

REVEALING RISKS:

Advanced Techniques for Investigating Corrosion in PT Structures

Pratik Murkute, Ph.D., PE, NACE CP-4

VCS Durability



Pratik is a professional engineer and a certified NACE Cathodic Protection Specialist (NACE CP4). He is a graduate of Oregon State University where he earned his Ph.D. in Materials Science, he completed his M. Tech in Materials Engineering from IIT Kanpur, India and a B. Tech in Metallurgical and Materials Engineering from VNIT Nagpur, India.

Pratik has authored over 15 peer reviewed papers. He is an expert in the ferrous metallurgy and electrochemical, corrosion assessment of metals, with a focus on chloride-induced corrosion of steel in concrete. Pratik specializes in corrosion forensics and has used these skills on a number of PT evaluation inspection projects.

Pratik also has experience in non-destructive techniques, such as ground penetrating radar, acoustic testing and impact echo with extensive knowledge inlaboratory corrosion tests, steel metallurgy and materials engineering.

He is an active member of The Association for Materials Protection and Performance (AMPP), American Society of Civil Engineering (ASCE), International Concrete Repair Institute (ICRI), Coasts, Oceans, Ports & Rivers Institute (COPRI).

Outline

Bonded PT Systems

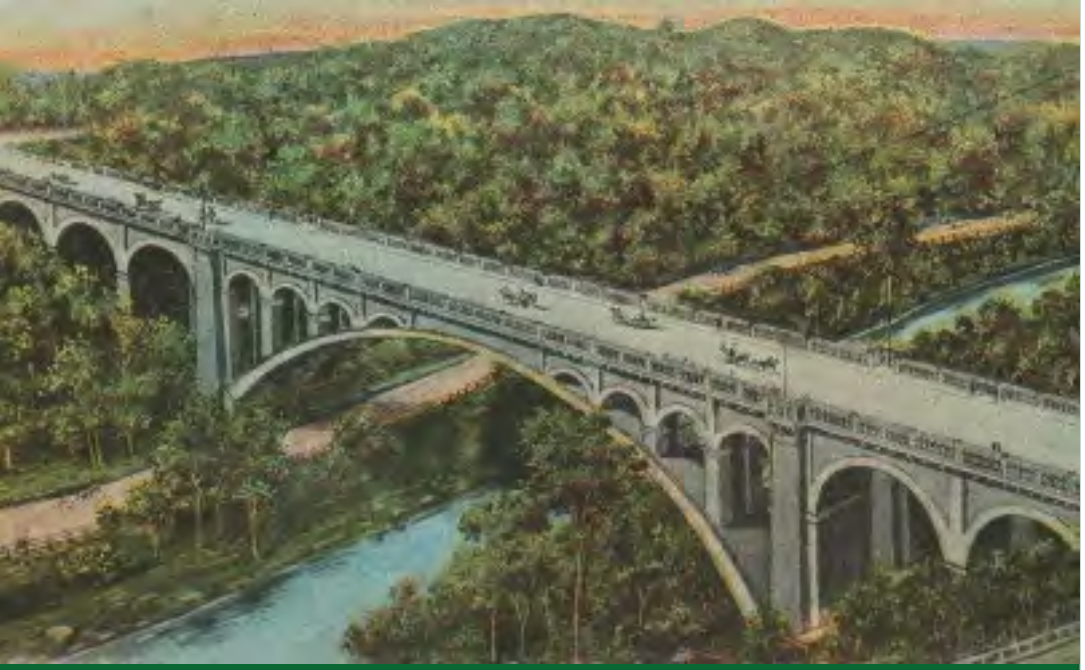
- Primary Concerns
- Investigation Tools
  - Ground Penetrating Radar
  - Impact Echo
  - Borescope
  - Moisture Testing
  - Materials testing

Unbonded PT Systems

- Primary Concerns
- Investigation Tools
  - Hammer Sounding
  - Ground Penetrating Radar
  - Corrosion Potential Survey
  - Moisture Testing
  - Lateral Deflection Test
  - Lift-off Test







BACKGROUND

- 1928: Eugene Freyssinet proposed the use of Post-tensioned concrete
- 1941: First PT bridge built in France
- 1946: Post-tensioning gains popularity in Europe due to steel shortage
- 1949-51: First PT bridge in US
  - Walnut Lane Bridge, Philadelphia
- Structurally efficient, Long span bridges

Major Bonded PT Failures in the US Bridges

Walnut Lane Bridge, PA (1990) – improper grouting

Niles Channel Bridge, FL (1999) – improper grouting, leaked chloride-contaminated water

Mid-Bay Bridge, FL (2000) – improper grouting, leaked chloride-contaminated water

Sunshine Skyway, FL (2000) – improper grouting, leaked chloride-contaminated water

Varina Enon Bridge, VA (2007 and 2017) – improper grouting

Cline Ave Bridge, IN (2009) – chloride-contaminated water leaked through the deck

Plymouth Ave Bridge, MN (2010) – chloride-contaminated water leaked through the deck

Ringling Causeway Bridge, FL (2011) – improper grouting

Wando River Bridge, SC (2016 and 2018) – improper grouting

Roosevelt Bridge, FL (2020) – chloride-contaminated water leaked through the deck

Causes of PT Corrosion

Moisture

- Voids and moisture between strands and between wires
- Water penetration from anchorage pocket, joints, cracks
- Water penetration due to floods

Grout

- Water bleeding from grout
- Grout Segregation
- Chloride -contaminated grout
- Soft grout and high corrosive ion concentration
- Dissimilar grouts in the same tendon

Typical Failures

- PT Tendons
- Corrosion due to grout defects and environmental exposure

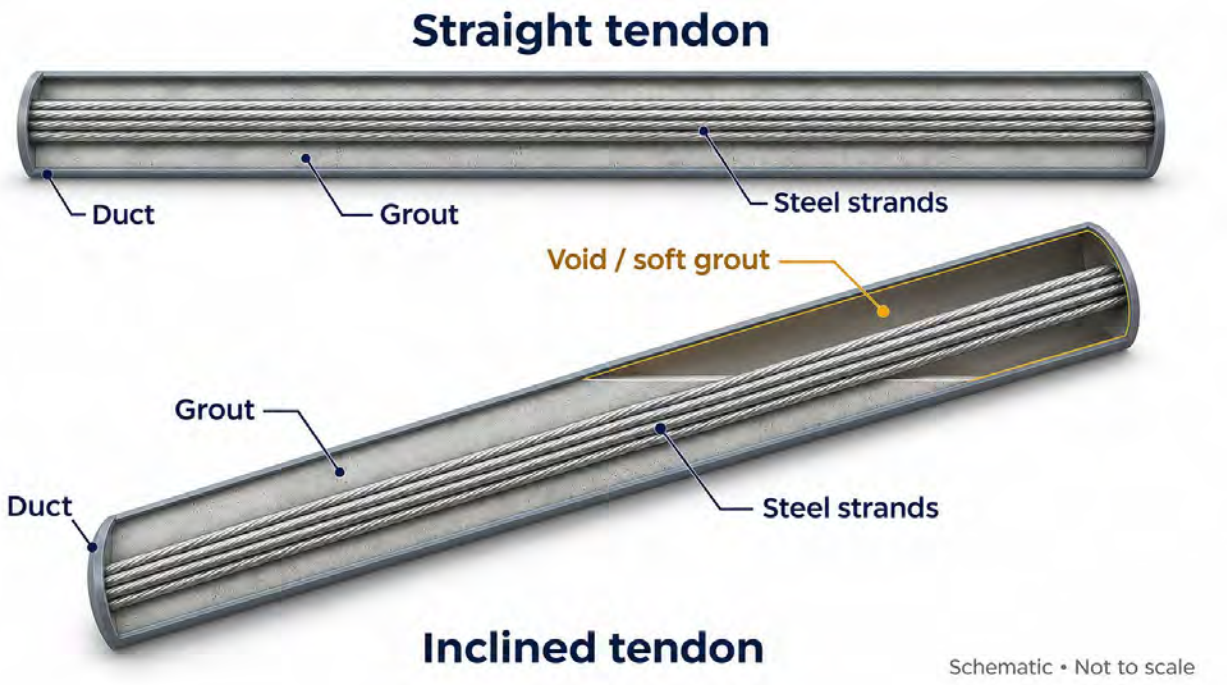






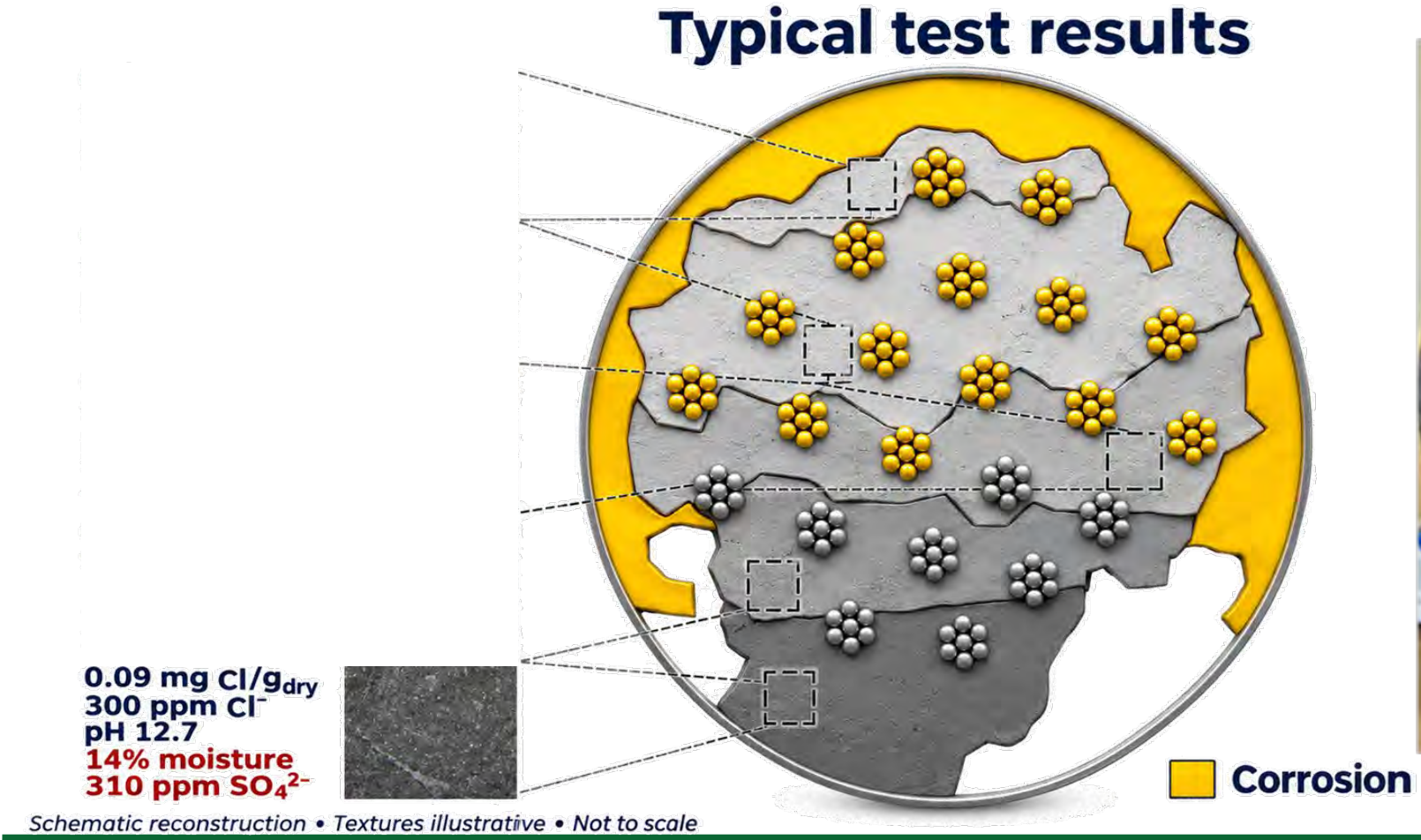


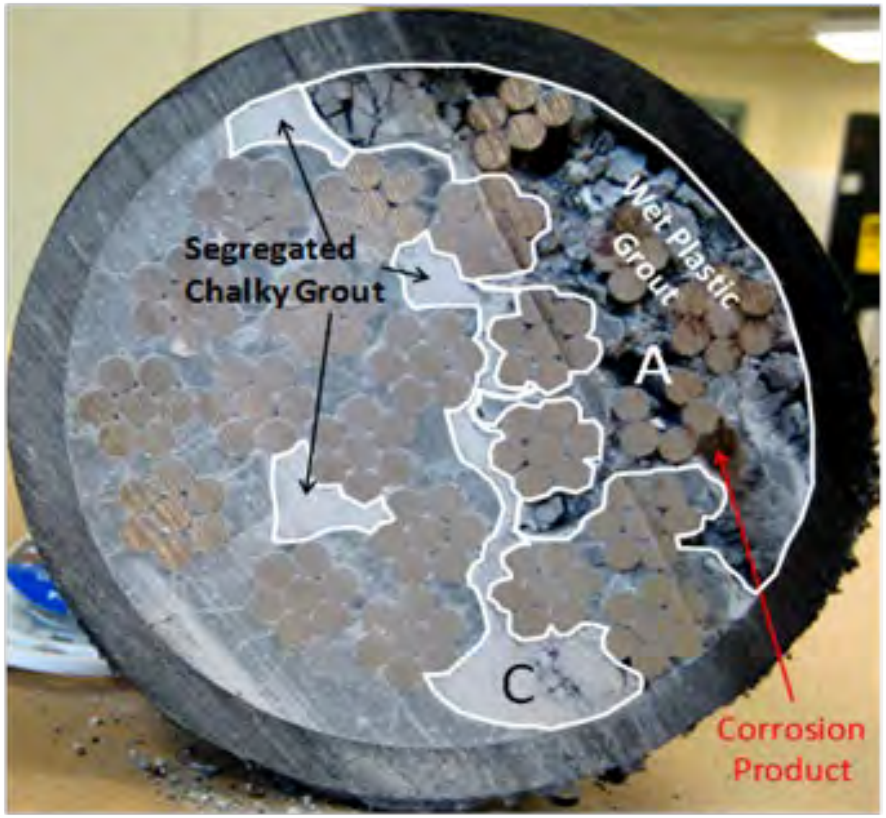
Straight vs Deviated Tendon





Defective Grout (Segregation)





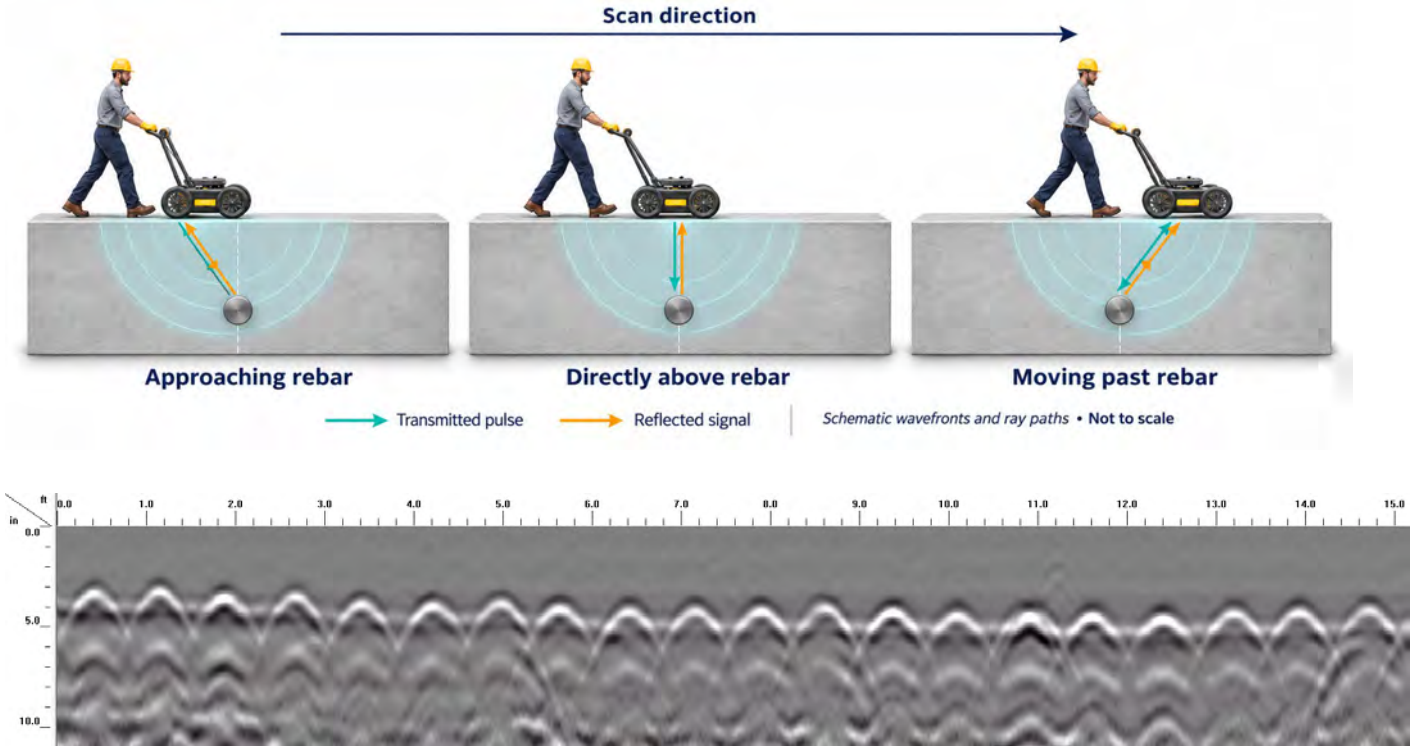
Investigation Tools

- Ground Penetration Radar (GPR)
- Impact Echo (IE) / Pulse Velocity (PV)
- Borescope Imaging
- PT Corrosion Evaluation by moisture testing
- Materials Testing
  - Chloride analysis of PT grout
  - pH and Chemical Testing
  - Petrographic analysis

Ground Penetrating Radar (GPR)

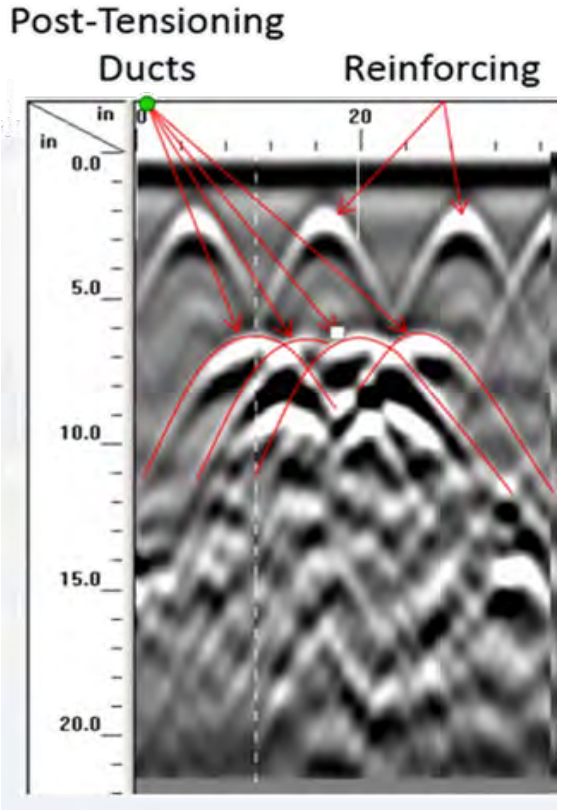
- Electromagnetic evaluation of concrete
  - EM reflected off conductive media (Metal, Water/saltwater, Air)





[1]https://cnilocates.com/services/ground-penetrating-radar/

GPR


Post-Tensioning
Ducts
Reinforcing
in
in
0
20
0.0
5.0
10.0
15.0
20.0

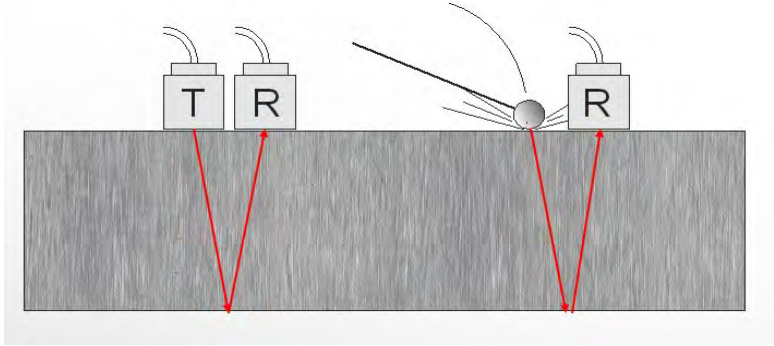


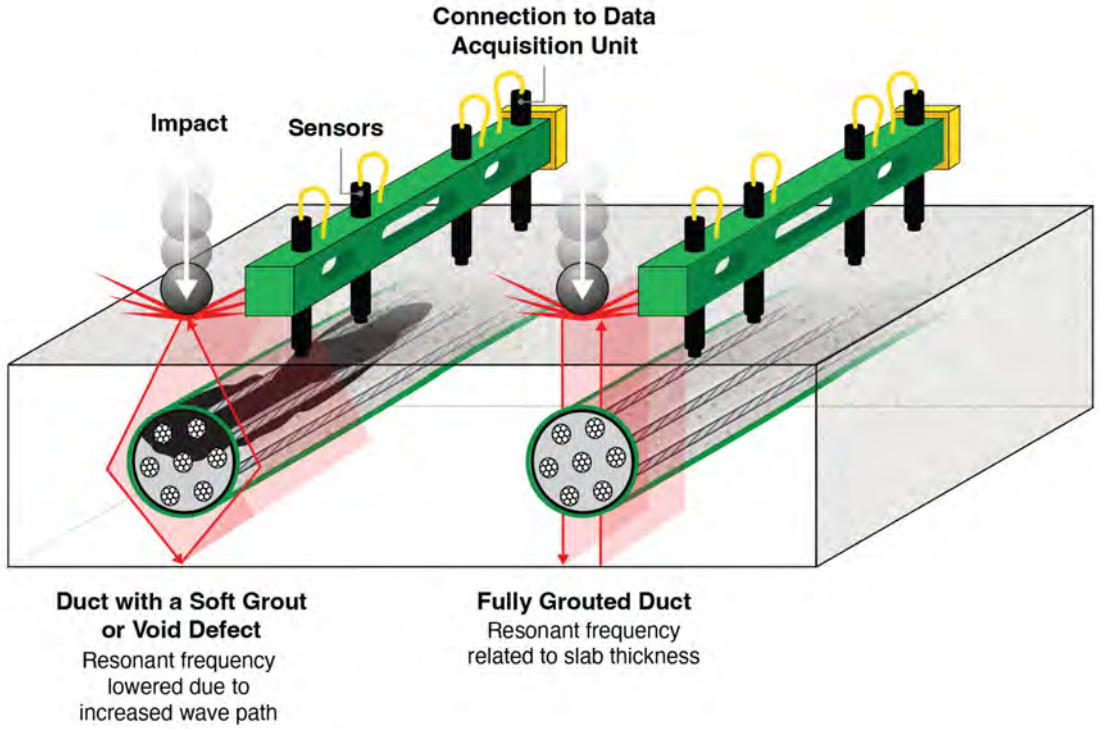
Impact Echo (IE)
Pulse Velocity (PV)

- Use of acoustic waves (vibrations) to characterize materials
  - Impact Echo: Frequency Domain
  - Pulse Velocity: Velocity Domain



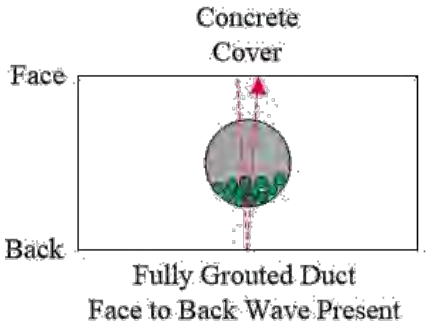
Impact Echo (IE)



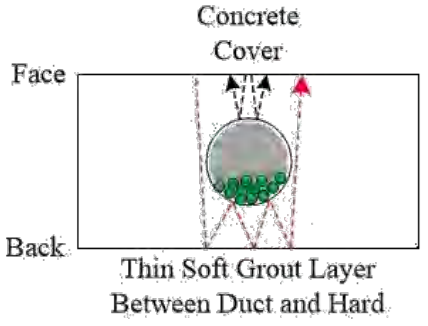


IE/PV- Wave Propagation

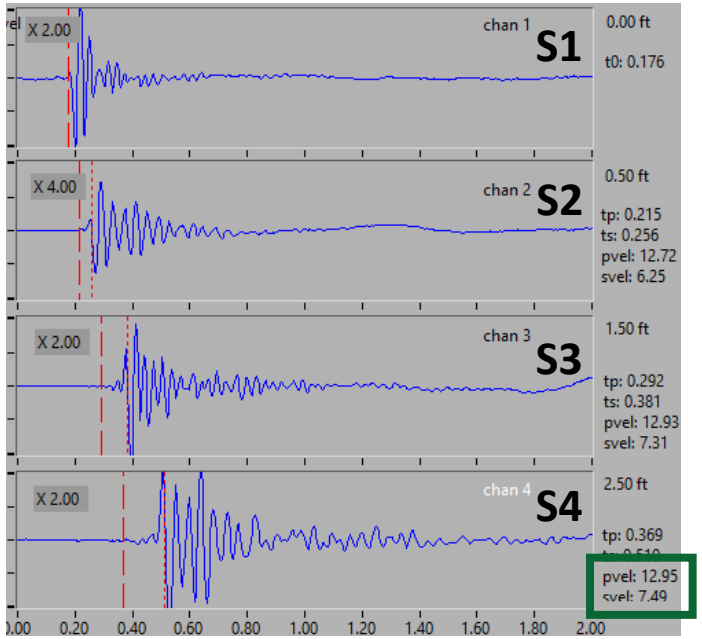




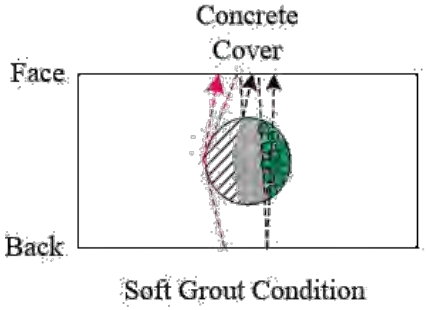
Fully Grouted Duct
Face to Back Wave Present



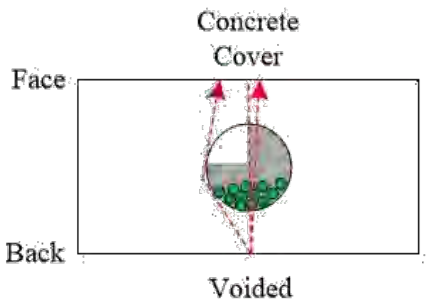
Thin Soft Grout Layer
Between Duct and Hard
Grout



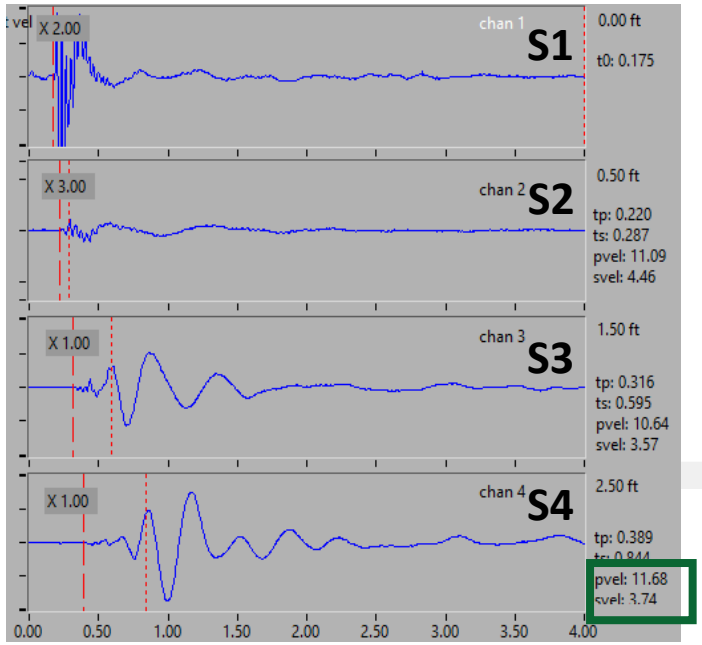
No Defect in PT Tendon



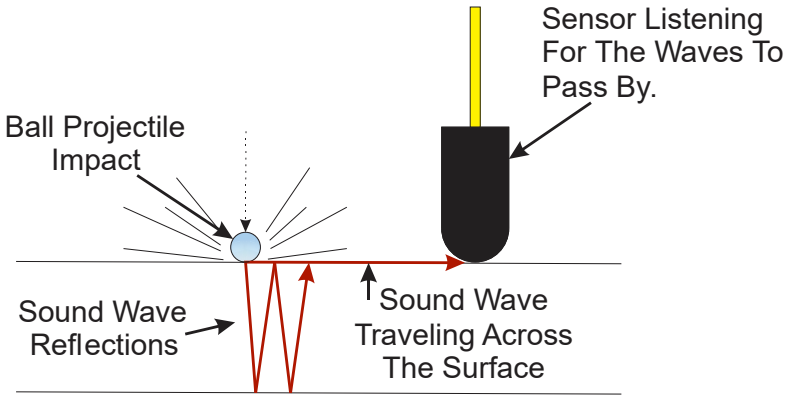
Soft Grout Condition



Voided
Face to Back Wave Interrupted
Lower Frequency Present
Tendons May be Covered



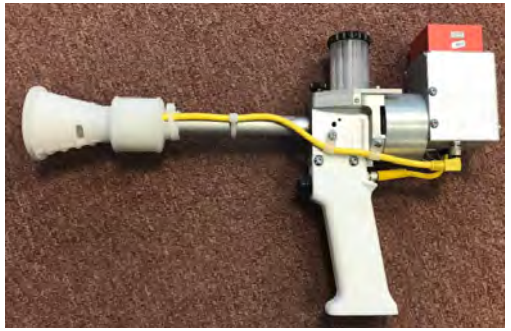
Possible Grouting Defect



IE/PV - INSTRUMENTATION



Ball Bearings (BB)



BB Impactor



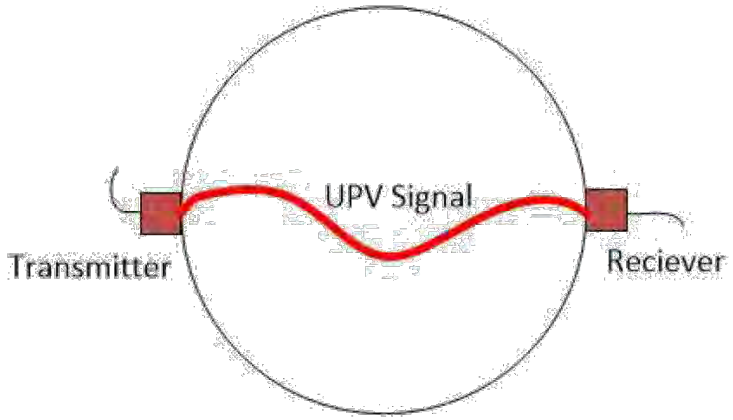
Sensor Array



Control and Data Collection



EXTERNAL TENDONS







BORESCOPE INSPECTION

- Visual inspection of voids with minor physical impact
  - Borescope Diameter = 4 mm











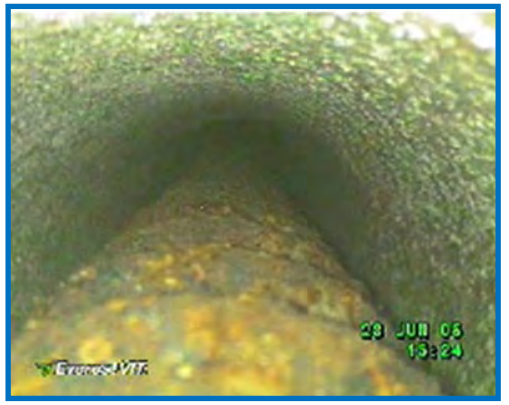
BORESCOPE INSPECTION PICTURES



Void Bottom Corrosion on Duct & Tendons



Corrosion on Duct & Tendon



Void in Pier With Dywidag Bar Instead of Tendons



Corrosion on Duct



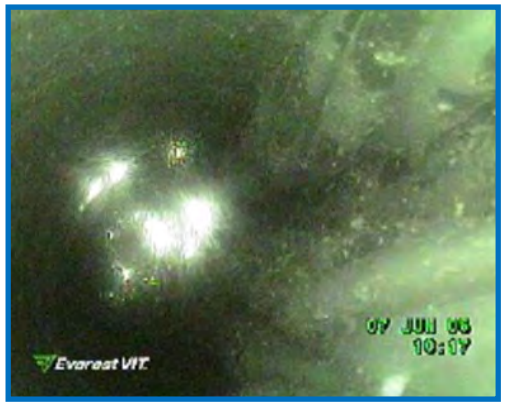
Void With Tendon Corrosion



Anchor Plate, Tendons & Duct are Grout Coated



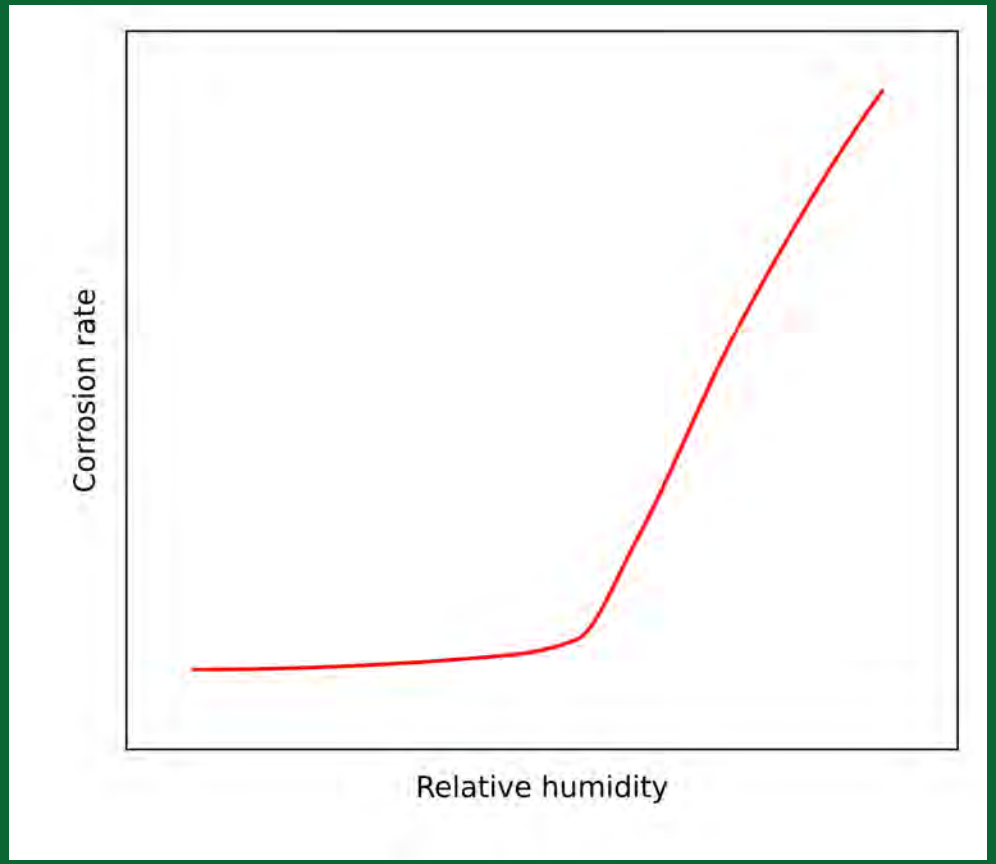
Anchor Close-Up, Top of Tendons Show Corrosion

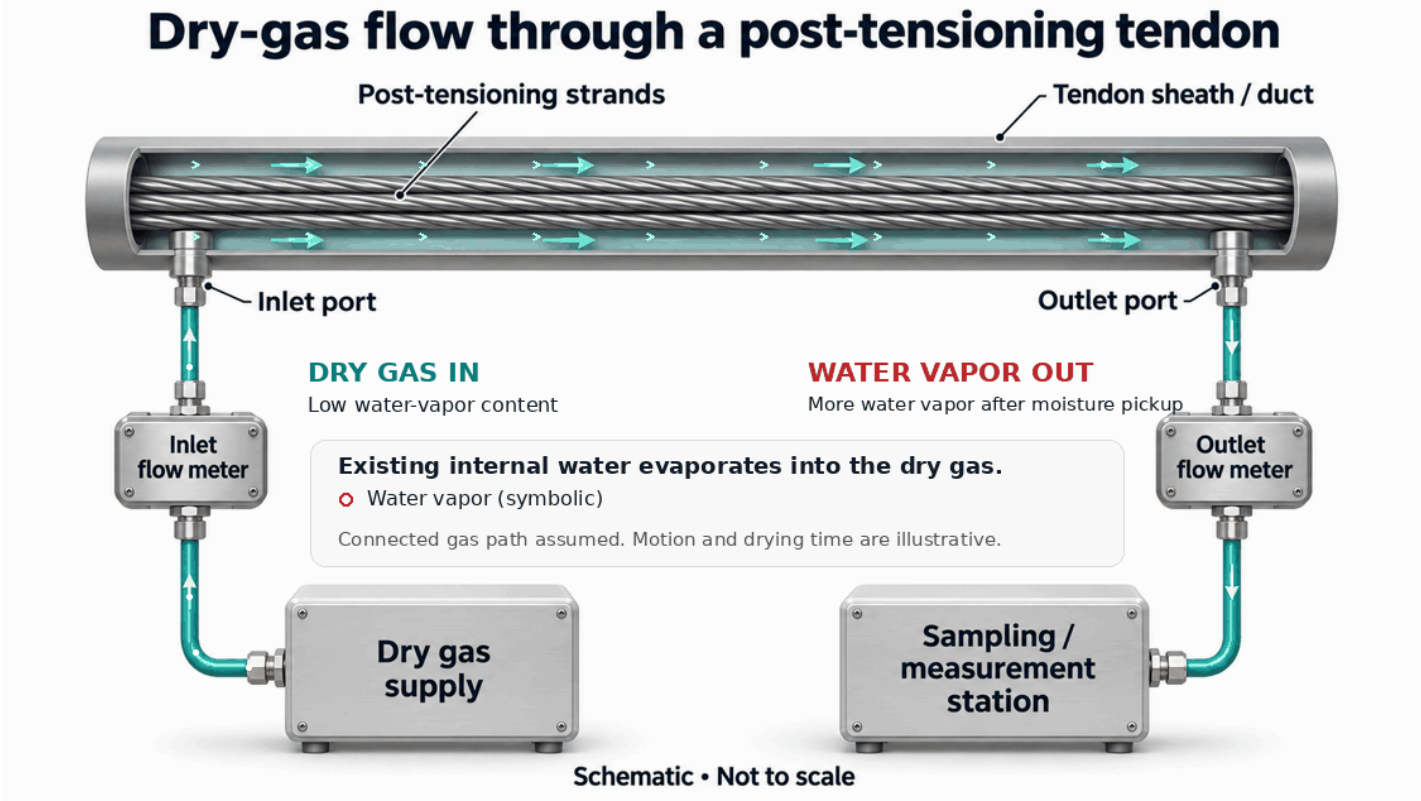


Tendon Found with Standing Water Inside

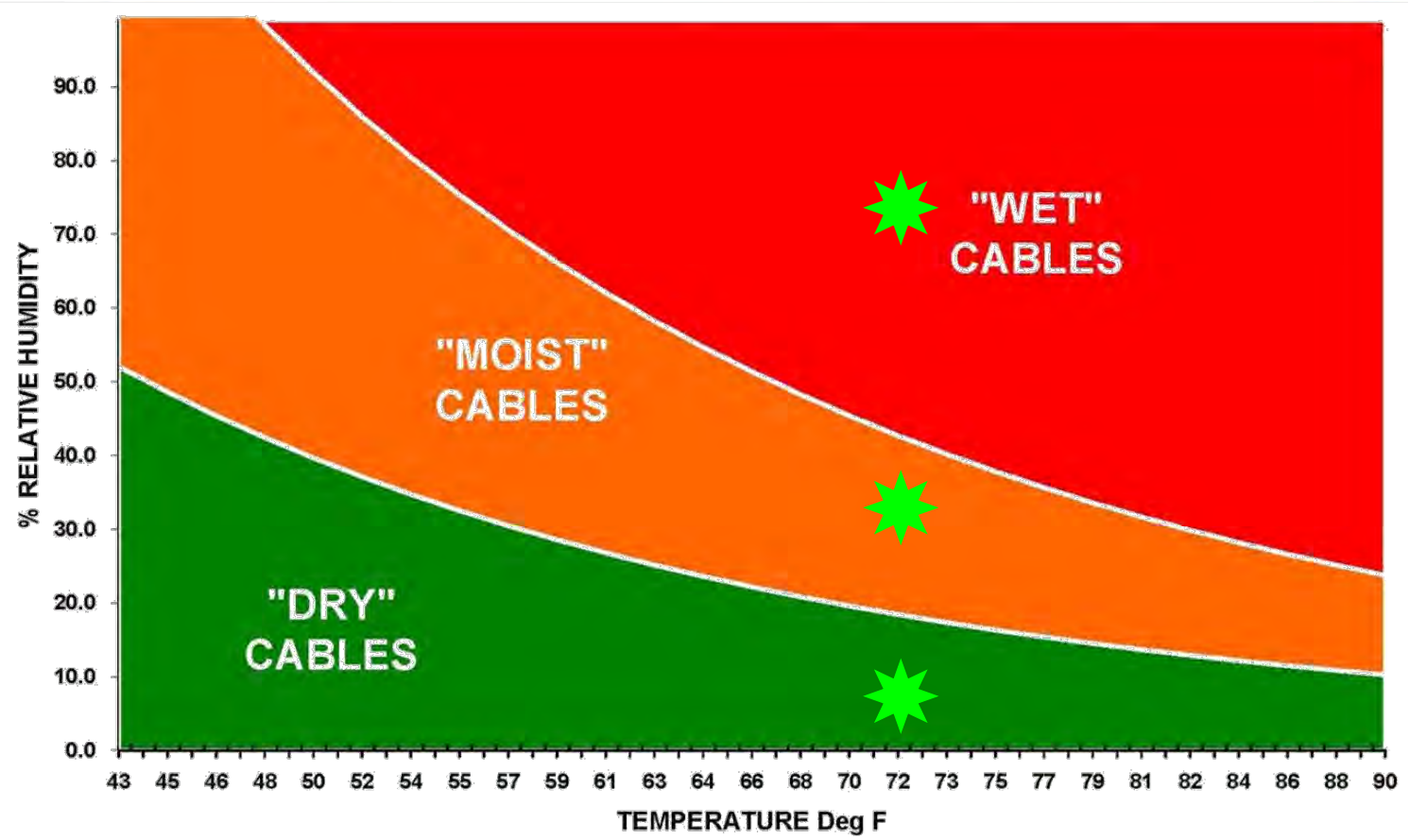
Moisture Testing

- Measures moisture content within the duct





PT Moisture Testing Grading Chart



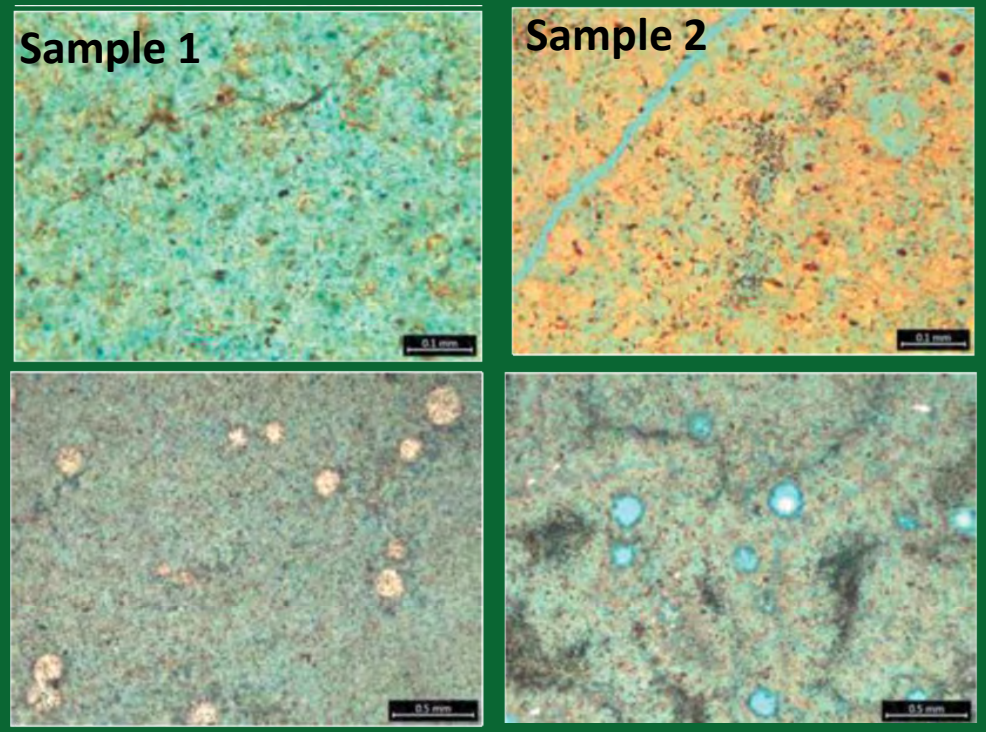
Risk of Corrosion

- Red – High
- Orange – Medium
- Green – Low

Materials Testing

- pH
- Chlorides
- Petrographic analysis

Petrographic Analysis



pH Testing



Chloride Testing

Table 1: Grout Chloride Concentration Results

Opening	Span	Cell	Web	Chloride Concentration (ppm by mass of grout)
#1	2	2	3	41
#2	2	2	2	5,908
#3	3	4	4	16,094

Table 2: Concrete Chloride Concentration Results

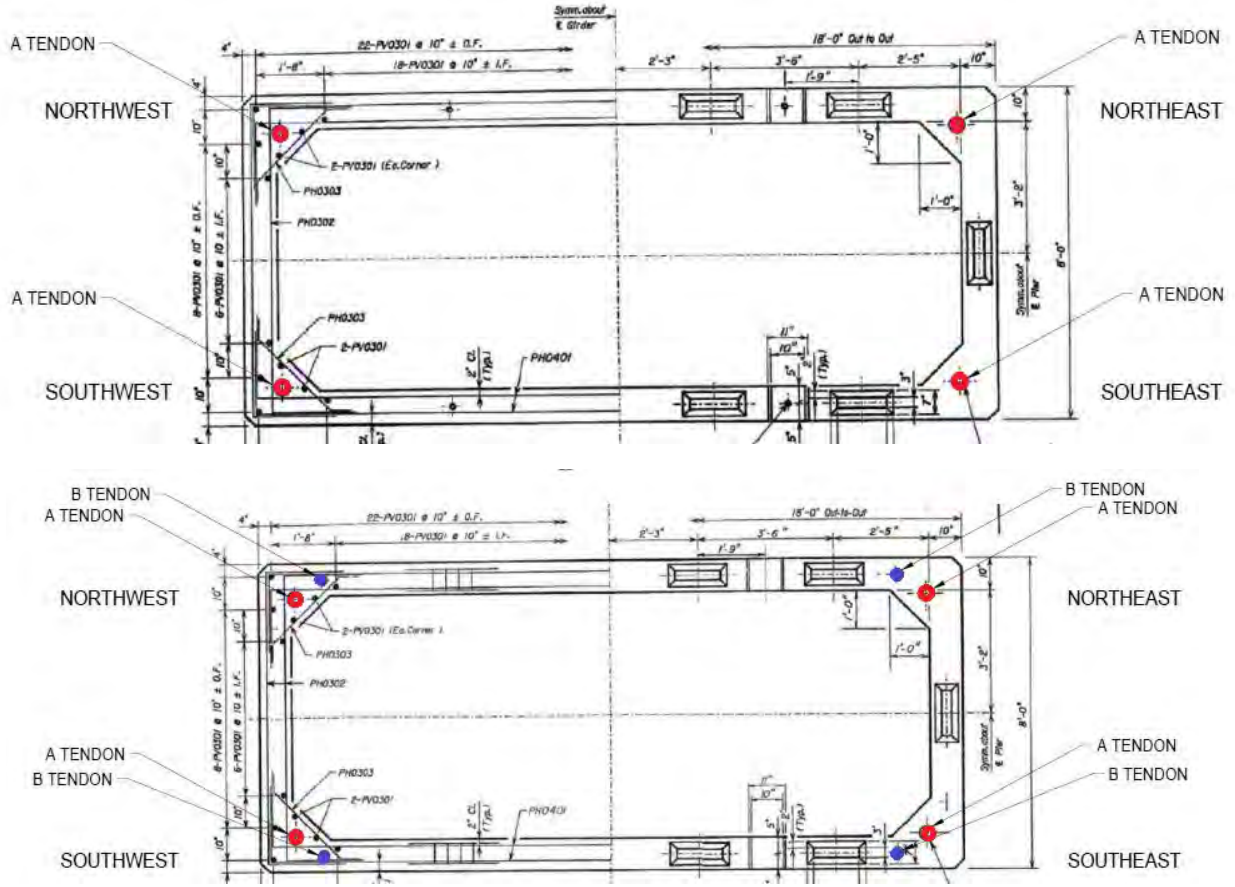
Location	Depth (in)	Chloride Concentration (ppm by mass of concrete)
Girder Floor	0.-0.5	2,950
	2.0 - 2.5	175
Bottom of Web	0-0.5	213
	2.5 - 3.0	112
Top of Web	0-0.5	101
	3.0 - 3.5	96

Case Studies

- Case Study 1: Post-Tensioned Bridge Piers
- Case Study 2: External Post Tensioning
- Case Study 3: Post-Tensioned Pier Caps

Case Study 1
Post-Tensioned Bridge Piers

Post-Tensioned Bridge Piers





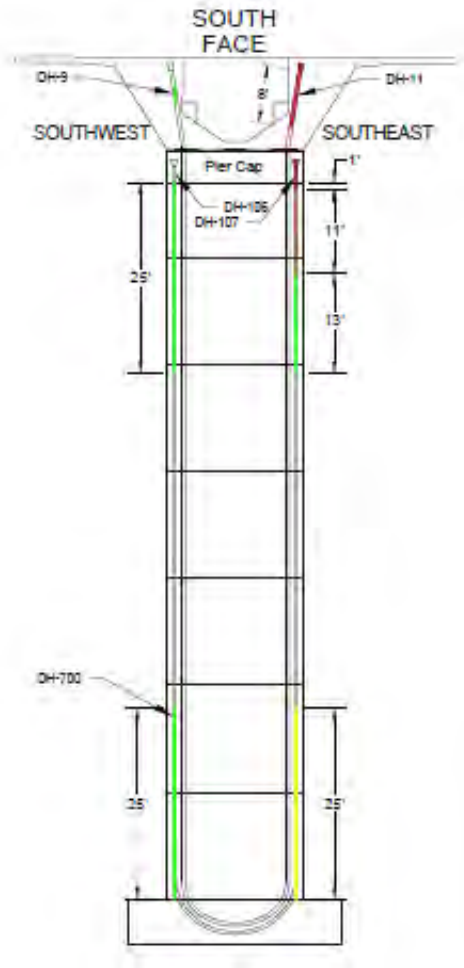
Post-Tensioned Bridge Piers

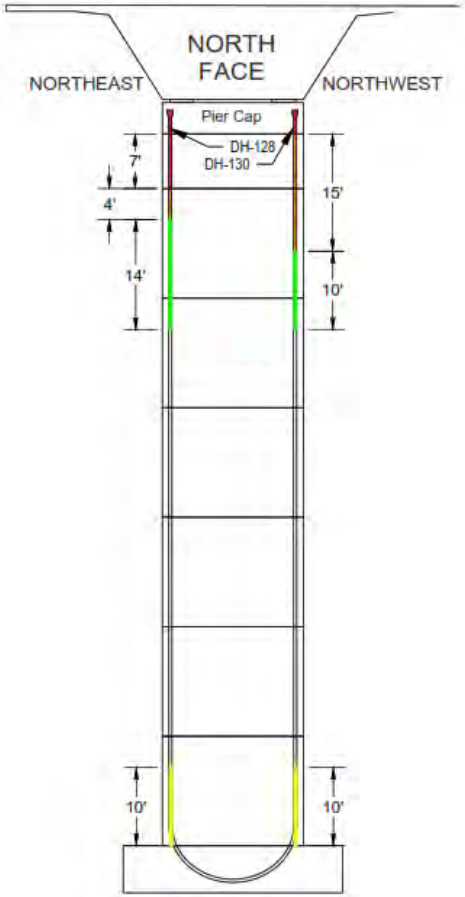
- IE/PV testing of the top and bottom 25 ft of tendon
  - 83% fully grouted, 17% grouting defects
- Borescope inspection of potential grouting defects identified by IE/PV
  - 63% of the tested tendons were voided, 17% had soft grout





LEGEND	
	VOIDED TENDON CONFIRMED BY BORESCOPE
	VOIDED TENDON NOT CONFIRMED BY BORESCOPE
	NON-VOIDED TENDON CONFIRMED BY BORESCOPE
	NON-VOIDED TENDON NOT CONFIRMED BY BORESCOPE
	SOFT OR WEAK GROUT
DH-###	DRILL HOLE LOCATION





Case Study 2
External Post Tensioning

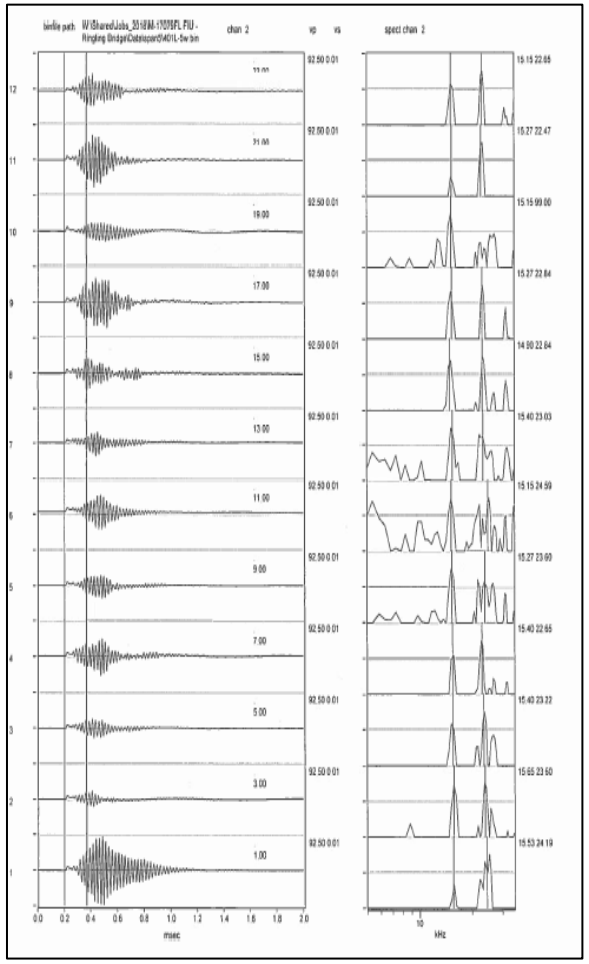
External Post-Tensioning



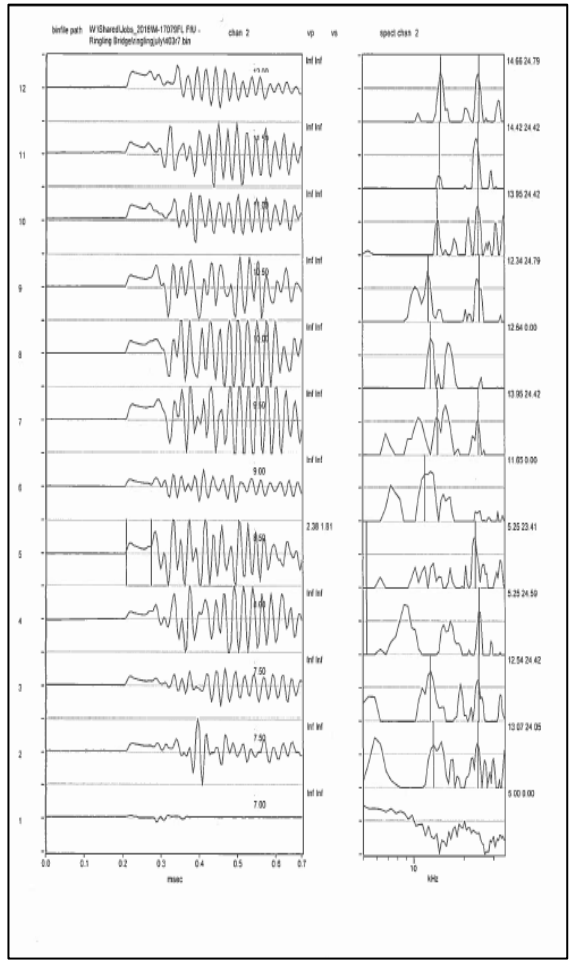
External Post-Tensioning



PV Data IE Data

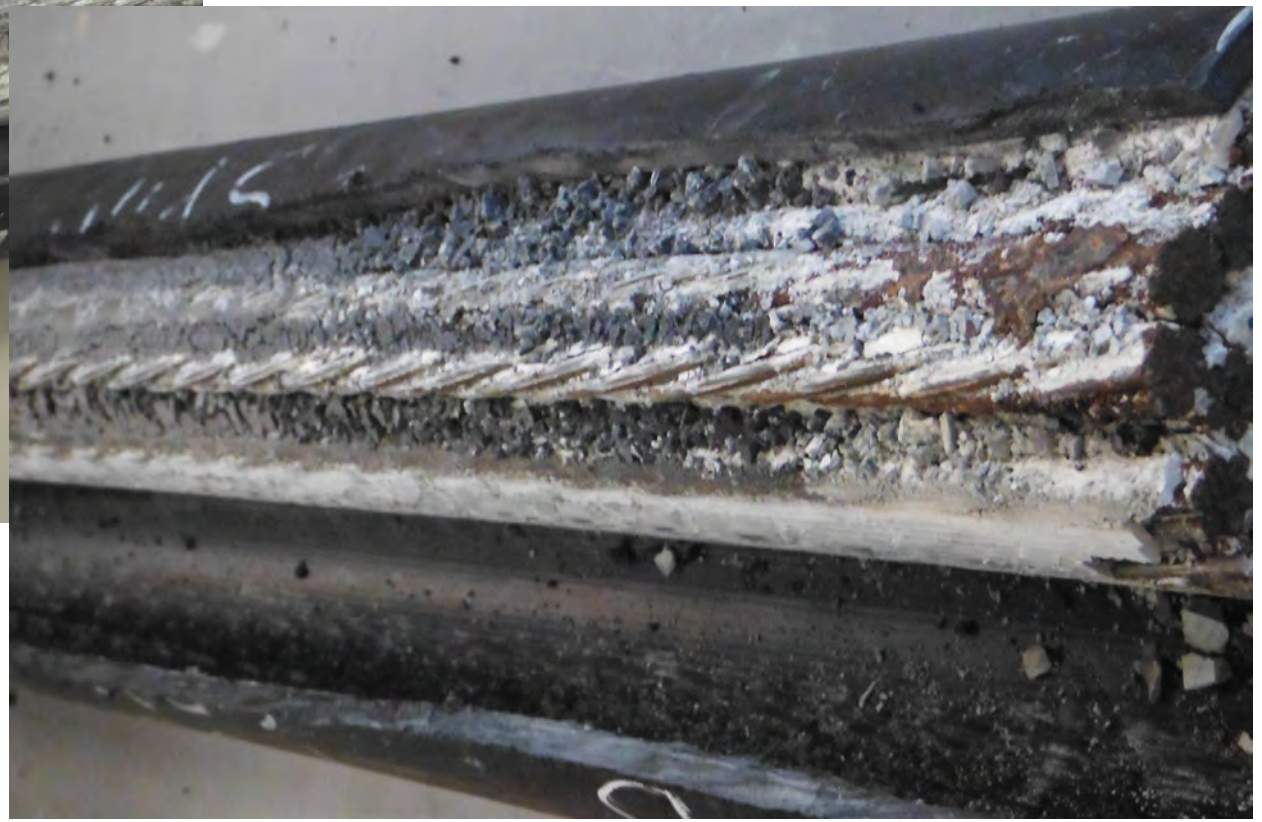


PV Data IE Data



External Post-Tensioning





Case Study 3
Post-Tensioned Pier Caps

Post-Tensioned Pier Caps

- Visual inspection of the anchorages
- Borescope inspection of the grout ports
- Moisture testing of the tendons
- Grout chloride testing









Post-Tensioned Pier Caps

- Majority of the grout ports were full
- Voided grout ports were inspected with borescope
- 6% had lens voids
- 13% were voided

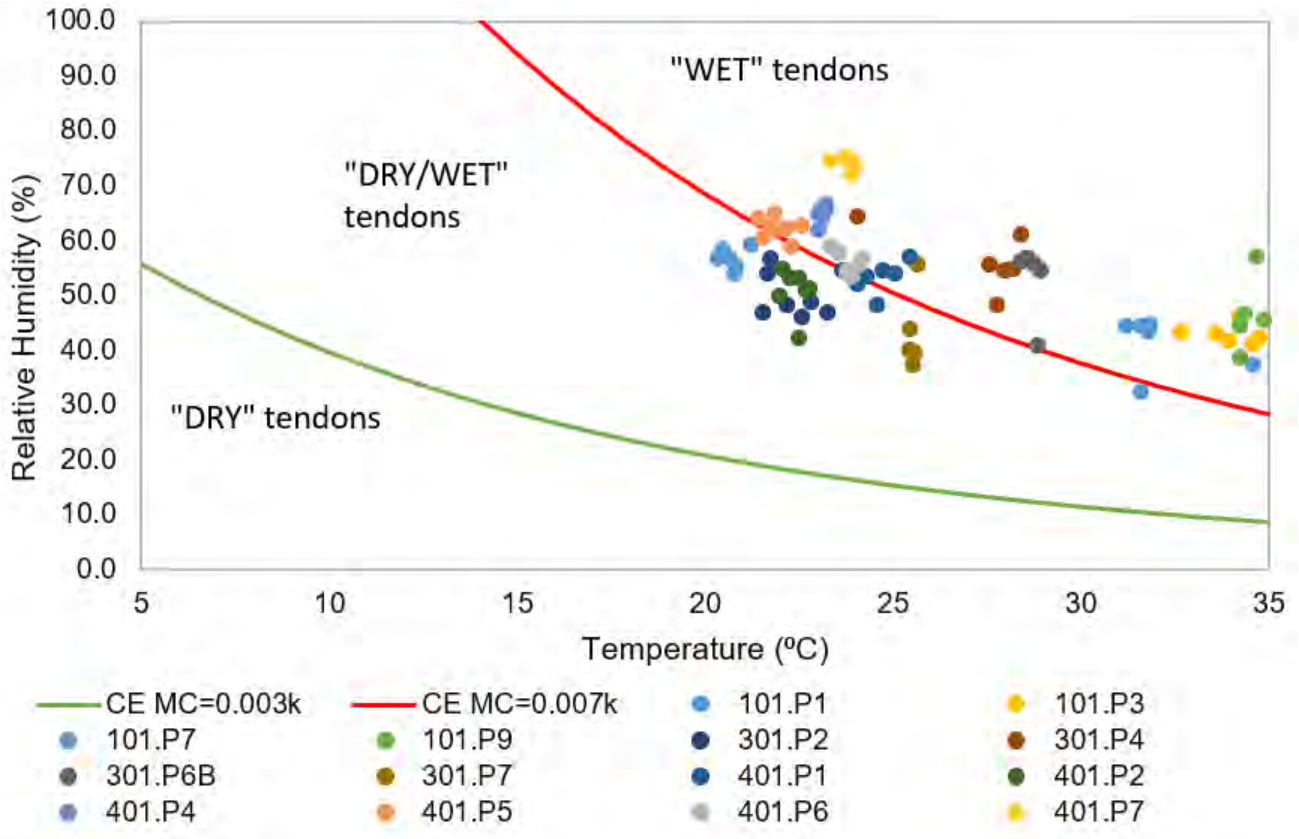




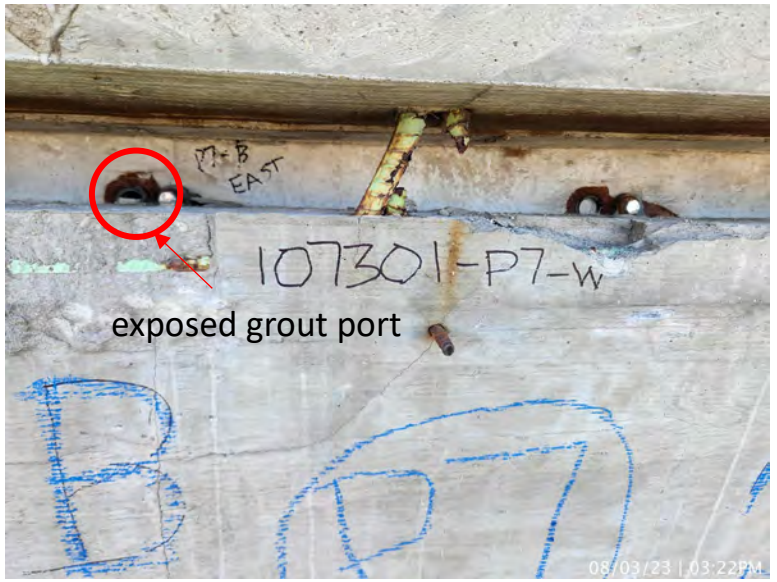




Moisture and Chloride Testing



Only 1 chloride sample was above the corrosion initiation threshold



Unbonded PT Systems

Outline

- Unbonded PT was introduced to the U.S. in the 1950's
- A five-fold increase in PT between 1965 and 1985
- Over 500 million sq ft of PT slabs in the U.S.



Evaluation – Approach

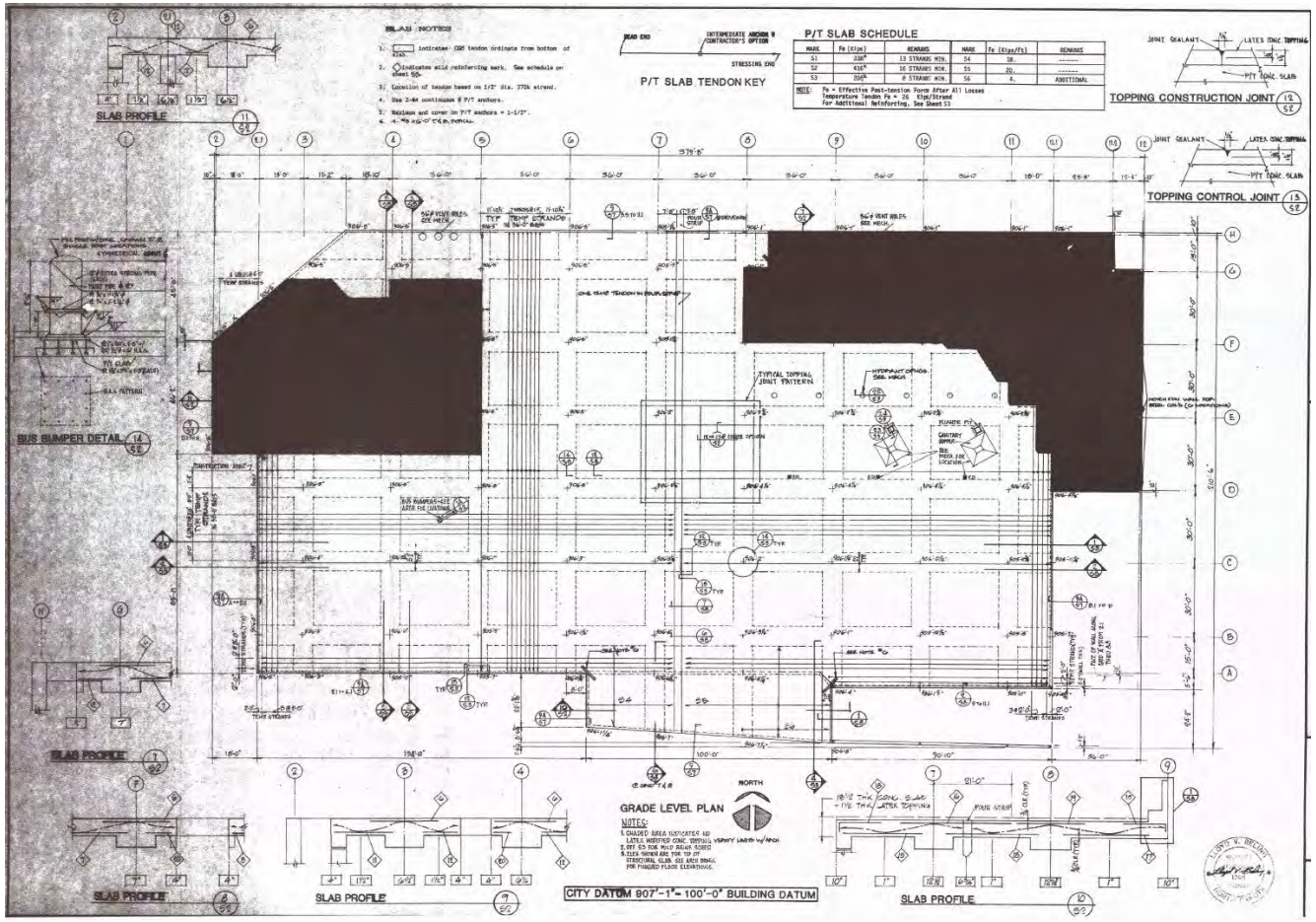
First Steps (Phase 1):

Evaluation may take multiple steps or phases:

- Document Review
- Visual Inspection
- Pull Broken Tendon

Develop a Plan to Perform (Phase 2):

- Tendon Excavations and Evaluation
- Moisture Testing
- Corrosion Testing
- In-Situ Tension Testing

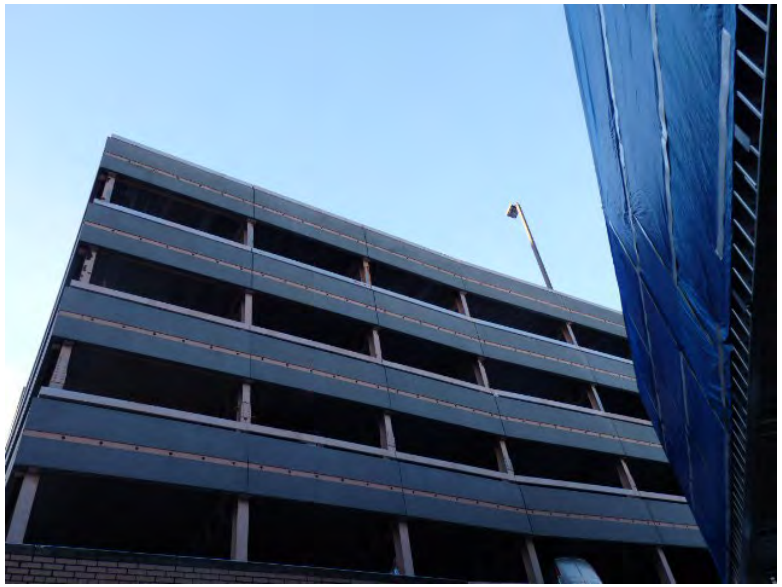


Plan 1982

Evaluation – Approach

- Age of the Structure
  - Anchors
  - Sheathing
- Past Documents
  - Blueprints
  - Shop Drawings
  - Past Inspection Reports
- Field Work – Visual Inspection
  - Maintenance / Address Visible Issues
  - Change of Use / Bring to Modern Standards

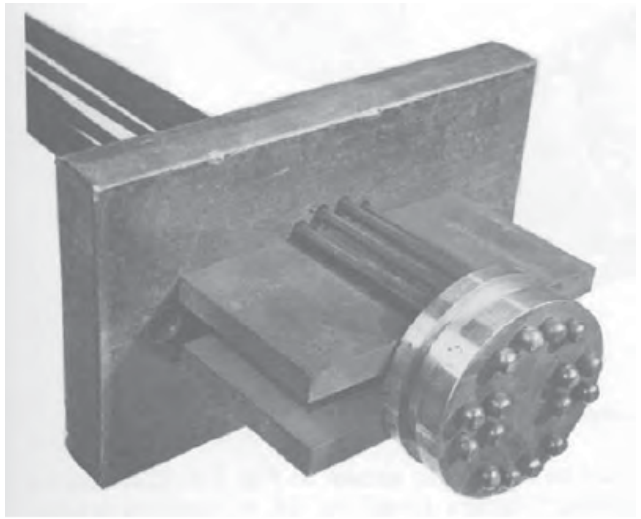
Safety





Challenges

- Growth and changing standards have created a plethora of repair challenges
- Modern day PTI standards introduced 1985
- Post-Tensioning Manual, 6th Edition 2006





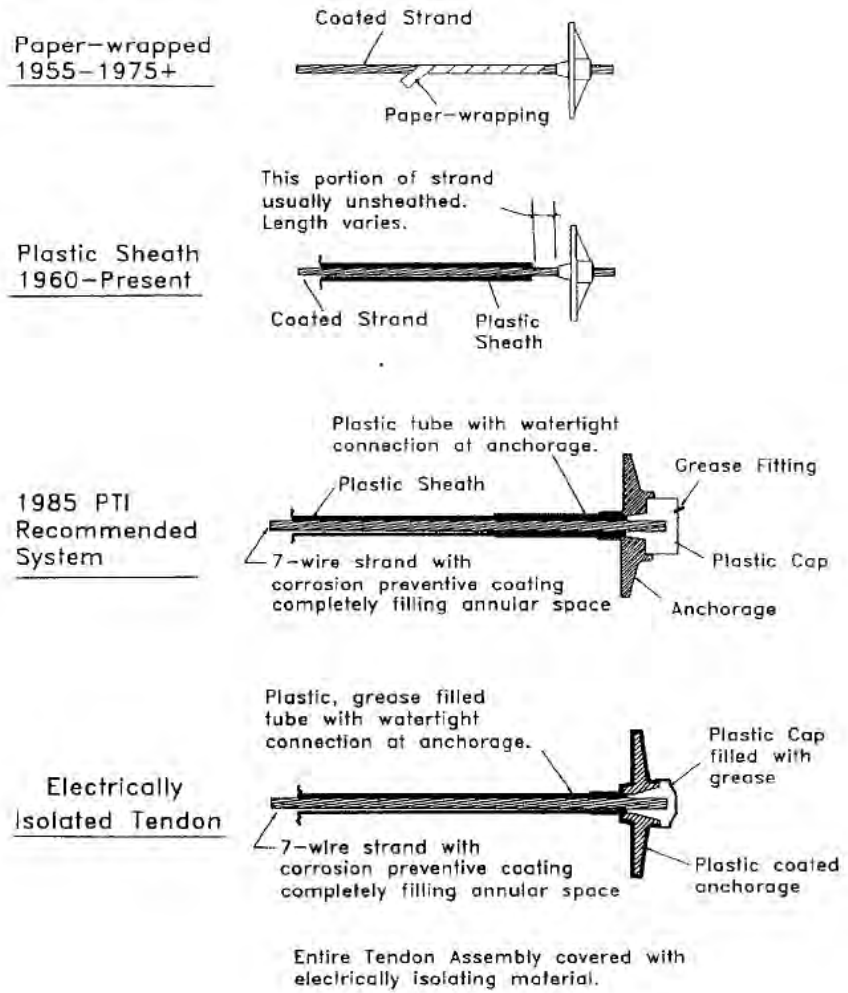


Fig. 3.2—Evolution of corrosion protection for unbonded single strand tendons for buildings (reprinted from Reference 2).

Construction Practices - Timeline

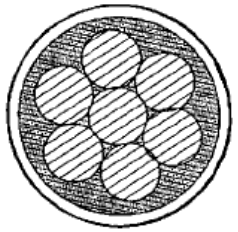


Buttonhead Wire - 0.25” diam



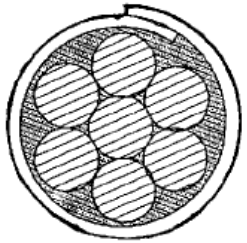
High Strength 7-wire strand

- Primarily 0.50”- 0.60” diam



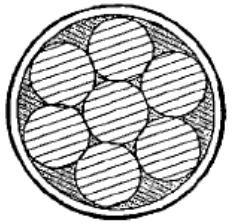
PUSH-THROUGH
PREFORMED TUBE

STRAND PUSHED THROUGH
AS GREASE IS APPLIED.



HEAT-SEALED

FORMED FROM FLAT STRIP
AS GREASE IS APPLIED.



EXTRUDED

FORMED BY EXTRUDING OVER
STRAND AS GREASE IS APPLIED.

Typical PT Features with Issues

Features

- Water Intrusion Through Anchors
- Expansion / Construction Joints
- Penetrations – Drains, Utilities, Railings, etc.
- Areas of Low Cover – Deck

Visible Signs of Damage

- Cracking over tendons – deck or soffit
- Cracking - stress
- Water staining – efflorescence / rust
- Erupted tendons / Popped grout caps









Evaluation

Non-Destructive Methods (Phase 1) → Visual Inspection, GPR, Sounding, Half Cell Potential

- Start a baseline understanding of the parking structures issues related to the post tensioning.
- Document and quantify findings/deterioration at present.
- Develop plan for more invasive testing.

Invasive Methods (Phase 2) → Excavations (SPT), Grout Cap Removal, Moisture Testing, Lift-Off, Load Deflection

- Extent of testing based off Phase 1 findings
- Used to assess whether deterioration is localized of global.
- Identifies if deterioration is based on construction defects, design concerns, and environmental factors.

Evaluation – Methods: Visual Inspection



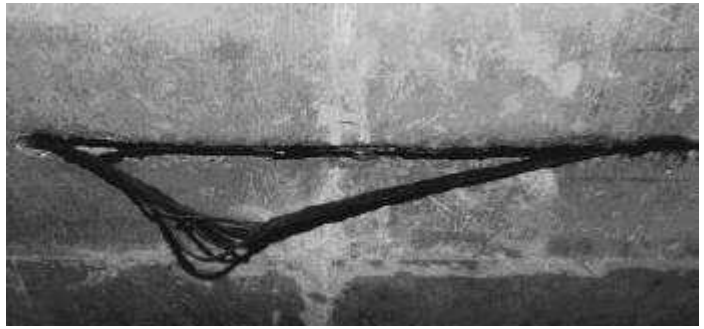
- Cracking in slab and beams
- Delamination





- Exposed anchorages or visible rust from grout pockets

- Tendon eruption through soffit or slab



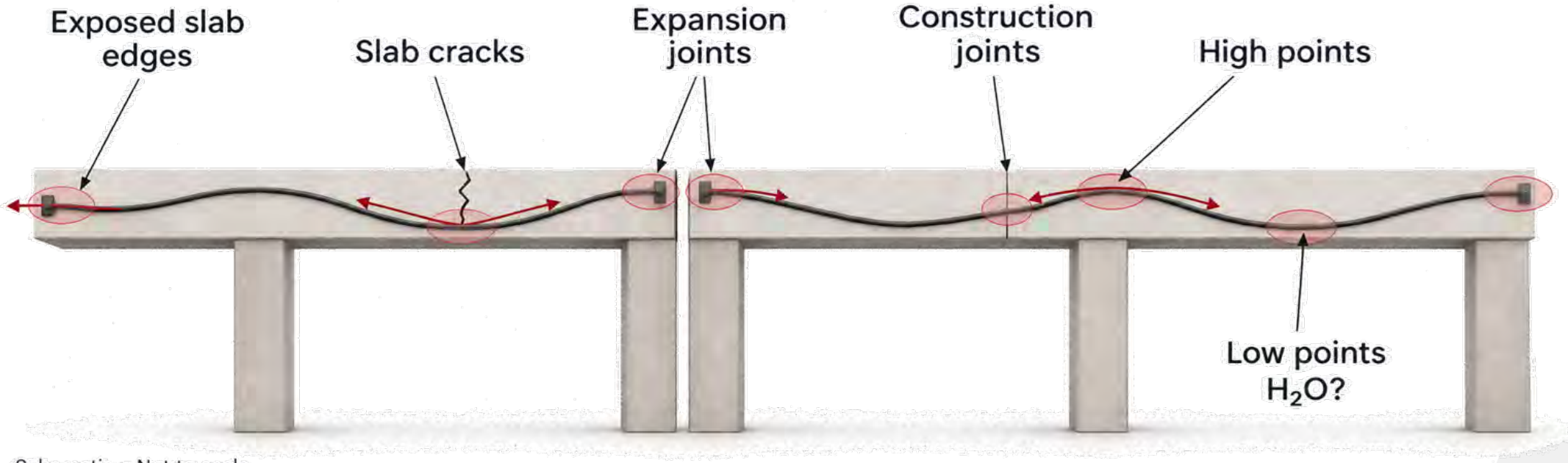


Evaluation – Methods: Visual Inspection









Schematic • Not to scale

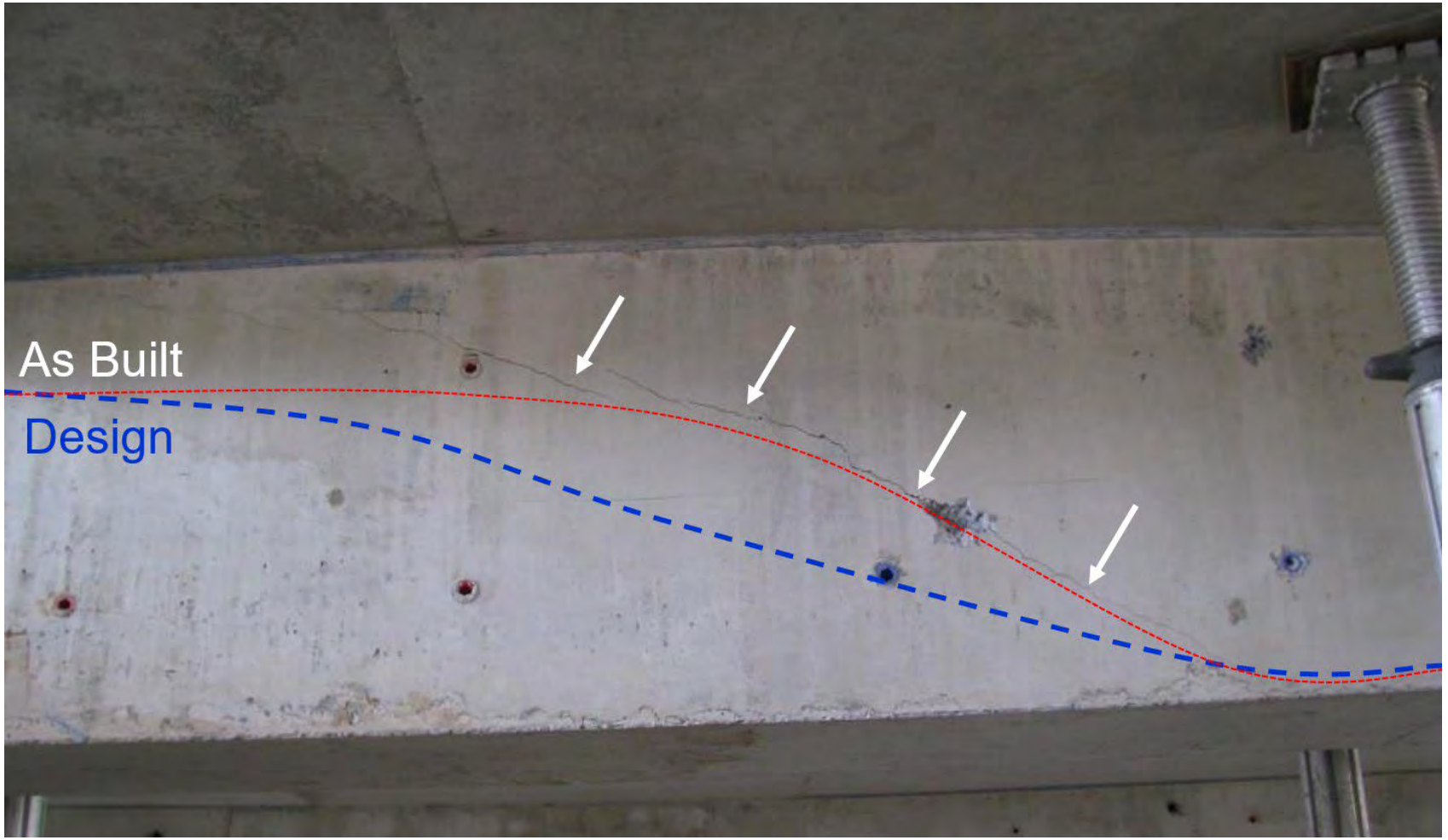
Moisture Issues



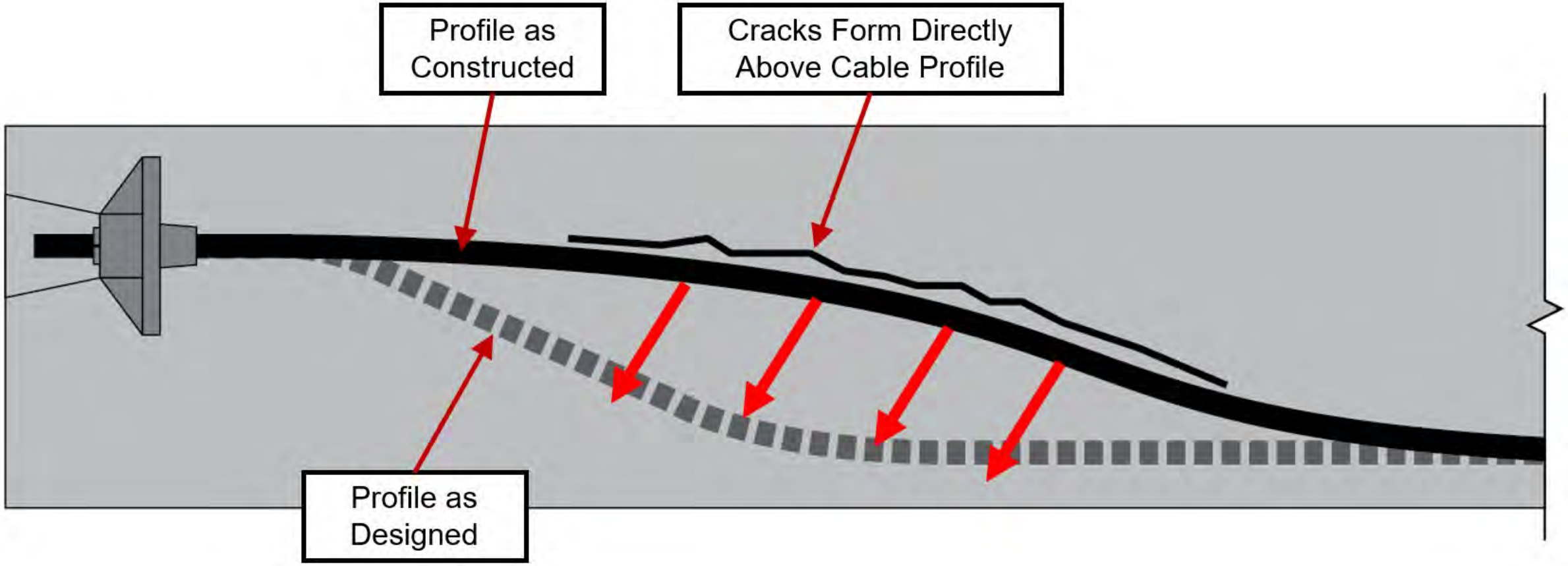




Evaluation – Methods: Visual Inspection



Evaluation – Methods: Visual Inspection

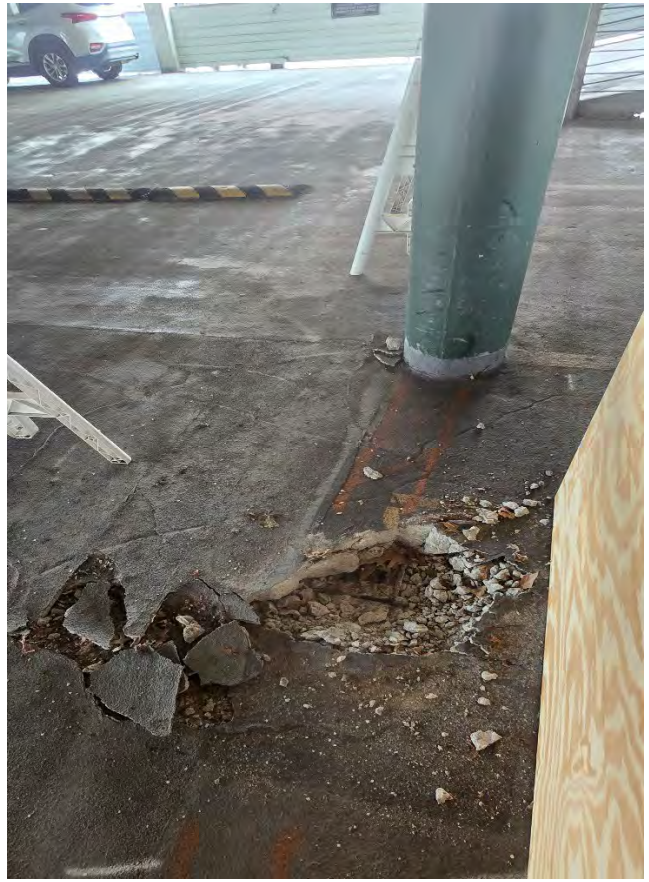


Evaluation – Methods: Visual Inspection

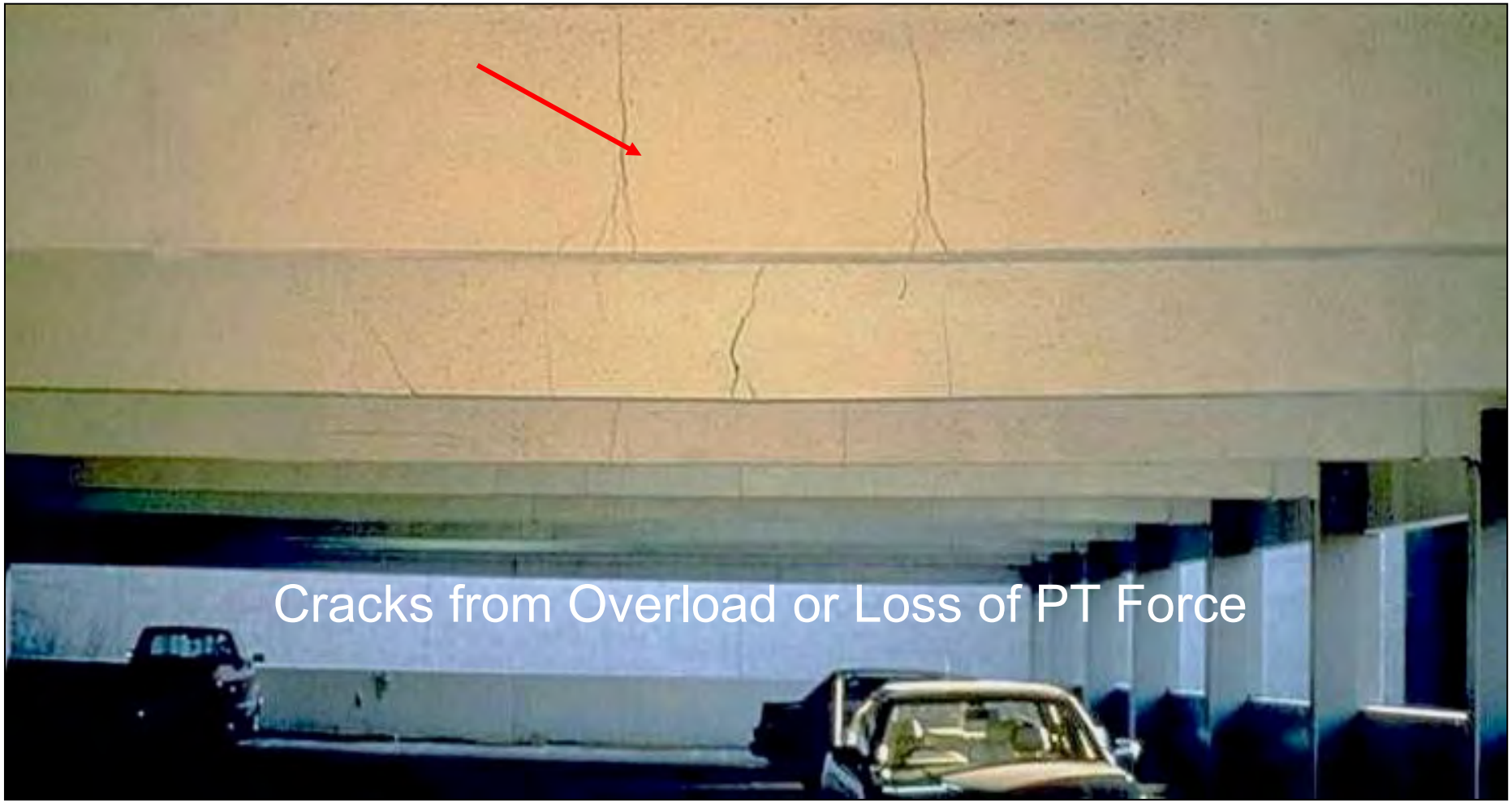
Punching Shear

- <u>Failure mechanism:</u>
  Punching shear occurs when a concentrated load from a column causes the slab to fail in a brittle manner around the column.
- Shoring

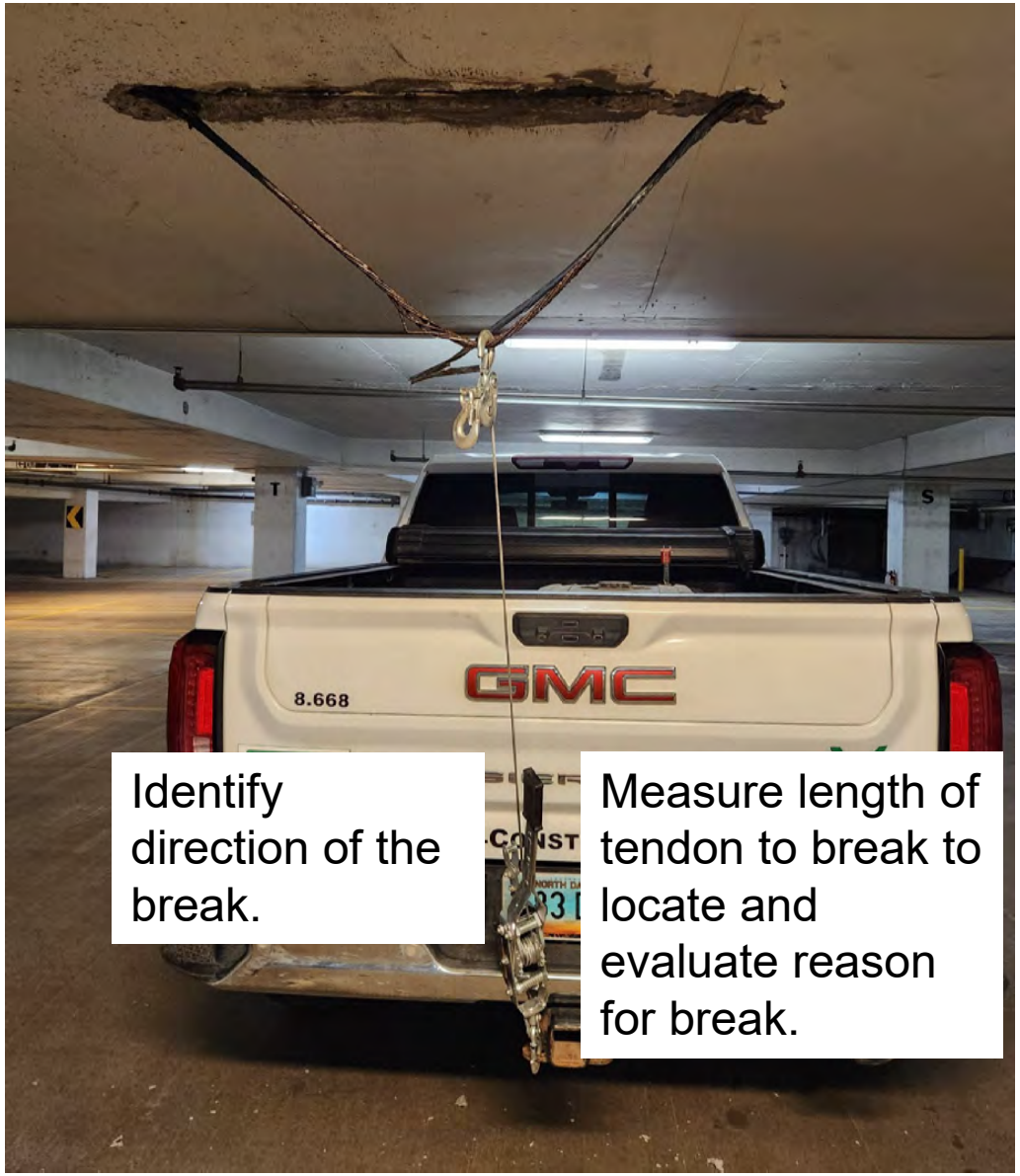




Evaluation – Methods: Visual Inspection



Extract Broken Tendons

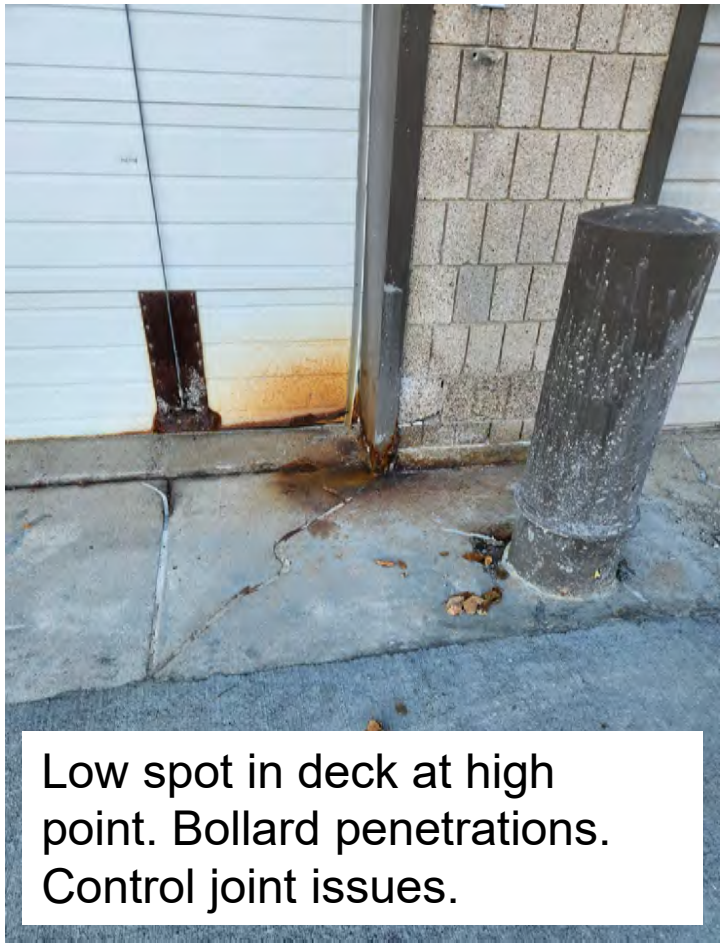


Identify direction of the break.

Measure length of tendon to break to locate and evaluate reason for break.



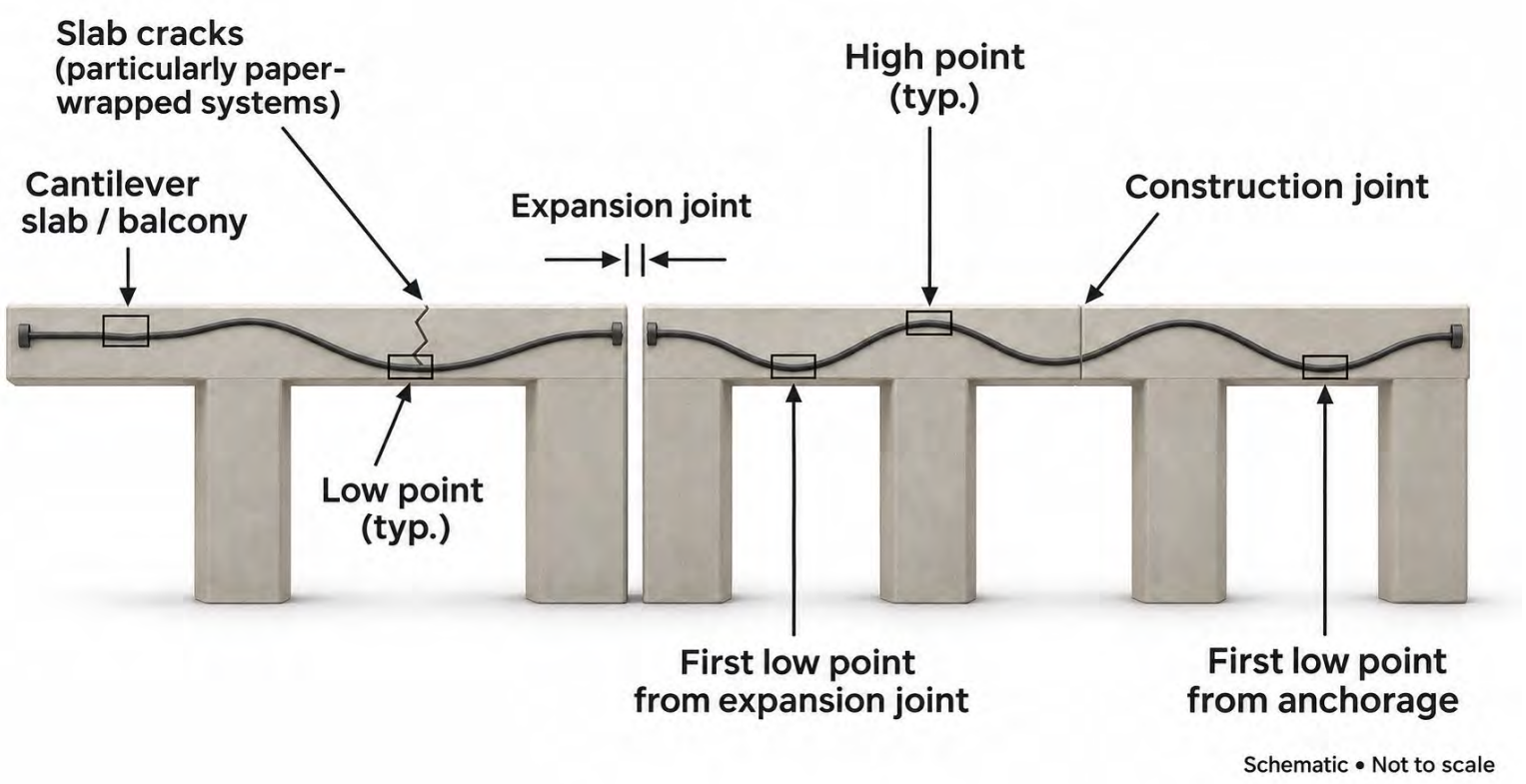
Corrosion at high point.



Low spot in deck at high point. Bollard penetrations. Control joint issues.

Effective Testing Procedures

- Hammer Sounding
- Ground Penetrating Radar to locate tendons
- Screwdriver Penetration Testing
- Corrosion Potential Testing (ASTM C876)
- Moisture Testing
- Lateral Deflection
- Lift-Off



Ground Penetrating Radar to Locate Tendons

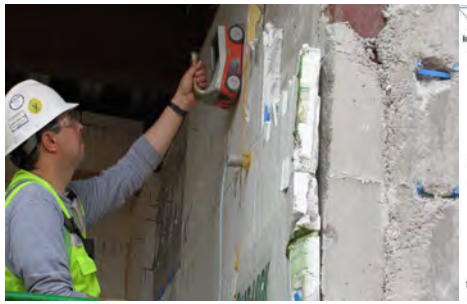


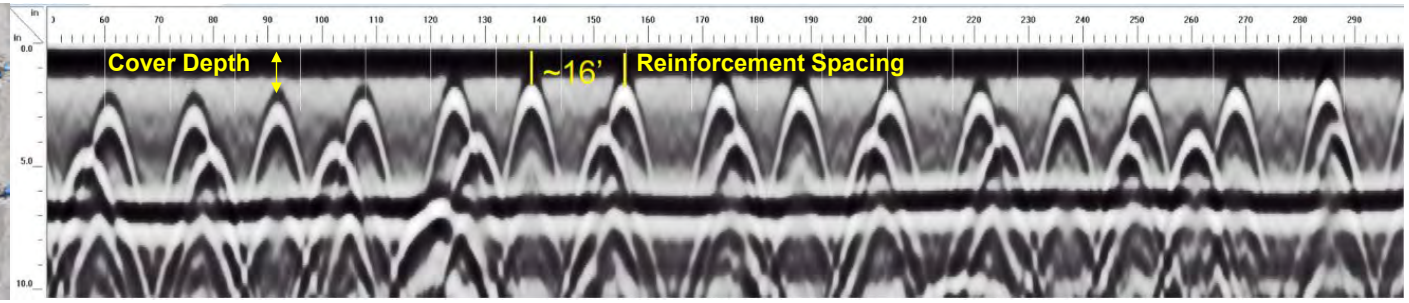






- Cover depth per plan
- Correct spacing between tendons

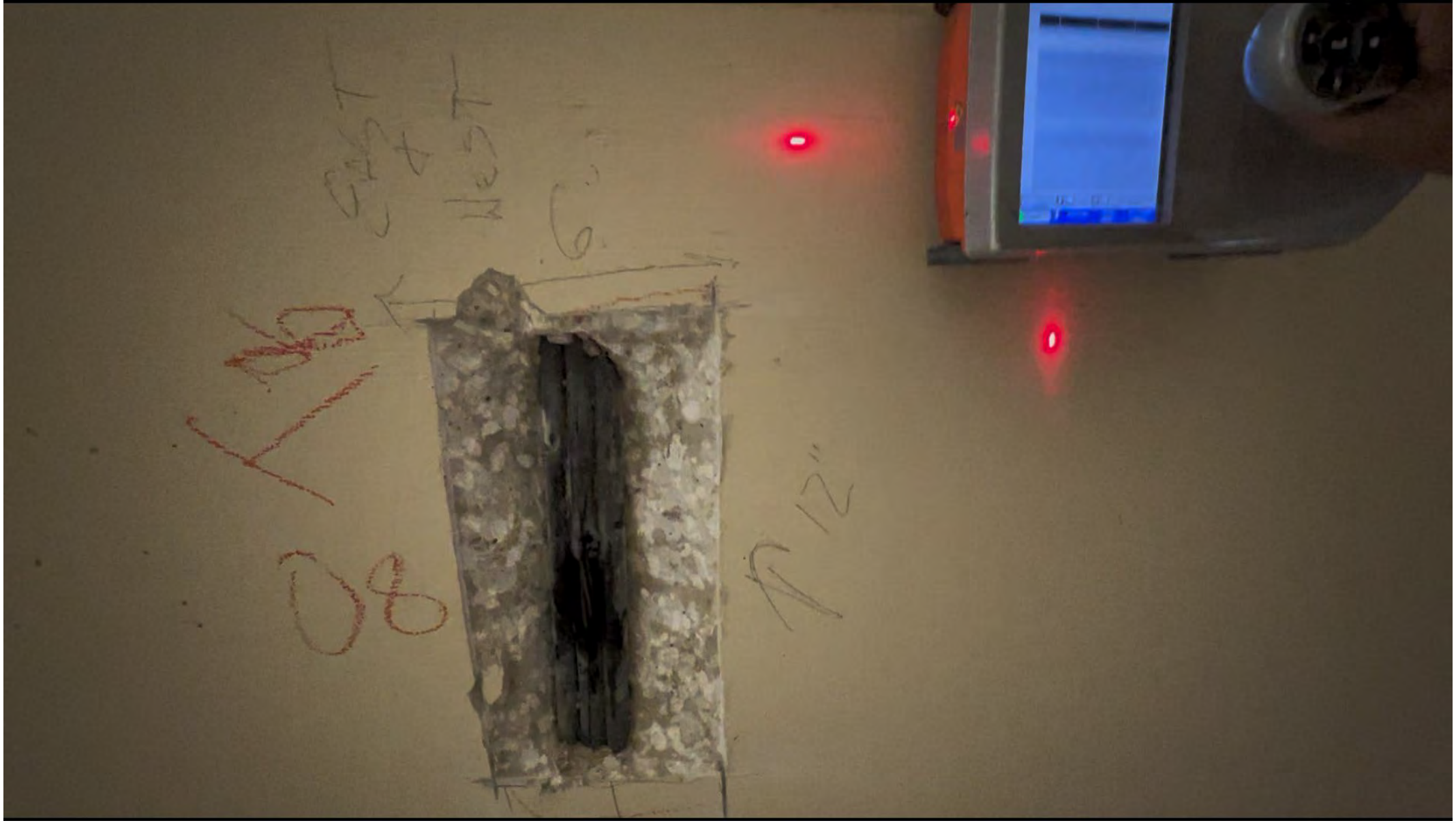




Poll #1

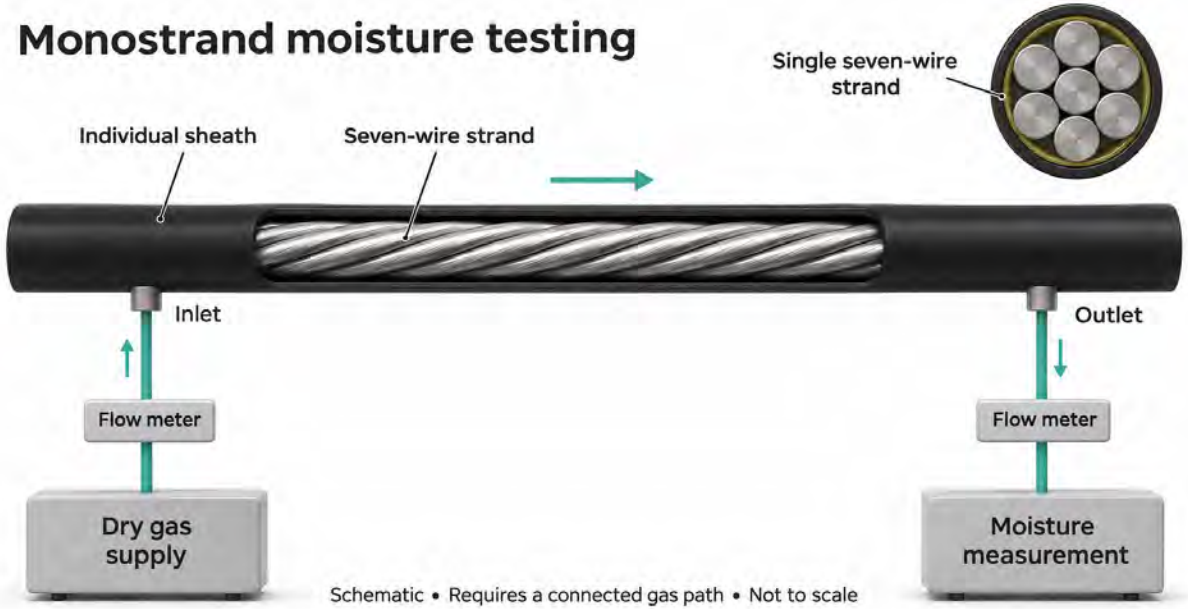
Can GPR determine Duct/strand size?

1. Yes
2. No


6"
12"
08

Moisture Testing

- Mono-strand Unbonded

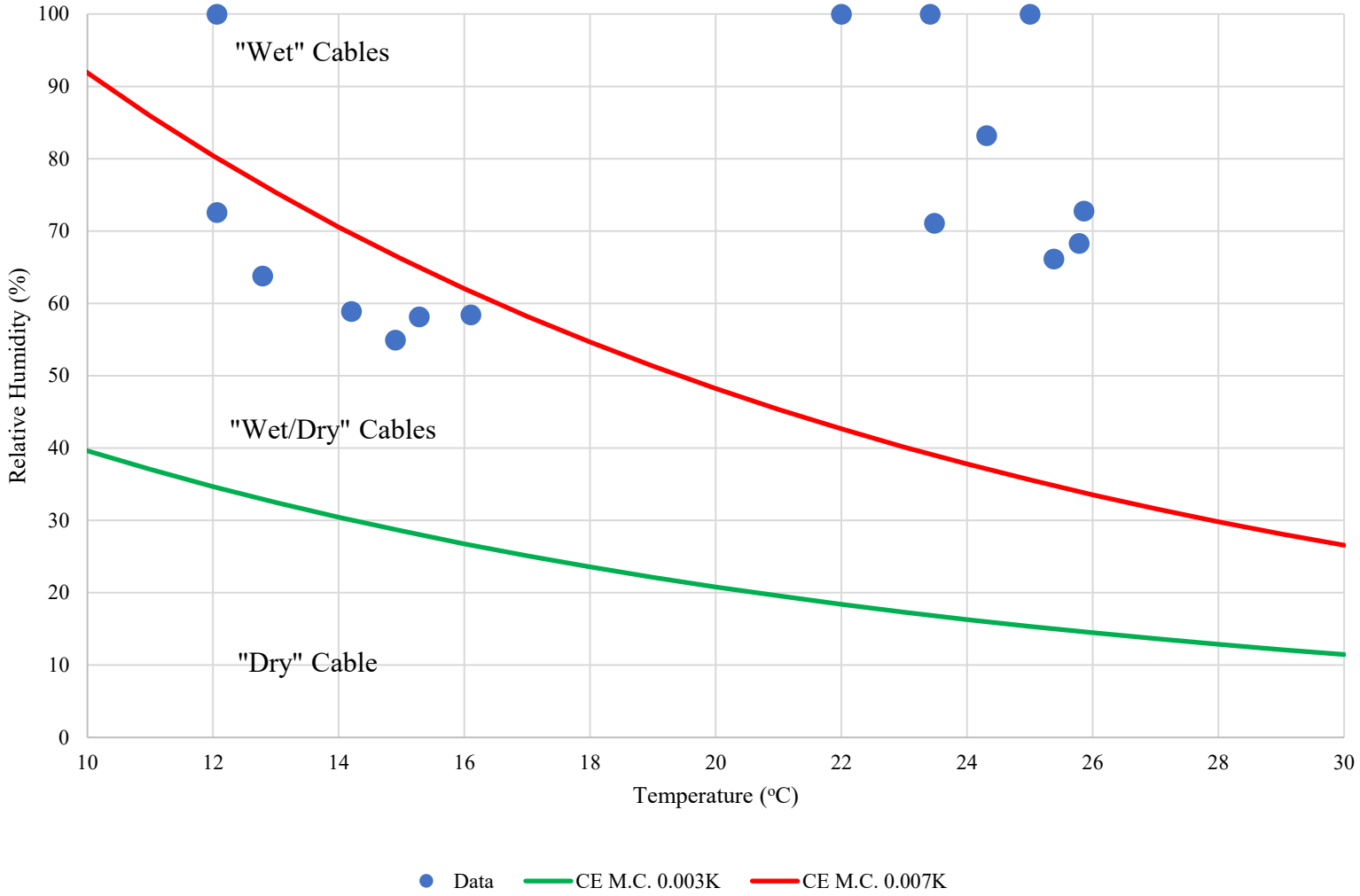








Moisture Testing





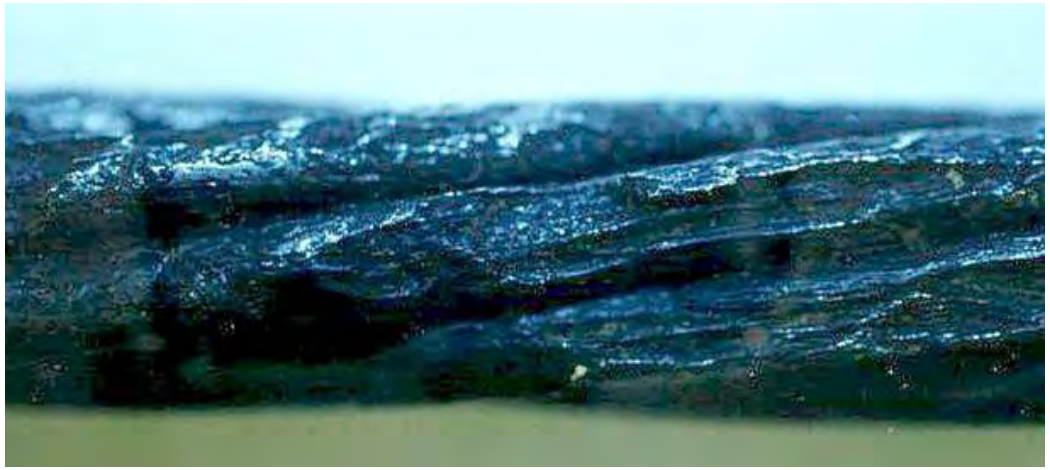
Excavations and SPT Tests

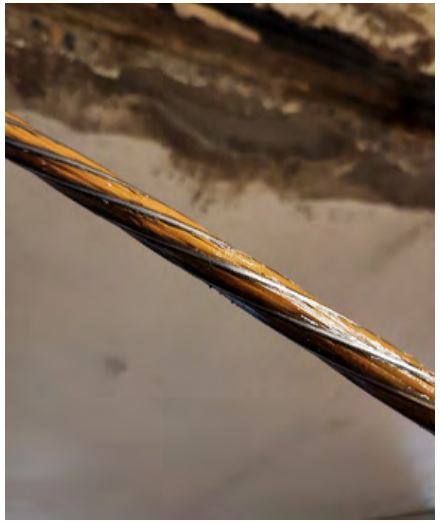
Tendons – Visual

- Presence of rust/water
- Corrosion pitting
- Emulsified grease

Screwdriver Penetration Tests

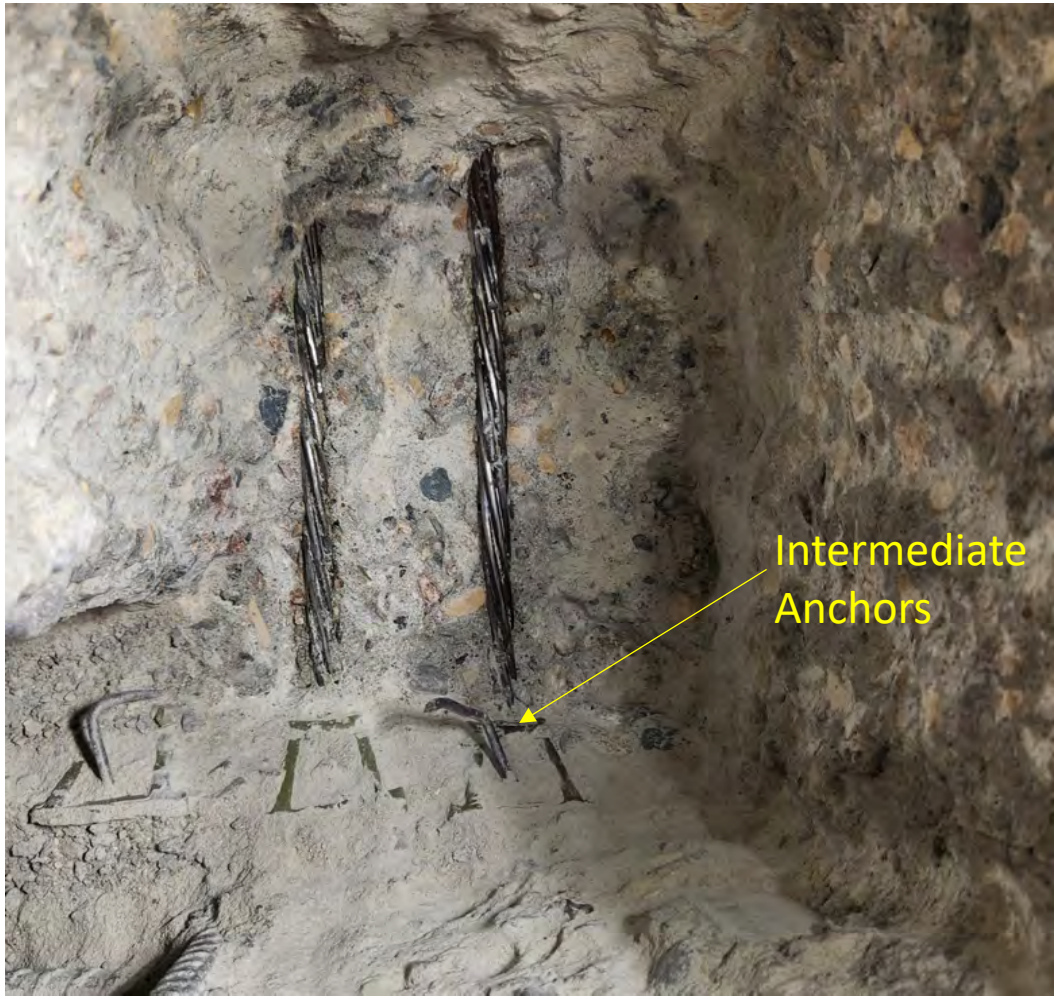
- Affordable and quick
- Pass/Fail – tendon is stressed/not stressed
- Qualitative







Excavate Tendons





Unbonded PT Opening

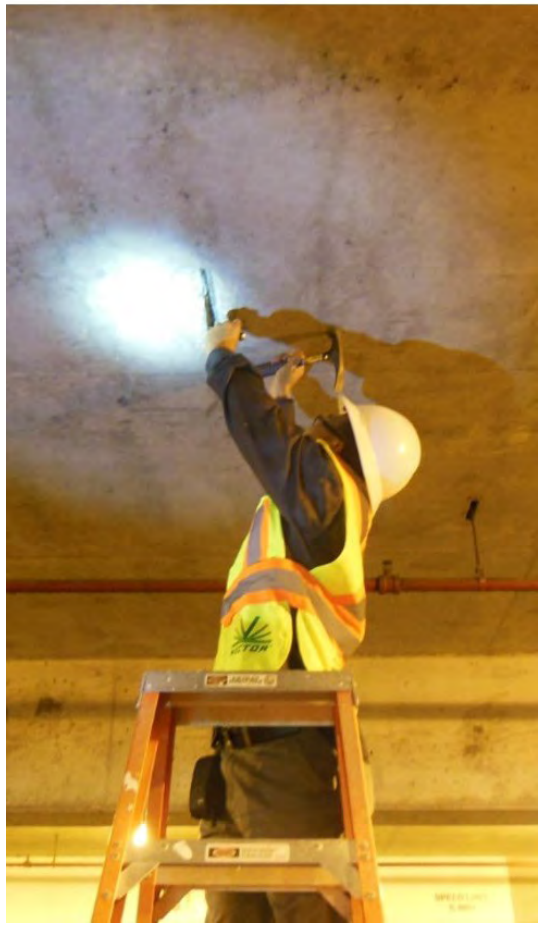








Screwdriver Penetration Test

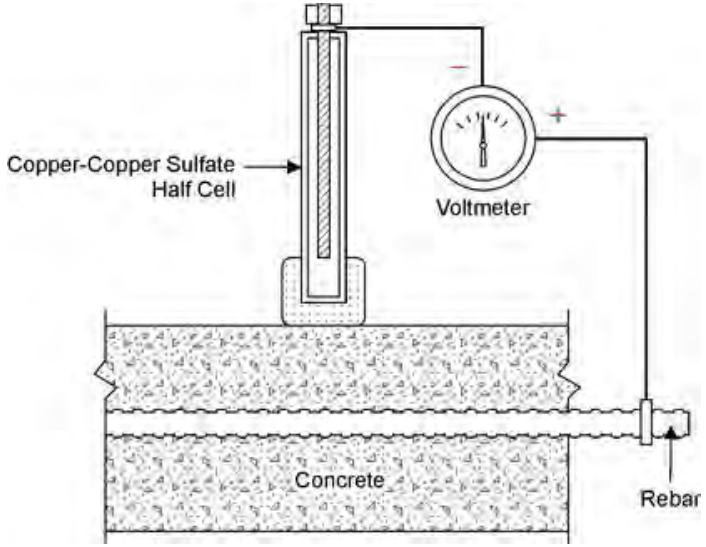




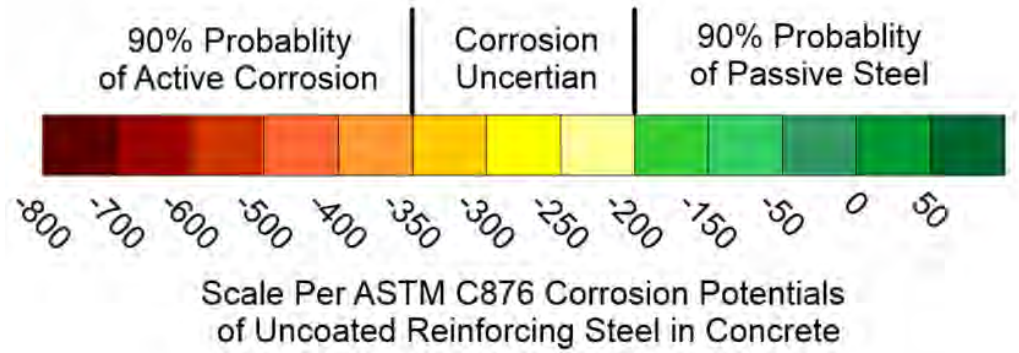


Corrosion Potential Testing

- ASTM C876 - also known as half-cell potential
- Determines the probability of active corrosion
- Can be performed only on anchorages
  - Tendons/strands shielded by the duct
- Potential difference between the steel reinforcement and a reference electrode to identify the probability of active corrosion

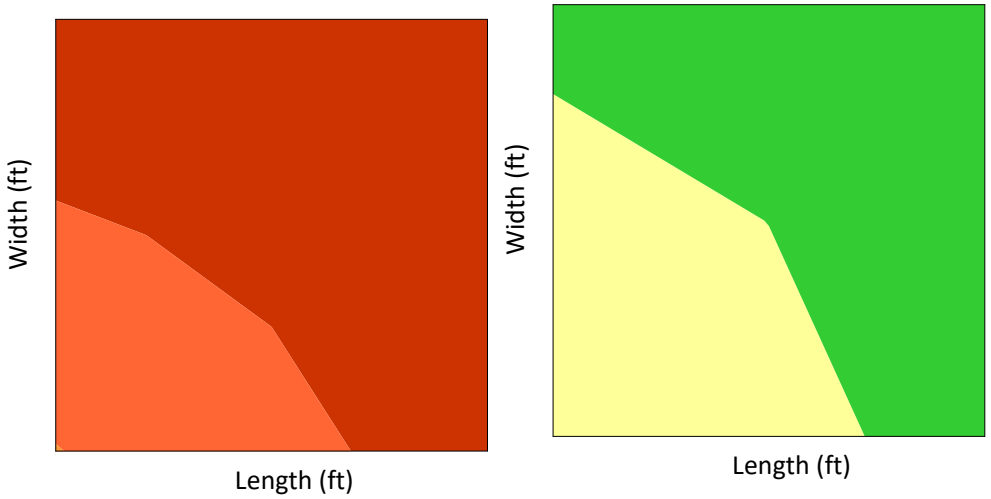






Scale Per ASTM C876 Corrosion Potentials
of Uncoated Reinforcing Steel in Concrete

Corrosion Potential Testing

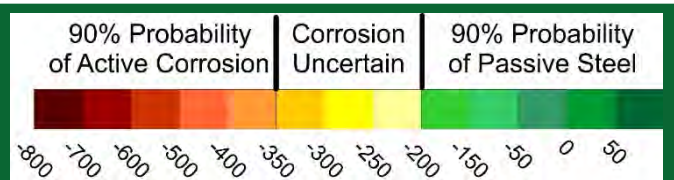


Evaluate rebar around anchors

- End anchors – bare
- Intermediate anchors
- Joints – expansion/construction
- Paper-wrapped tendons







Poll #2

Can a Corrosion Potential Survey detect corrosion activity on the monostrand PT Cables?

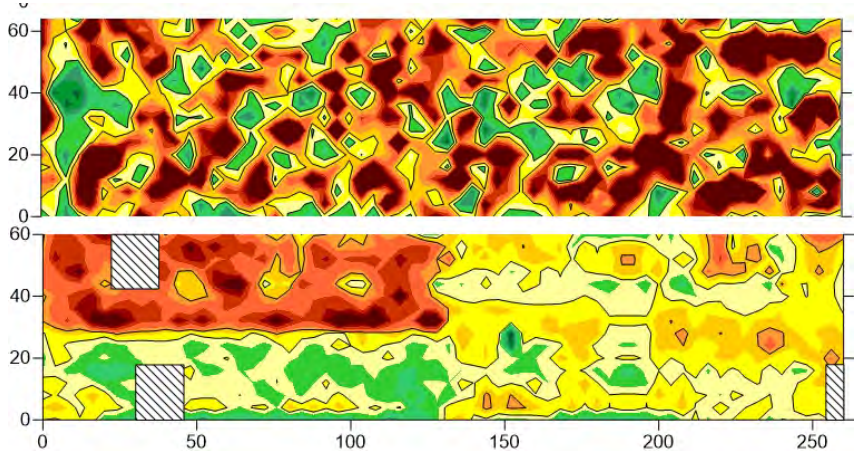
1. Yes
2. No

Corrosion Potential Testing

Considerations:

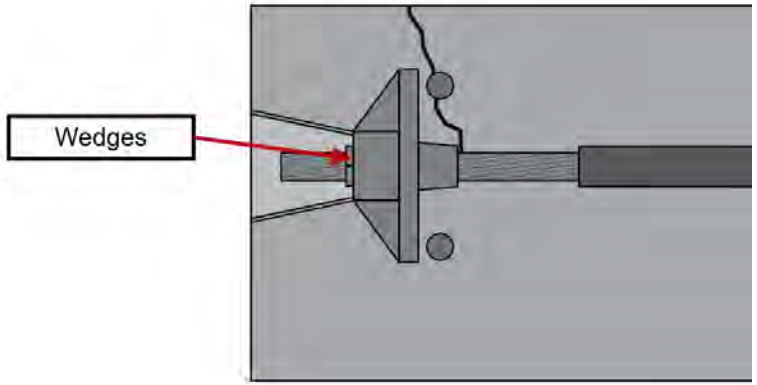
- Not possible on fully encapsulated electrically isolated tendon systems (after 2014).
- Traffic coating and painted areas require removal to test.
- Pairs well with chloride testing (deicing salts / marine environment) and carbonation testing.
- Identify Corrosion Hot Spots
  - Wheel Paths
  - Parking Spots



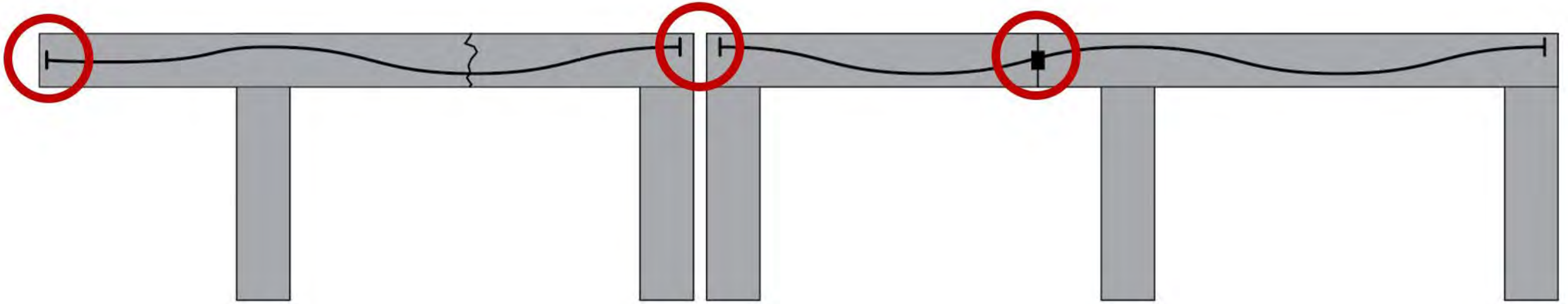


Excavate Anchor Pockets

- Inspect wedges for corrosion and seating
- Inspect anchor for corrosion











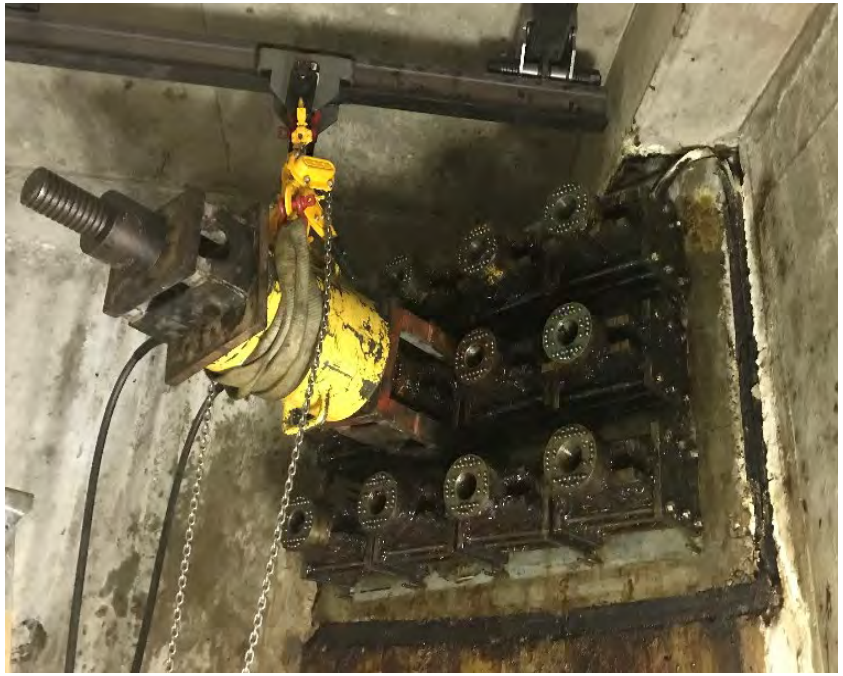


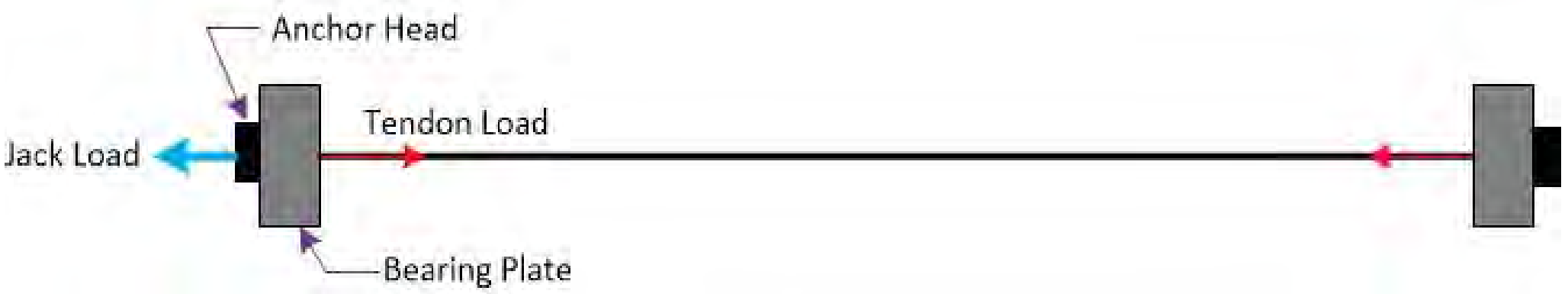


WE SAVE STRUCTURES
CONCRETE PRESERVATION ALLIANCE

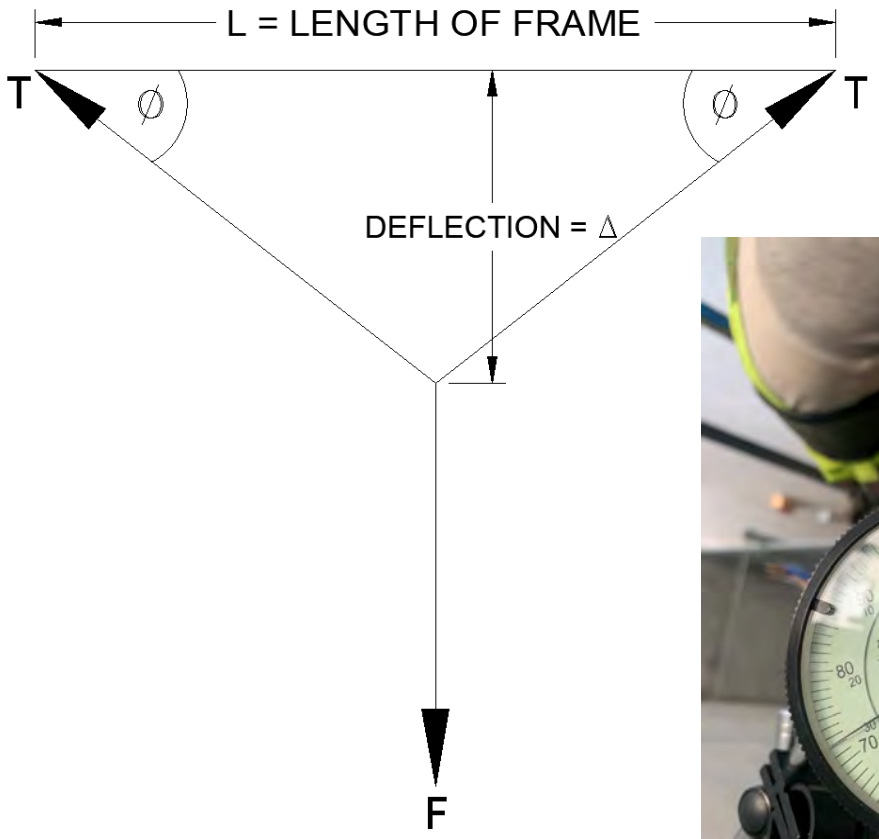
Lift Off Testing

- Determine current stress tendons are under

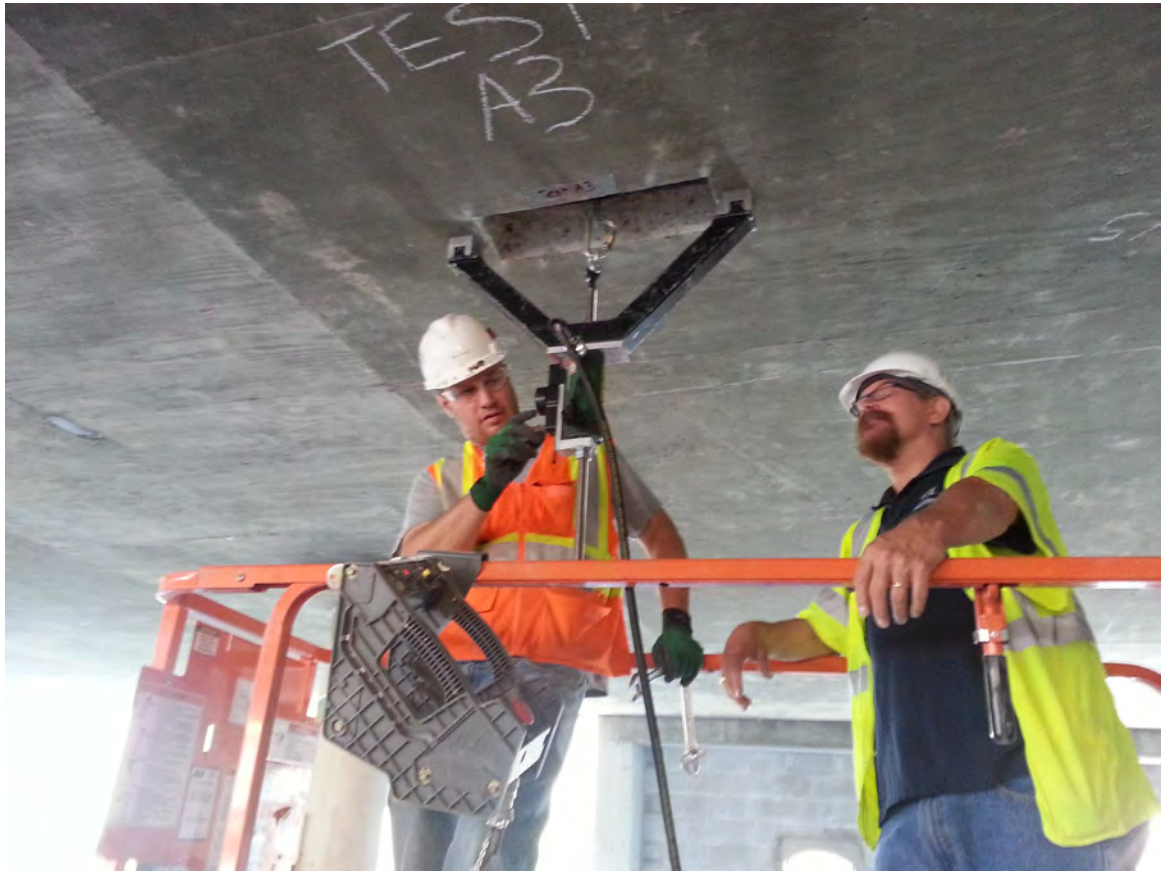




Lateral Deflection Testing







Lateral Deflection Testing





Lateral Deflection Test Results

Location ID	Δ2 Average (in.)	Δ1 Average (in.)	Δ2 - Δ1 Average (in.)	Average Theoretical Tension (lb)	Average Calculated Tension (lb)	Average Calculated Tension (kips)
1	0.434	0.231	0.203	26419	26778	27
2	Not Tested - Tendon Bundling					
3	0.375	0.234	0.141	37896	40865	41
4	0.426	0.244	0.182	29428	30471	30
5	Not Tested - Tendon Bundling					
6	0.566	0.407	0.159	33816	35858	36
7	0.515	0.286	0.228	23750	23502	24
8	0.393	0.202	0.190	28037	28765	29
9	0.520	0.290	0.230	23524	23225	23
10	Not Tested - Tendon Bundling					
11	0.540	0.304	0.236	22702	22217	22
12	0.381	0.192	0.190	28619	29478	29
13	0.411	0.211	0.200	26705	27129	27
14	0.382	0.209	0.173	30878	32251	32
15	0.378	0.192	0.186	28657	29526	30

Flexible Filler-PT System



- Multistrand Unbonded System
  - Easy Repairs
- Microcrystalline wax (Hydrocarbon)
  - High-Temperature Injections
  - Shrinkage Voids
  - Air/Water Voids- If leaks are present
  - Great food for corrosion-causing bacteria
    - APB- Acid-Producing Bacteria
    - IRB- Iron-reducing bacteria
    - SLYM-Slym Producing Bacteria

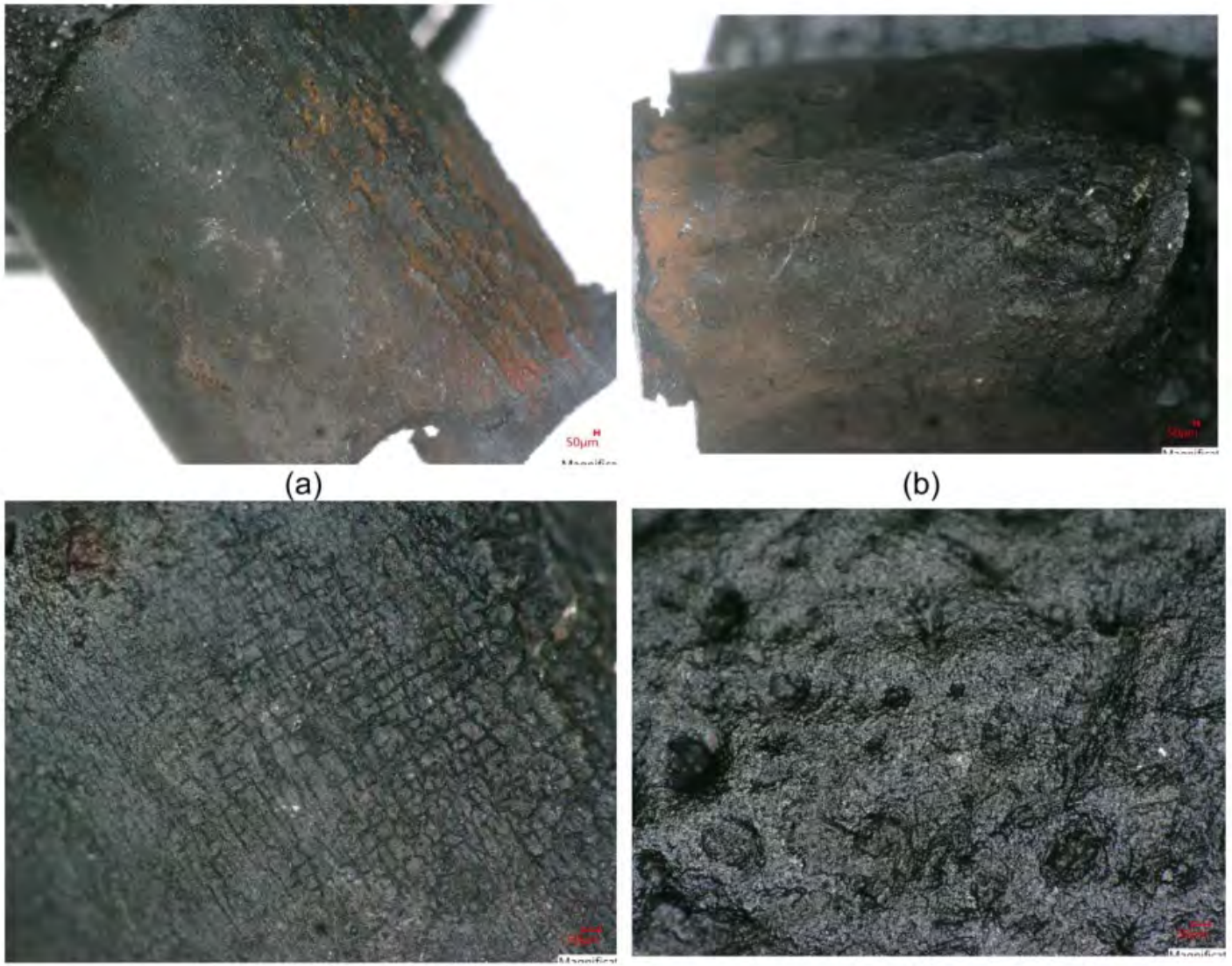


Figure 2: Optical Micrographs showing (a) (b) Surface Rust of the Failed Wire, (c) Flaked and Superficial Cracks on the Wire

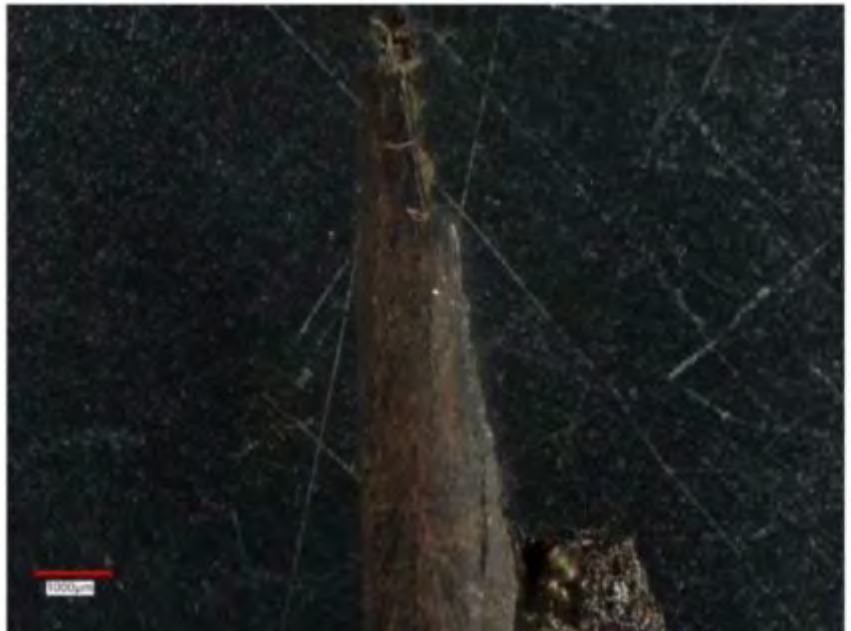
Materials Testing – Flexible Filler

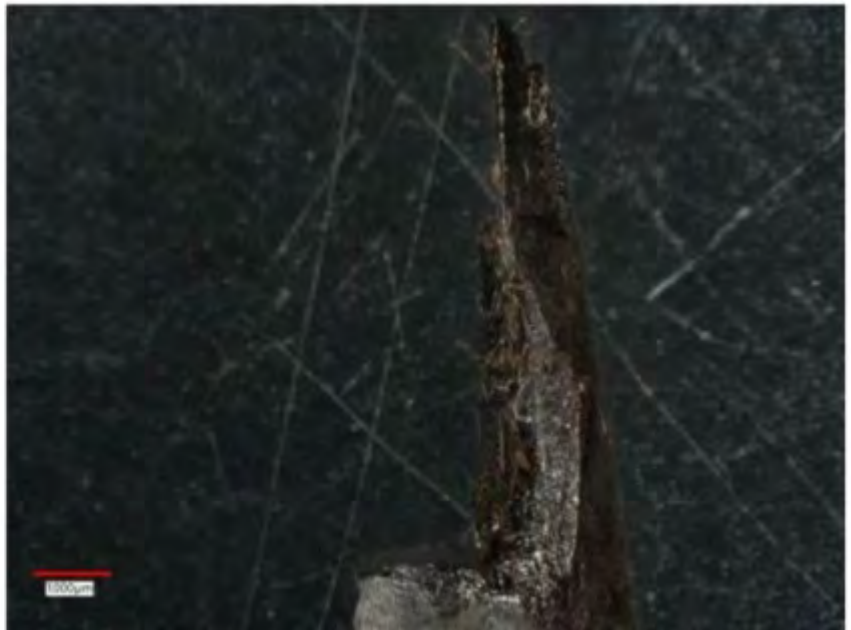
Sample Location	Bacteria Type	Exposure Severity	Bacterial Species Identification
Sample 1	• APB	• Aggressive	• Not detected
Sample 2	• APB	• Aggressive	• Staphylococcus epidermidis →APB/SLYM
Sample 3	• IRB • SLYM • APB	• Moderate • Moderate • Aggressive	• Gram-negative rod → SLYM • Gram-positive rod →APB • Pseudomonas aeruginosa → SLYM
Sample 4	• IRB • SLYM • APB	• Moderate • Moderate • Aggressive	• Brevundimonas diminuta → APB/SLYM • Pseudomonas aeruginosa →SLYM • Xanthobacter flavus →APB/SLYM

Failure Mode - Fractography



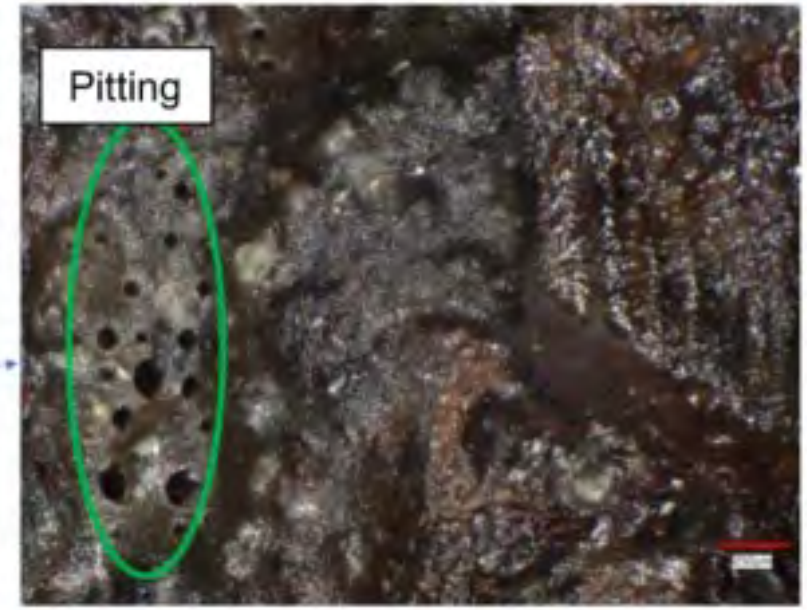




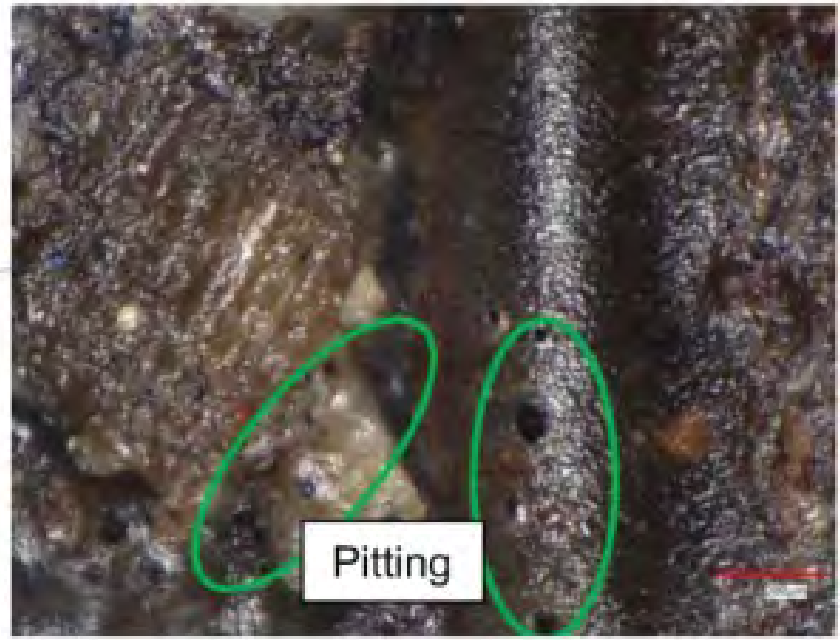


Failure Mode - Fractography









Summary

- Each structure is different and requires a tailored approach to evaluation.
- PT tendons are susceptible to corrosion
  - Document review and visual inspection is a good place to start.
  - Based on those findings, perform a more comprehensive evaluation.
- Evaluation techniques are available to determine the cause, extent and location of problems

QUESTIONS?

CONTACT OUR SPEAKER

Pratik Murkute

Ph.D., PE, NACE CP-4

Senior Project Manager

VCS Durability, Inc.

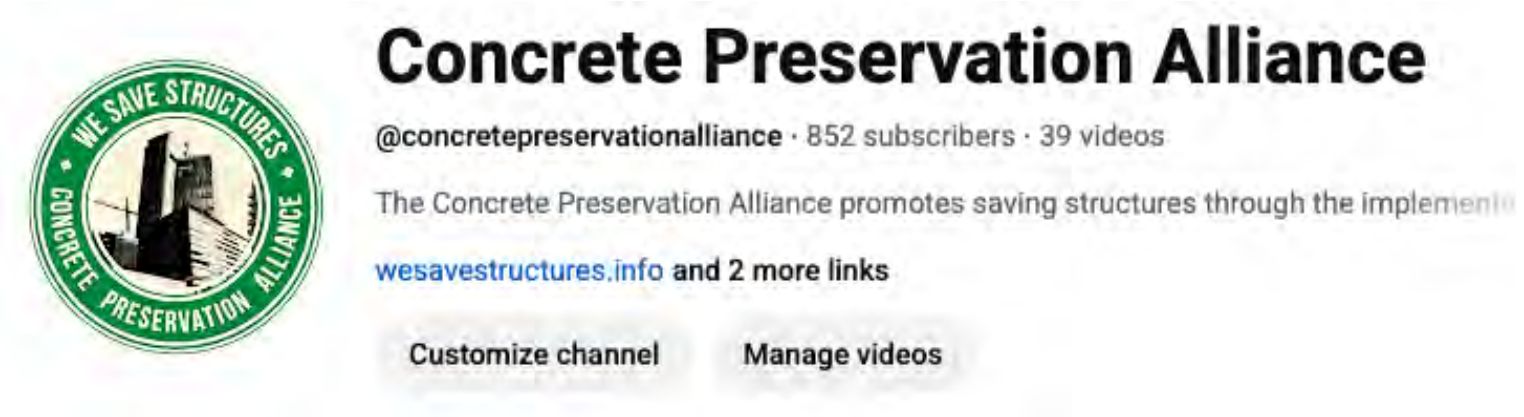
Office: 813-501-0050

Mobile: 813-310-1245

PMurkute@VCSDurability.com



FIND US ON YOUTUBE



NEXT SESSION



Scan here to register for session 2!

THANK YOU FOR ATTENDING!