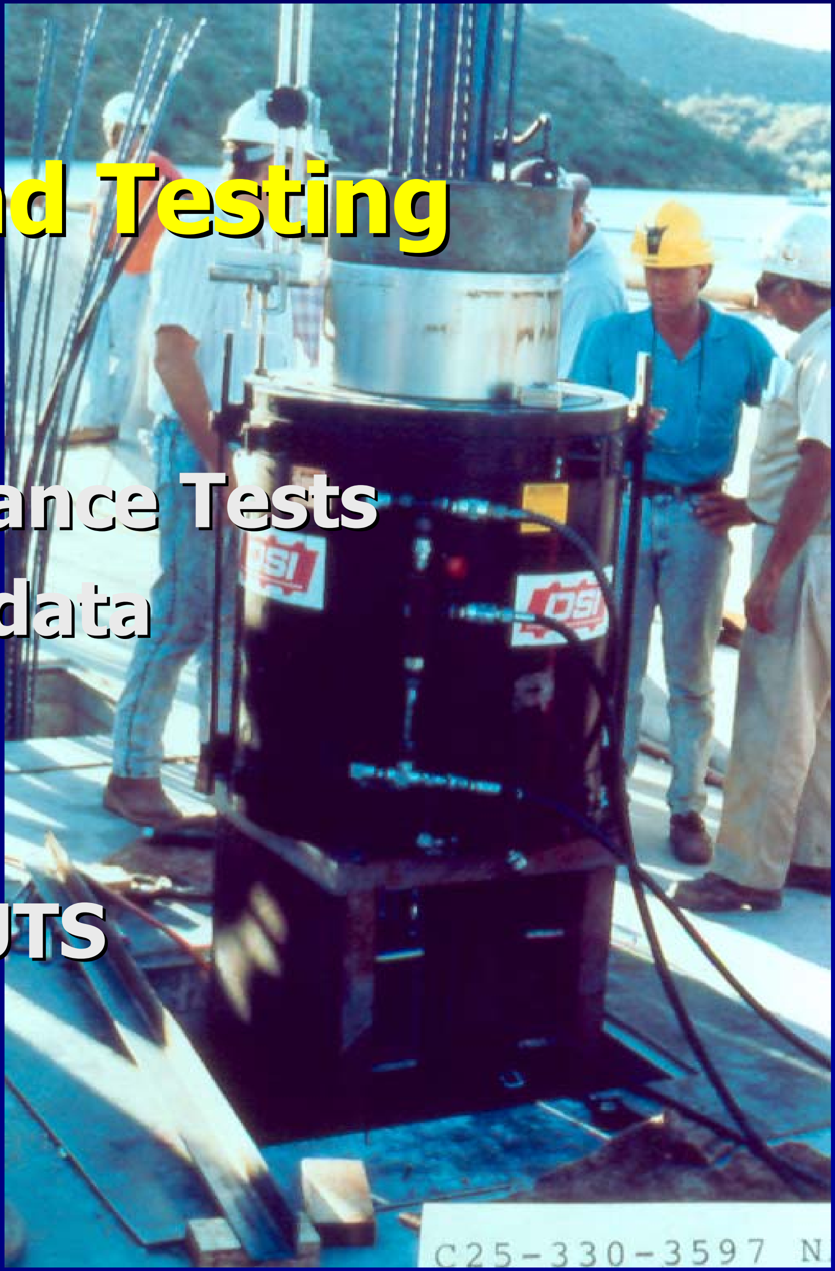
4. Stressing and Testing

Then:

- Progressive simple loading to 100% Design Working Load
- No cycling
- Lock off at ≤ 70% GUTS
- Lift off test
- No creep test



4. Stressing and Testing



Now:

- Proof and Performance Tests
- Analysis of elastic data
- Creep test
- Lift off
- Lock off ≤ 60% GUTS

Anchor Tests - General

1. **Pre-production Tests**
   Carried out on one or two anchors, to confirm the grout / ground bond stress assumed. These tests are carried out on non-production anchors.
2. **Performance Tests**
   Carried out on the first two to three anchors, plus a minimum of 2% thereafter, to confirm that the anchors meet the detailed design and specification. These tests are carried out on production anchors.
3. **Proof Tests**
   Carried out an all other production anchors, to confirm that the anchors meet the general requirements of the design and specification.

Plus:

Supplementary Extended Creep Tests

At least two extended tests shall be made on permanent anchors in soils having a Plasticity Index greater than 20.

Performance Tests

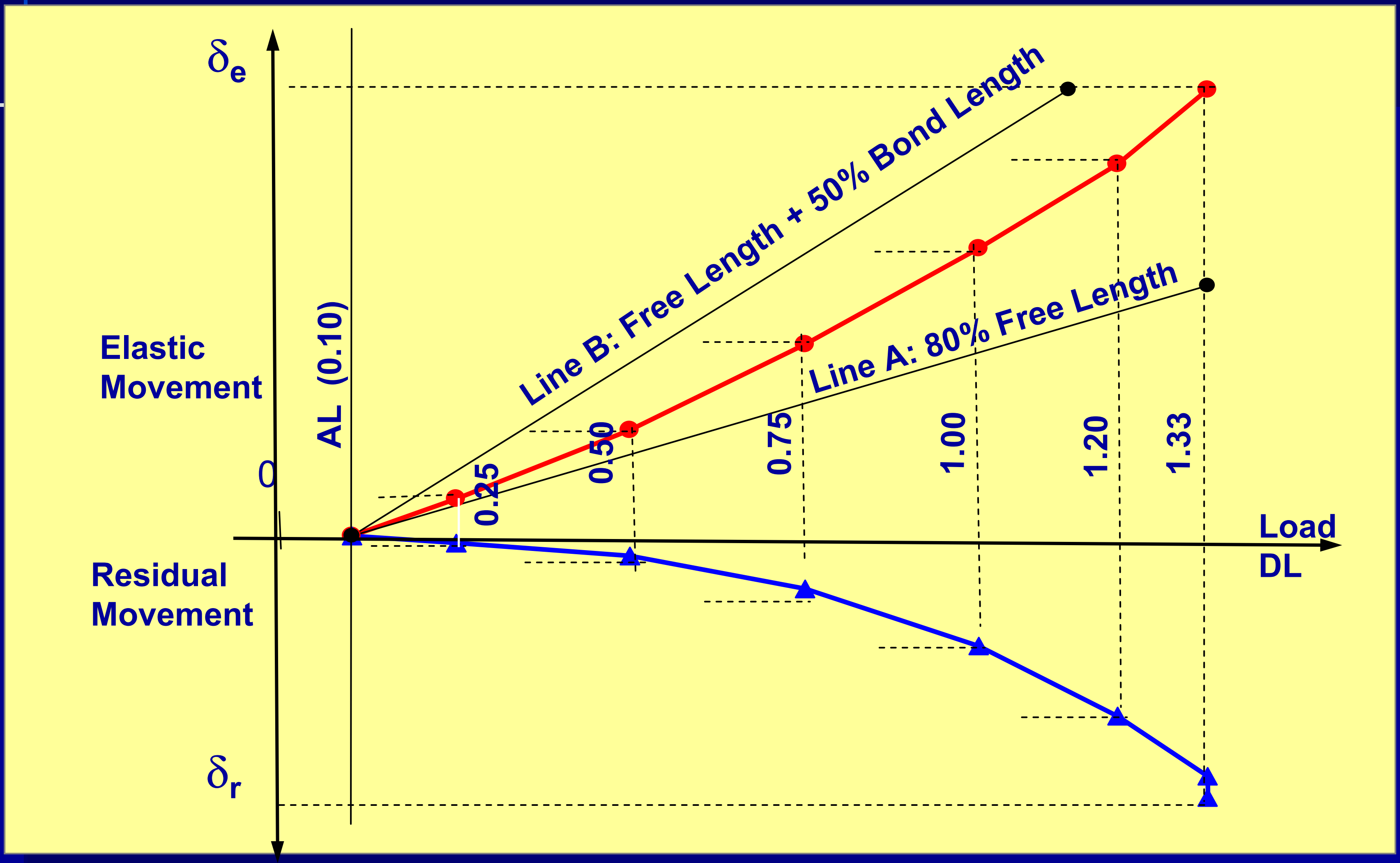
To Determine:	Acceptance Criteria:
a) whether the anchor has sufficient load carrying capacity,	133% of design load
b) that the apparent free tendon length has been satisfactorily established,	minimum > 80% Free length maximum < (Free length + 50% of bond length)
c) the magnitude of the residual movement,and	no absolute criterion, but must be determined t evaluate the elastic movement for calculating “ above”
d) that the rate of creep stabilizes within the specified limits.	< 1 mm at Test Load during 1 to 10 minutes or if this is exceeded < 2 mm at test Load for a period of 6 to 60 minutes

Cycling loading to: 25%, 50%, 75%, 100%, 120%, 133%(TL) of the design load(DL)

Load is decreased to alignment load (AL) after each cycle

After acceptance , adjust to lock-off load

Graphical Analysis of Performance Test Data



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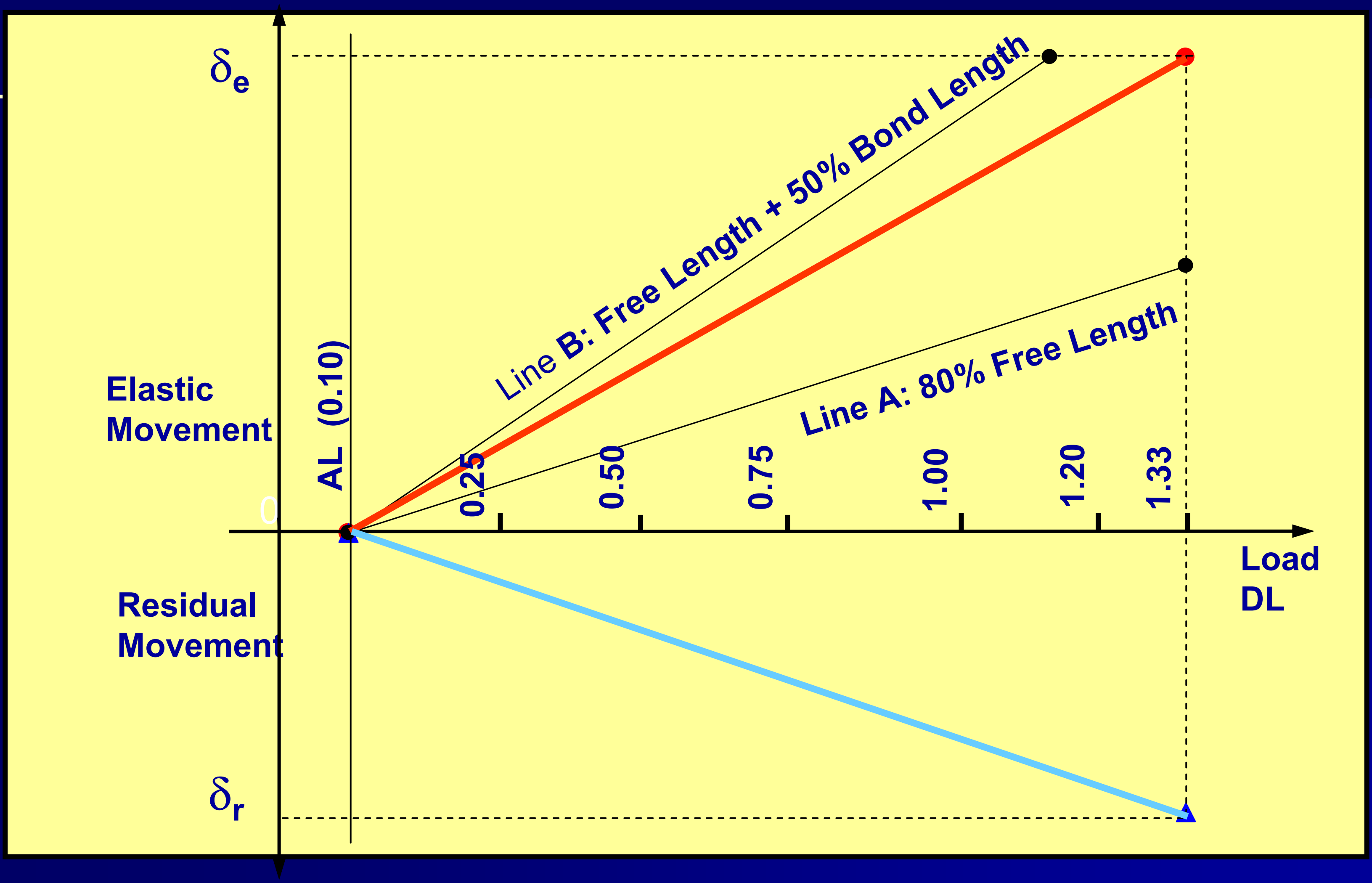
Proof Tests

To Determine:	Acceptance Criteria:
a) whether the anchor has sufficient load carrying capacity,	133% of design load
b) that the apparent free tendon length has been satisfactorily established, and	minimum > 80% Free length maximum < (Free length + 50% bond length
d) that the rate of creep stabilizes within the specified limits.	< 1 mm at Test Load during 1 to 10 minutes or if this is exceeded < 2 mm at test Load for a period of 6 to 60 minutes

Incrementally loading to: 25%, 50%, 75%, 100%, 120%, 133%(TL) of the design load(DL)

After acceptance , adjust to lock-off load

Graphical Analysis of Proof Test Data



Supplementary Extended Creep Tests

To Determine: that there is no indication that future unacceptable movement or creep failure is probable.

A family of creep curves is plotted on a semi-logarithmic chart.

Creep movement < 1 mm at Test load during 1 to 10 minutes

or

Creep movement < 2 mm at Test load during 6 to 60 minutes

Testing in accordance with the schedule in Table 8.3

. *Note: Epoxy coated strand itself has a significant value and thus should be accounted for when assessing the creep of the anchor*

Special Considerations for Epoxy Coated Strand Anchors

- ASTM A-882 alone is not quality guarantee.
- Inspect strands during fabrication

  Patch any coating holidays or holes.
- Very abrasive surface causes need to protect men and equipment
- Strand has more curvature memory making handling and fabrication more difficult.
- Coiling very much more difficult due to friction of strands when tendon bent.
- Handling of anchors may cause coating damage.
- Efficient patching methods needed.
- Stressing has extra requirements and must be very disciplined. Little tolerance for variation.

  Slippages have occurred causing rejected anchors.

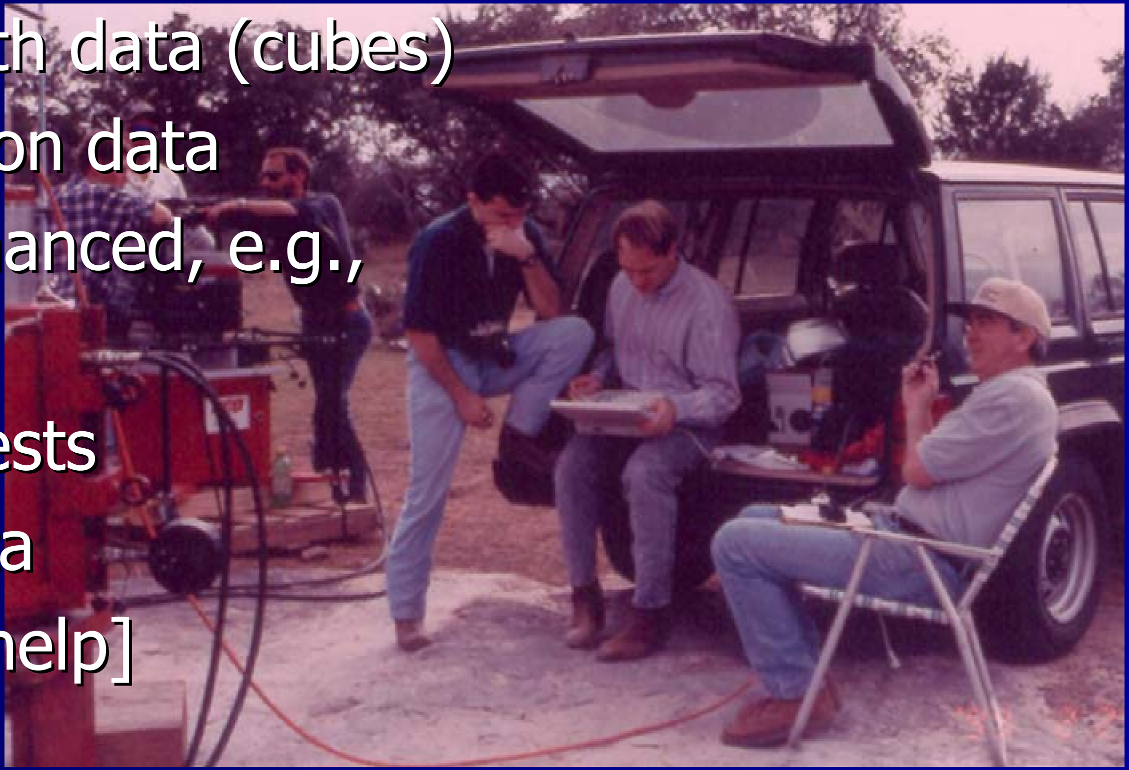
5. As Built Records

Then:

- Focus on drilling logs via cores
- Grout strength data (cubes)
- Load-extension data

Now: Much enhanced, e.g.,

- MWD
- Fluid grout tests
- Stressing data
- [Computers help]



6. Overview

	THEN	NOW
Geotechnical design	Same – equally conservative	
Construction ▪ Drilling	Investigation	Production
▪ Water pressure testing		✓
▪ Grouting		Better material knowledge
▪ Tendon		✓
Stressing and Testing		✓
As-Built Records	Equally good, but quality reflects construction process	