Multistrand :

Probabilistic Assessment of the Reduced Capacity of Multistrand Post Tensioned Ground Anchored Hydraulic Structures Due to Tendon Corrosion

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Technology Exchange Meeting

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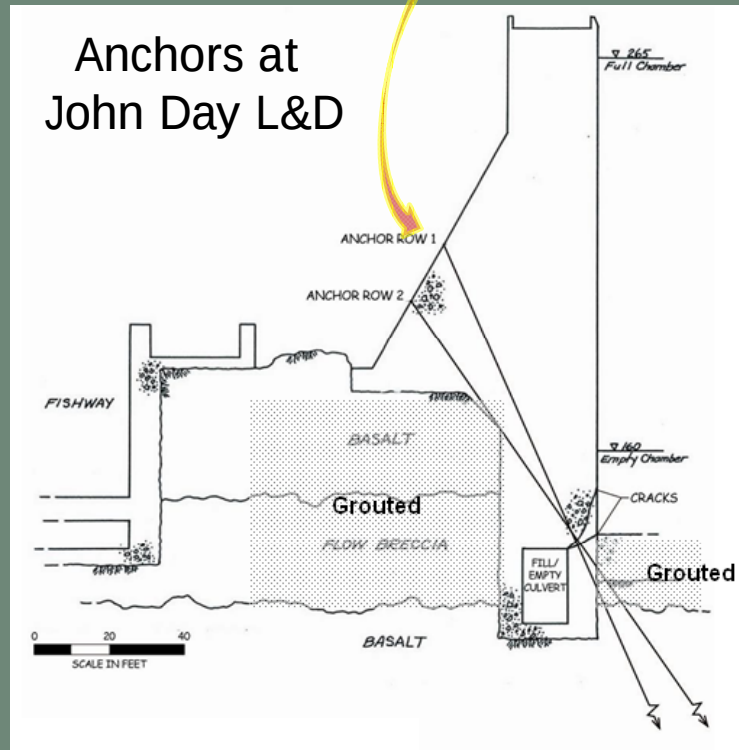
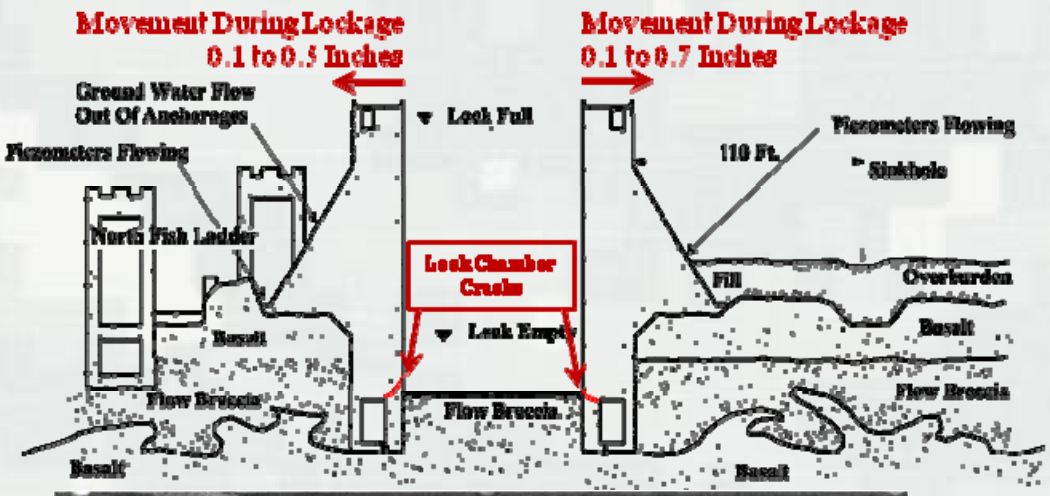
US Army Corps of Engineers®

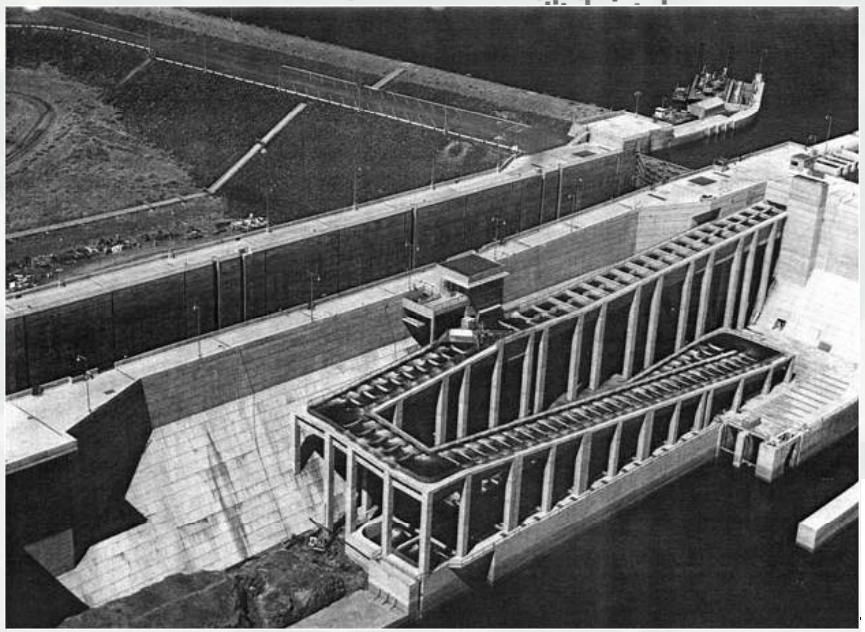
NAVSYS Navigation Systems Research Program

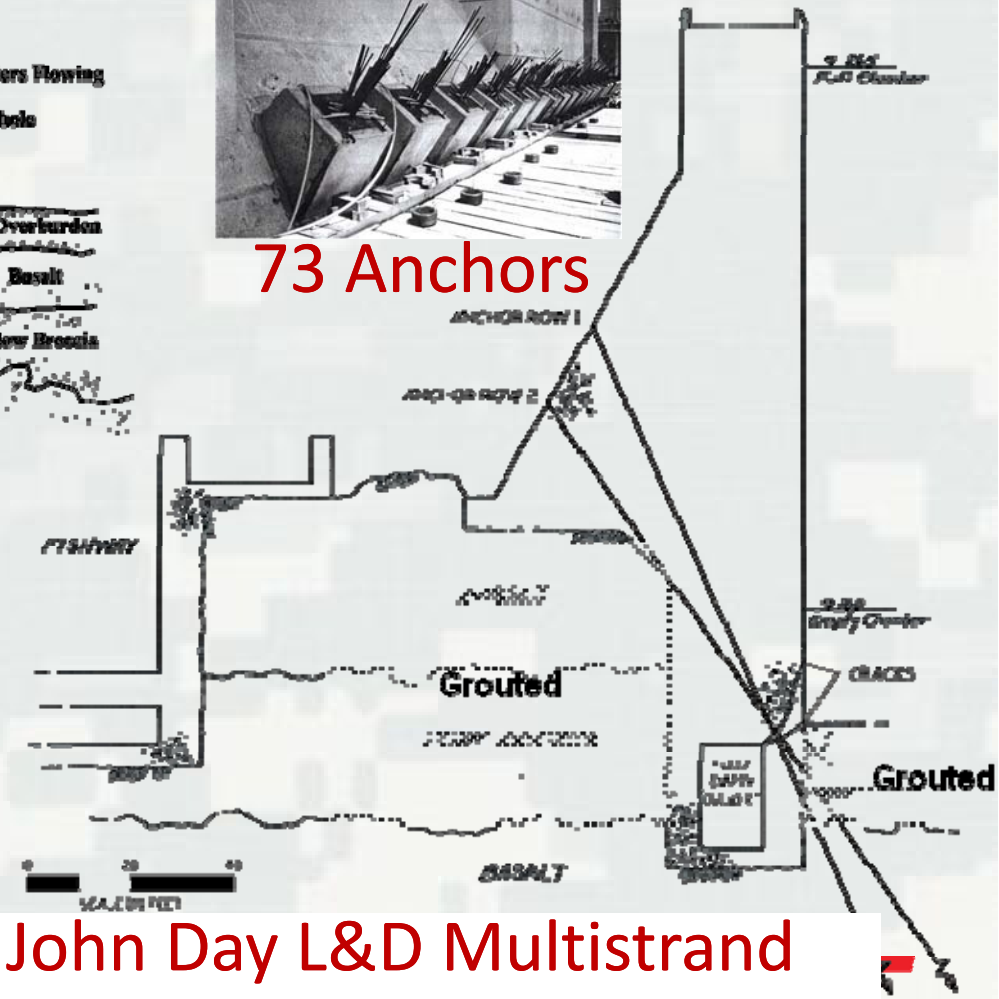


Multistrand Anchor Lock Wall Repair



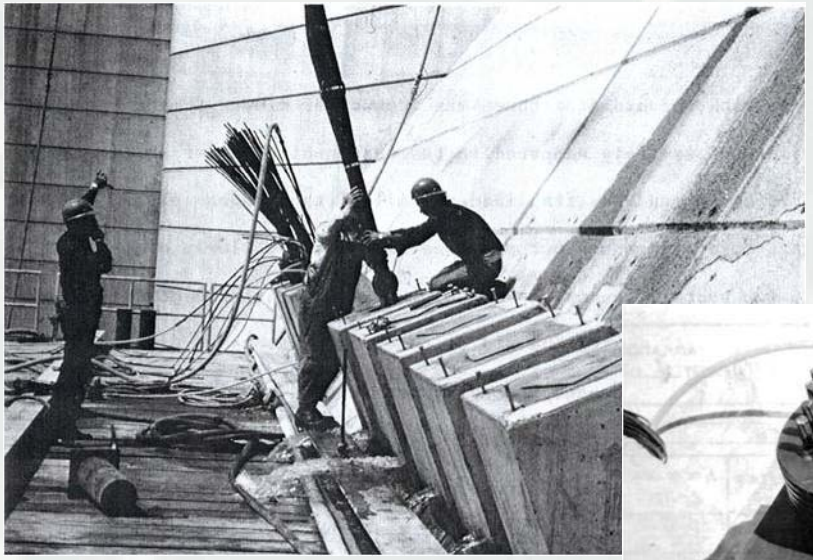
73 Anchors

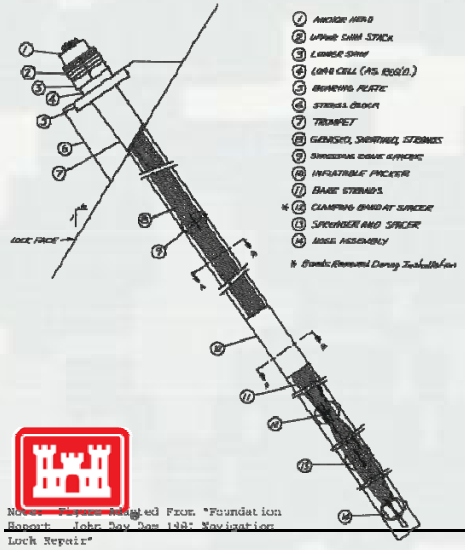


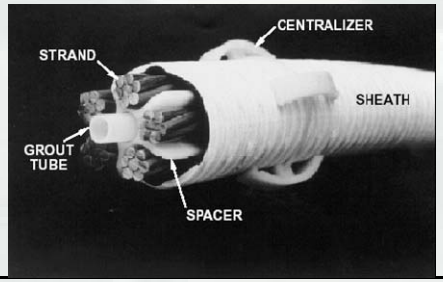


John Day L&D Multistrand Anchor Repair (1981)

Anchor Installation and Post-Tensioning at John Day Lock







Notes: Figures Adapted From "Foundation Report - John Day Dam 1983 Navigation Lock Repair"

Corrosion Induced Anchor Loss at John Day

New and corroded anchor head

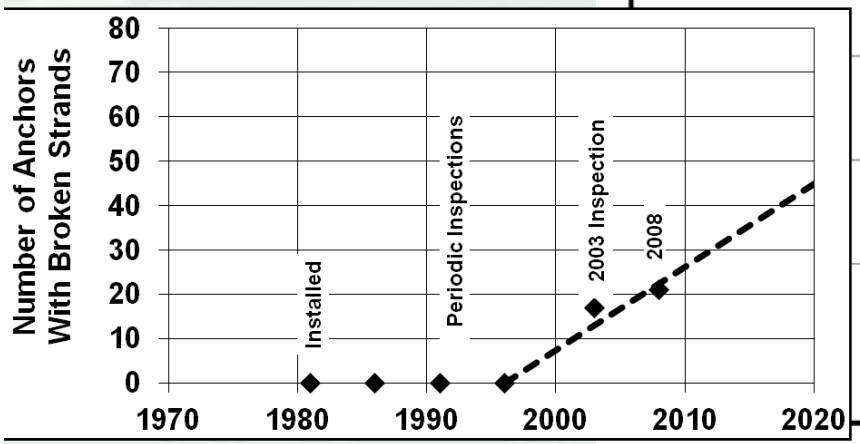
John Day Lock
South Lock Wall Anchor Lift-Off Tests

Date: 11/24/2008
Completed: 20 of 21 Tests Done
95%

Testing Anchors
- Visually "Good" Anchors
- Visually "Intermediate" Anchor
- Visually "Bad" Anchors

Anchor Tests

Date	Anchor			Original	2003 Lift-Off	2008 Lift-Off		Change in 5 yrs	Change in 25 yrs
11/19/2008	11-02	1	5%	1500 kips	1350 kips	1350 kips	90%	0 kips	-150 kips
11/20/08	11-10	2	10%	1500 kips	1340 kips	1260 kips	84%	-80 kips	-240 kips
11/20/2008	11-32	3	14%	1500 kips		920 kips	61%	Mod. Corrosion	-580 kips
11/21/2008	11-38	4	19%	1500 kips		1350 kips	90%		-150 kips
11/24/2008	13-21.5	5	24%	1500 kips		20 kips	1%	Broken strands	-1480 kips
11/24/2008	13-28.5	6	29%	1500 kips		1370 kips	91%		-130 kips
11/25/2008	15-21.5	7	33%	1500 kips		20 kips	1%	Heavy Corrosion	-1480 kips
11/25/2008	15-25.5	8	38%	1500 kips		1280 kips	85%		-220 kips
12/1/2008	21-6	9	43%	1500 kips		1020 kips	68%	Heavy Corrosion	-480 kips
12/2/2008	21-17.5	10	48%	1500 kips		1350 kips	90%	Moderate Corrosio	-150 kips
		11	52%	1500 kips		1310 kips	87%		-190 kips
		12	57%	1500 kips		1040 kips	69%	Moderate	-460 kips
		13	62%	1500 kips		1260 kips	84%	1 Broken Strand	
		13	62%	1500 kips		1200 kips	80%	2 Broken Strand	-300 kips
		14	67%	1500 kips		1310 kips	87%		-190 kips
		15	71%	1500 kips		890 kips	59%		-610 kips
		16	76%	1500 kips		1290 kips	86%		-210 kips
		17	81%	1500 kips	1400 kips	1320 kips	88%	-80 kips	-180 kips
		18	86%	1500 kips		1310 kips	87%		
		18	86%	1500 kips		1230 kips	82%	Broke a Strand	-270 kips
		19	90%	1500 kips		1400 kips	93%	Severe Corrosion	-100 kips
		20	95%	1500 kips		1380 kips	92%		-120 kips
		21	100%	1500 kips		kips	0%		
					Average (All)	1130.909 kips	72%	-11 kips	-17 kips
					Average (Good)	1329 kips	88%	per yr	per yr
					Average (Bad)	574 kips	21%	-1%	-1%



John Day Forensic Investigation

Anchor Heads

New Corroded

In the 2008 Cornforth Consultants Inspection Report it was observed that nearly all the anchor heads were experiencing some degree of seepage. Previous theories were that water was traveling up the individual cables from the grout protected regions at or below the packer.

Disassembly of two deteriorated anchor heads (September 2012) revealed that water was actually traveling up the ungrouted vent tubes (lower stage grouting below the packer).

High water flow rates were observed during lockages through all four of the **yellow** vent tubes.

Corrosion product between Strands. Clay-like consistency

Large voids where "plastic" grout should be (extended beyond 7 feet)

Water flowing through grout Vent tubes during lockage. This was the only observed water migration path

Contaminated Greases under anchor heads.

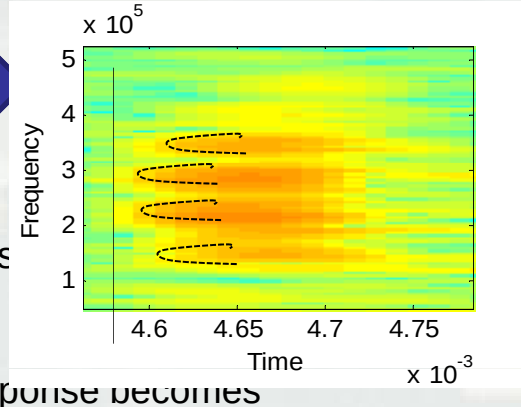
- Concrete repair patch was placed in affected trumpets at John Day L&D
- Recovered Heads are now being utilized in ERDC test bed investigations

An NDT Condition Assessment of Seven Strand Cable is VERY MUCH NEEDED

Acoustical Guided Waves Technology is most promising at this stage

Present Guided wave findings on Seven Strand Post Tension Cable Inspection:

- Low order modes (< 1Mhz) rapidly attenuate due to
  - Wedge / bulkhead loading
  - Energy loss into surrounding grease and grout
    (Note: These also damp Many of the higher propagating modes)



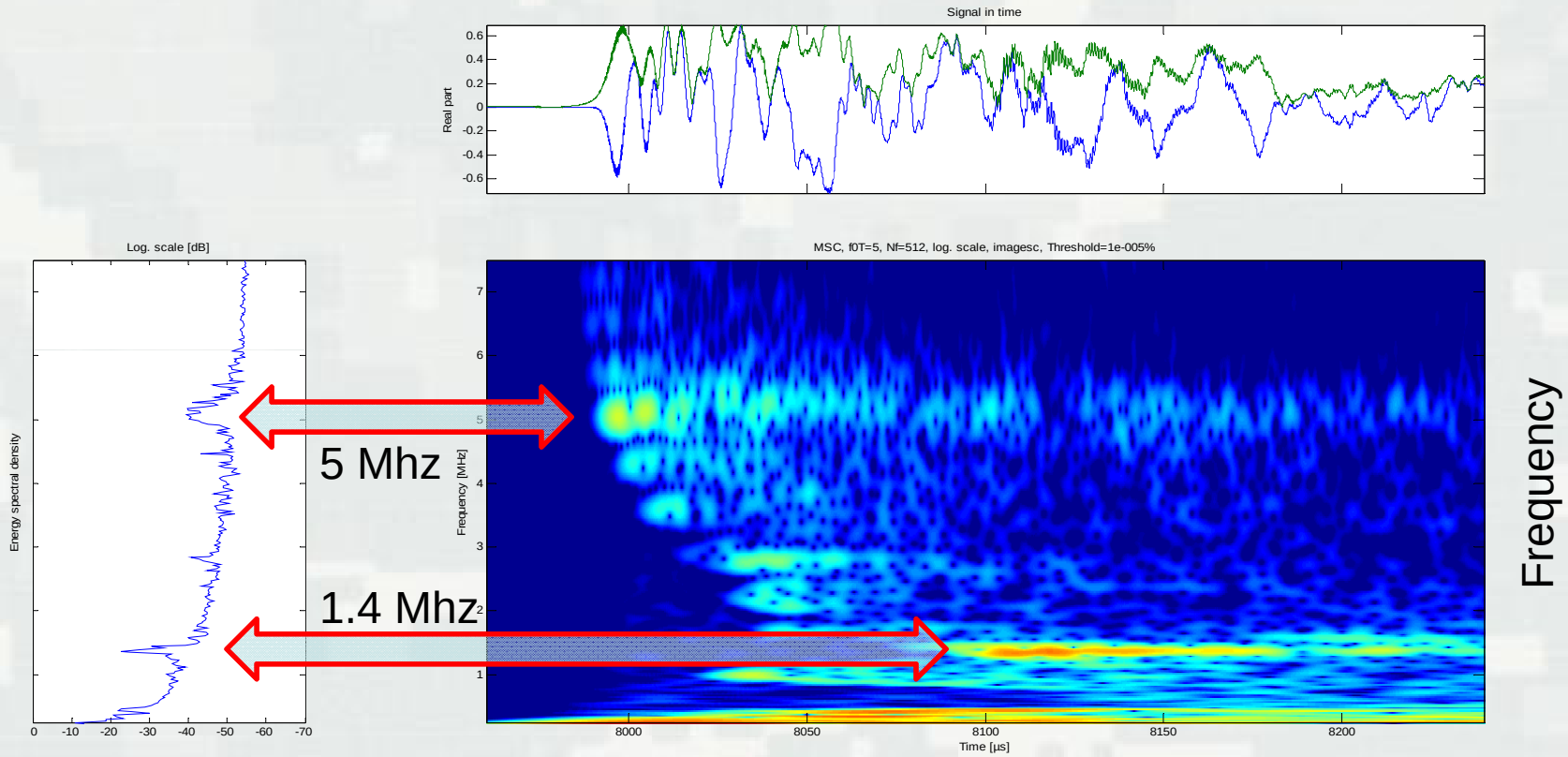
- Under no load the perimeter and king wires exhibit different dispersion curves
  - Perimeter wires loose energy to surroundings and cut angle (8 degrees)
- As tension is increased inter-wire coupling is increased and guided wave response becomes more monolithic
- Cable Inspection requires careful consideration of transducer coupling
- It is intrinsically difficult to obtain High Power / High Frequency Narrowband Ultrasound
  - Newly developed …Mn doped PMN-PT materials are on order to extend detection range (> ~ 26 ft)
  - broadband high power transducers in a compact, energy efficient package under development

Two candidate inspection modes have been identified

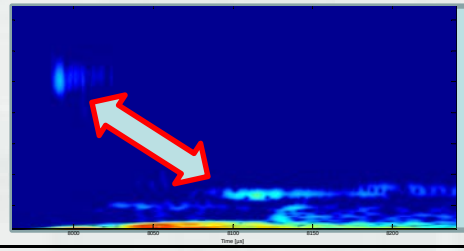
- A strong ~1.4 Mhz frequency (appears only under tension and couples into surrounding grease/grout)
- A ~ 5 Mhz frequency which is weaker but attenuates at a slower rate

Practical Cable Investigations require Both Load control and strand encasement

NDT: Broadband Transmission through King Wire
18,000 LBS Tension – Greased Cable
Time-Frequency Visualizations

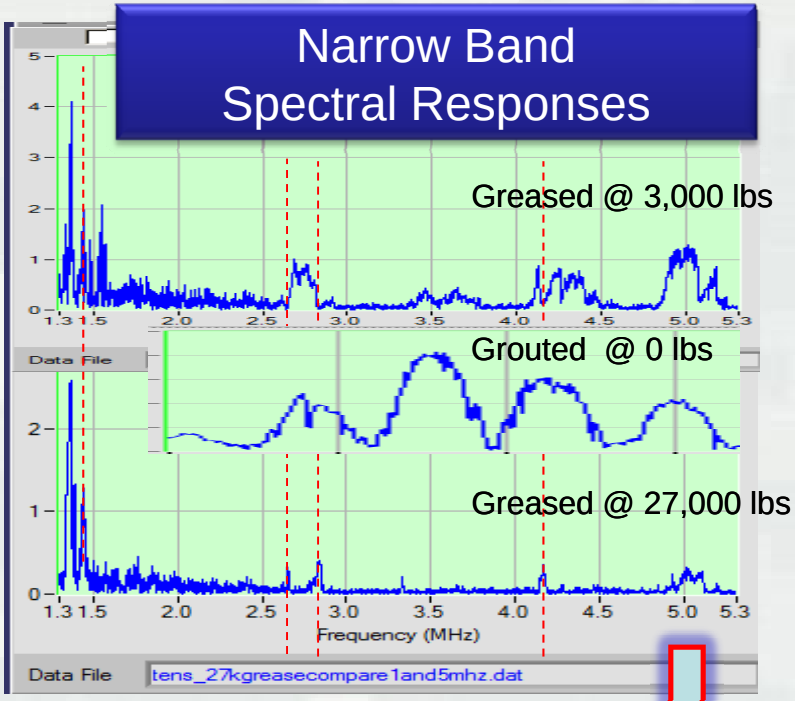


Time (~ Group velocity)



Alternate
Time Frequency
Processing

ERDC NDT for a Cable on the Test Bed and Test Frame



Tensioner on Test bed

New Test Frame for fine load control of short cable sections

Grouted cable Tested @ 5 Mhz with TCG circuit

26 feet of total propagation

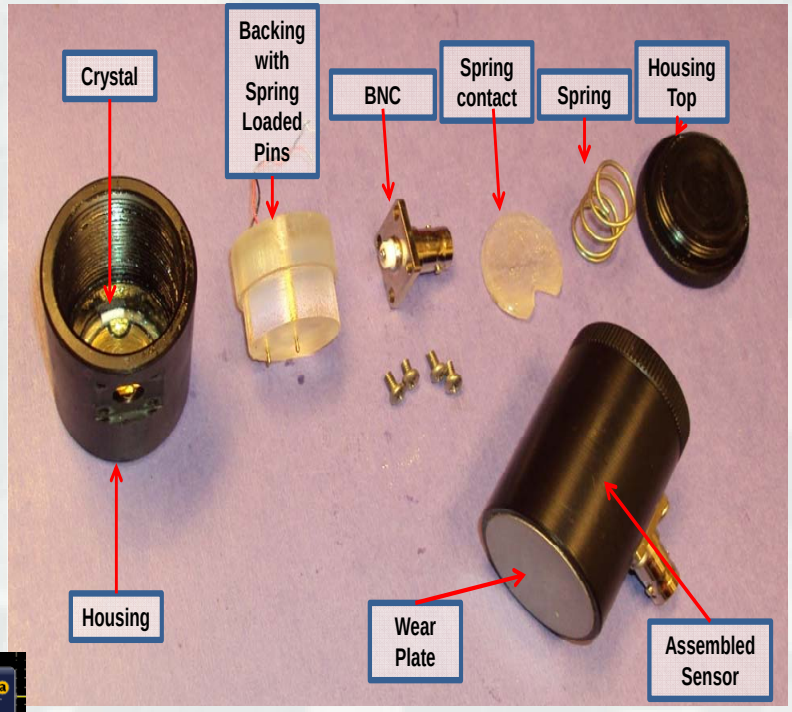
Increasing Power to Multistrand Cable By Using New Piezoelectric Materials

Testing of Multistrand Cable pushes the limit of PZT based piezoelectric based transducers.

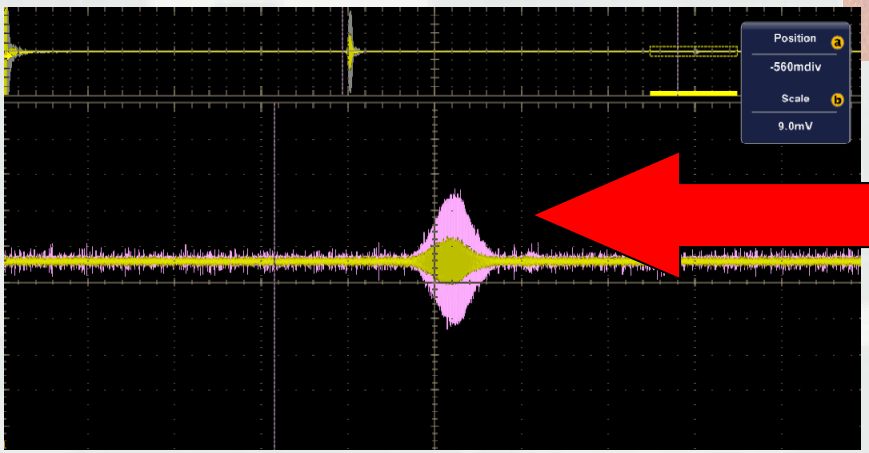
PMN-PT is a new and emerging material

PMN-PT- mechanical Q is about 8 x as high as PZT material with a 25% greater reported bandwidth.

Present design exhibits a smaller bandwidth then required



Sensor Design



Power output Comparison PZT vs PMN-PT

FY14 Pull-Tests of Corroded and Pristine Cables

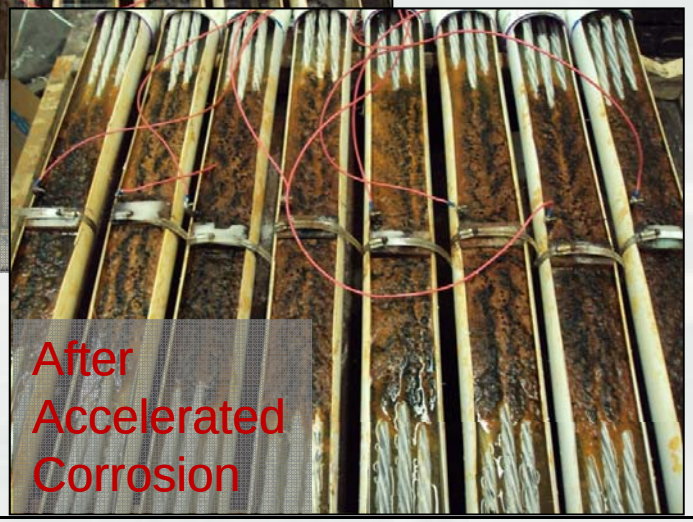
John Day Anchor Heads

New Corroded

Pull Test Machine

Pristine Anchor Wires Required Special Grips to Keep From Breaking at the Grip. 12 methods were tested to find a proper method.

Before Accelerated Corrosion

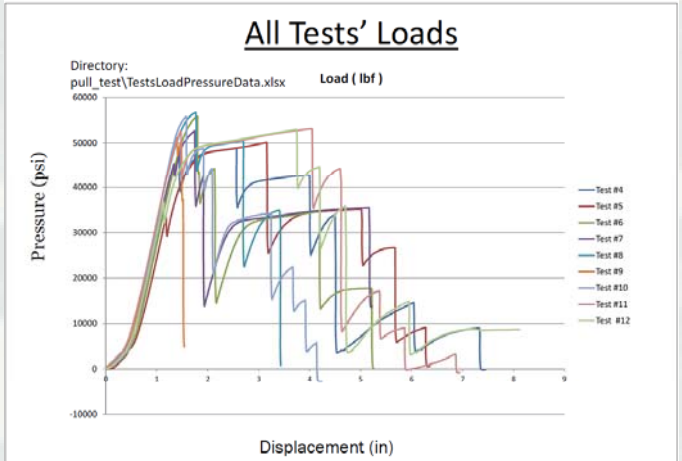


After Accelerated Corrosion

Pull-test data for:

22 Pristine

161 Corroded

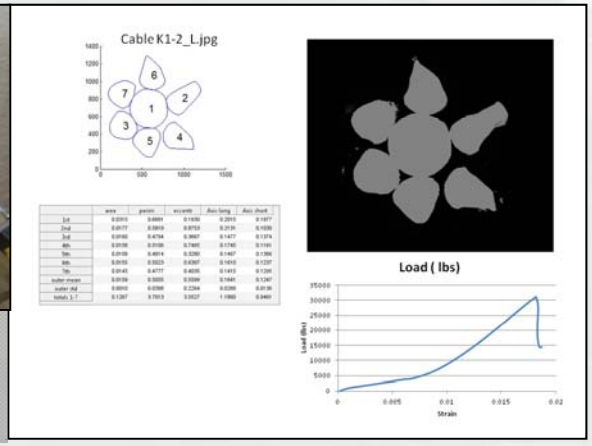


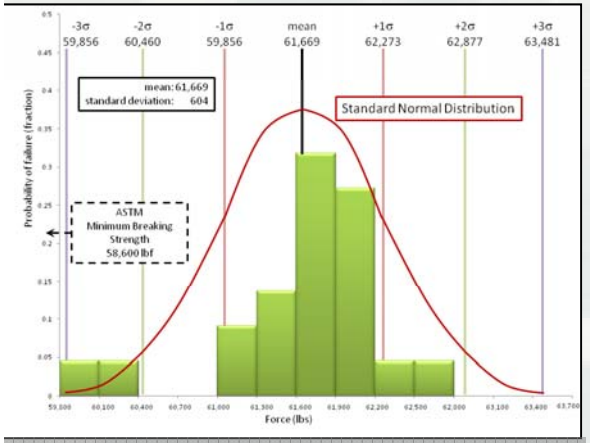
Data Collected for Pristine and Corroded Specimen

FY14 Interpretation of Pull-Test Results

Pull-Test Results

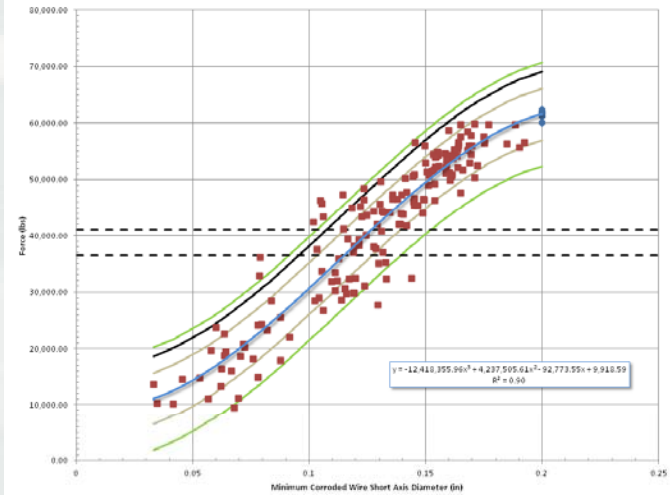
Optical Scans of Corroded Cable with Morphological Analysis

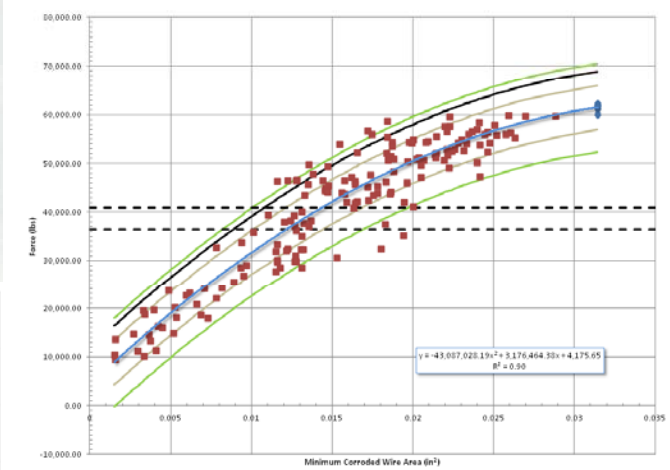




Pristine Specimen Distribution of Pull-Test Results

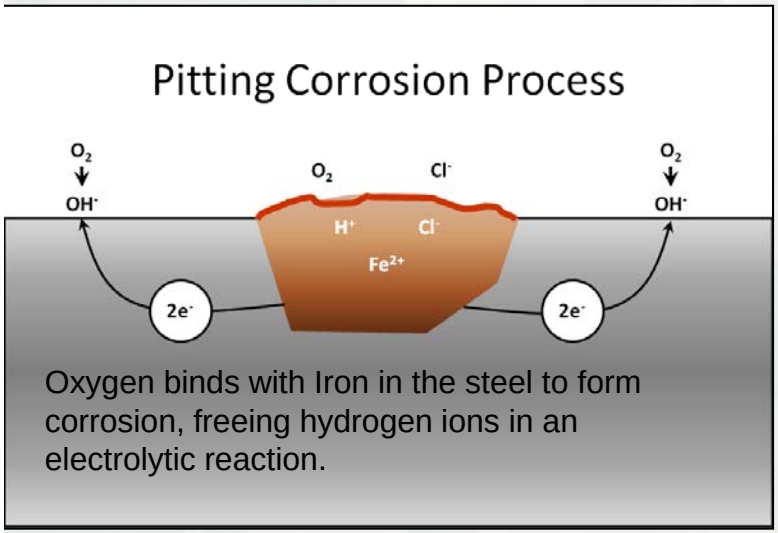
Using Minimum Individual Wire Short Axis Diameter to Predict Cable Capacity





Using Minimum Individual Wire Area to Predict Cable Capacity

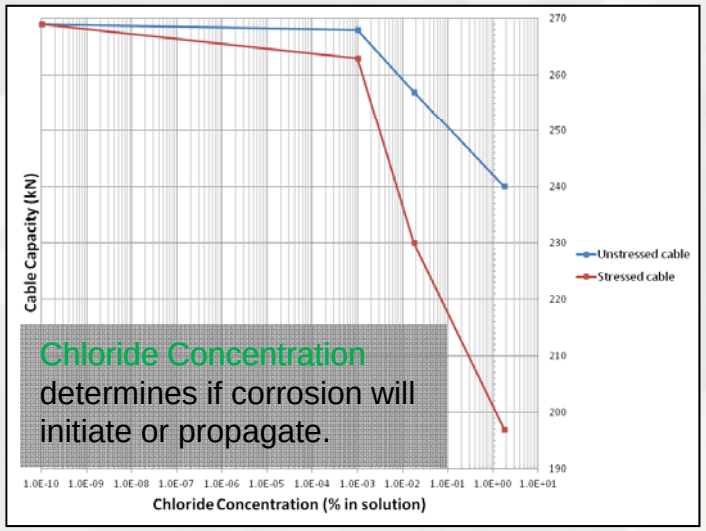
FY14 Corrosion Rate Information



Oxygen binds with Iron in the steel to form corrosion, freeing hydrogen ions in an electrolytic reaction.

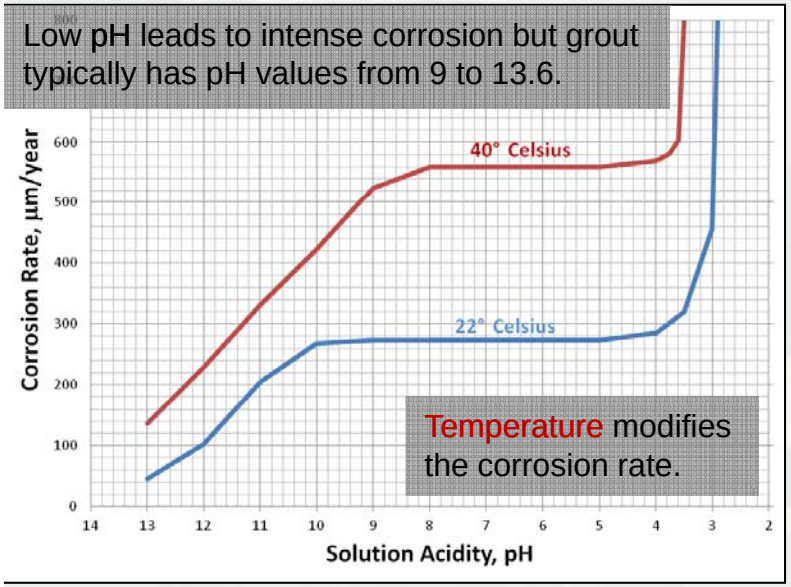
Corrosion Rate is affected by 4 major parameters:

- pH
- Chloride Concentration
- Oxygen Concentration
- Temperature

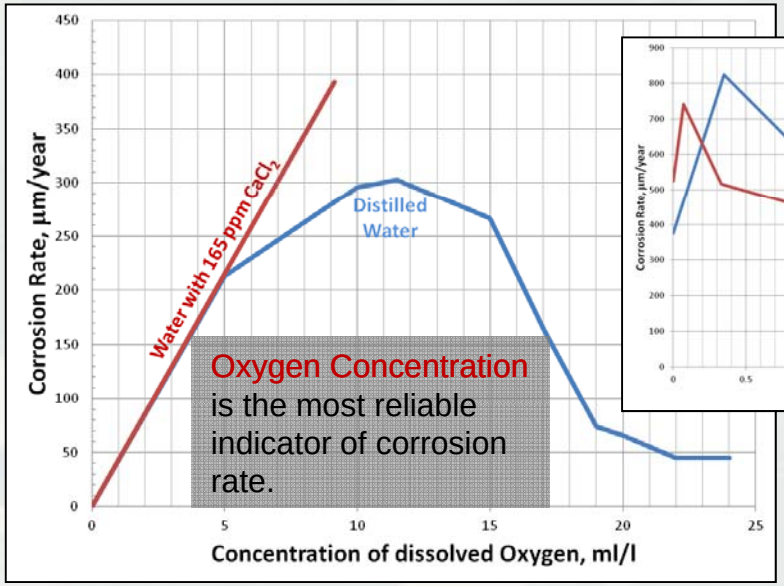


Chloride Concentration determines if corrosion will initiate or propagate.

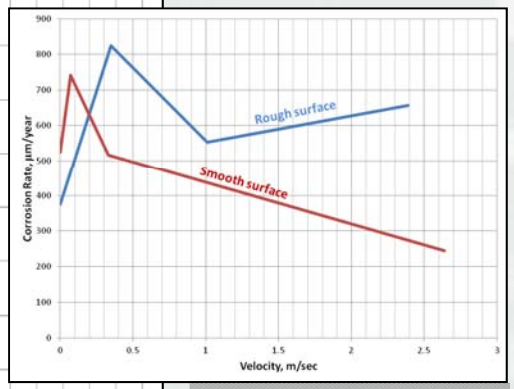
Low pH leads to intense corrosion but grout typically has pH values from 9 to 13.6.



Temperature modifies the corrosion rate.



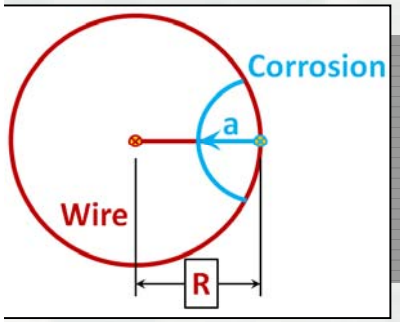
Oxygen Concentration is the most reliable indicator of corrosion rate.



Water Velocity will also affect Oxygen Concentration

Priority of Corrosion Effects:
Temperature and Oxygen have the most influence
Chlorides affects only initiation
pH has little effect

FY14 Corrosion Rate Information

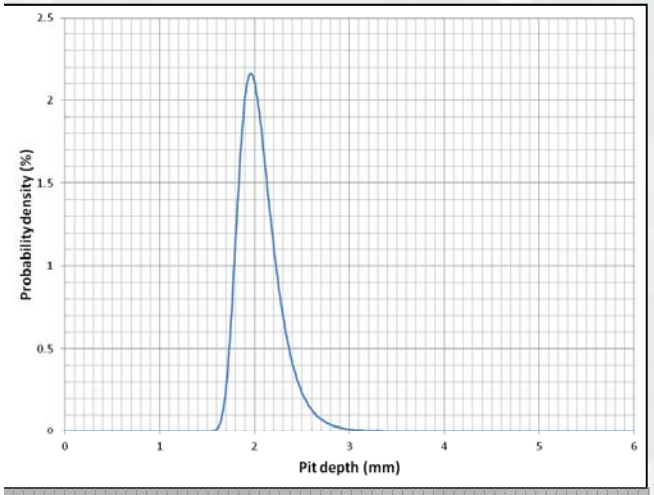


Extreme Value Distributions (such as the Gumbel distribution) can be used to estimate the probability of pitting of a certain depth given:

- Length of wire
- Time of corrosion exposure
- i_{corr} (current density)

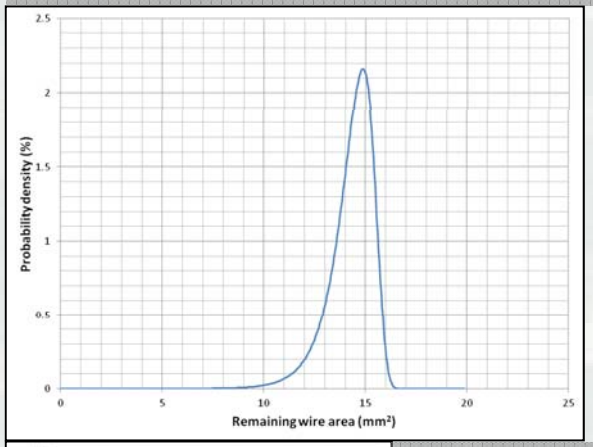
$$f_a(T, i_{corr}, L) = \frac{\alpha}{\lambda^{0.54}} e^{-a\left(\frac{\alpha}{\lambda^{0.84}} - \mu\right)} e^{-a\left(\frac{\alpha}{\lambda^{0.84}} - \mu\right)}$$

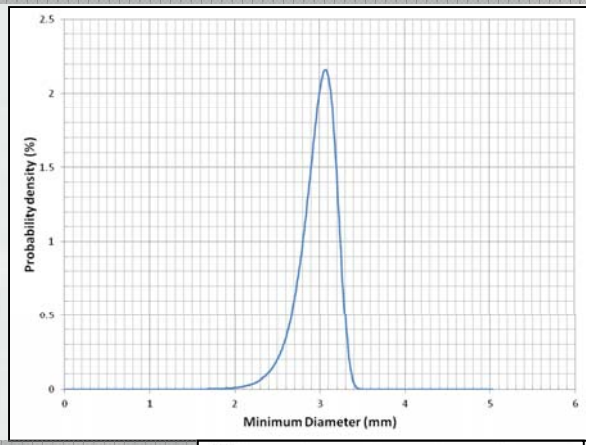
From Darmawan and Stewart (2007)



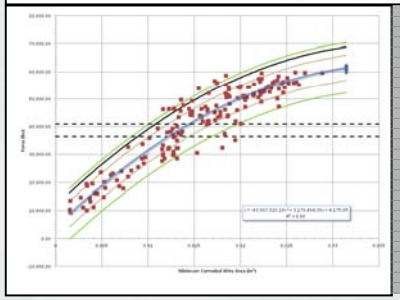
Pit Depths Probability Distribution

Given pit depth, the individual cable minimum wire area and minimum wire short axis diameter can be computed in a distribution.

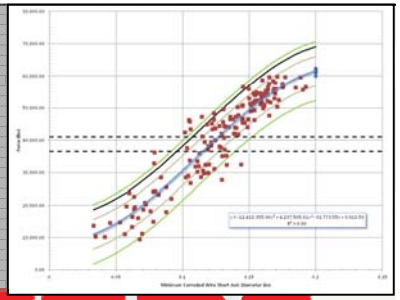




For General Corrosion, a range in corrosion rate values are determined from the provided charts. The standard deviation in corrosion rate is determined by using the 3-σ rule.



Estimated pit depth remaining area and diameter distributions can be used to stochastically determine the capacity of cables in simulations.

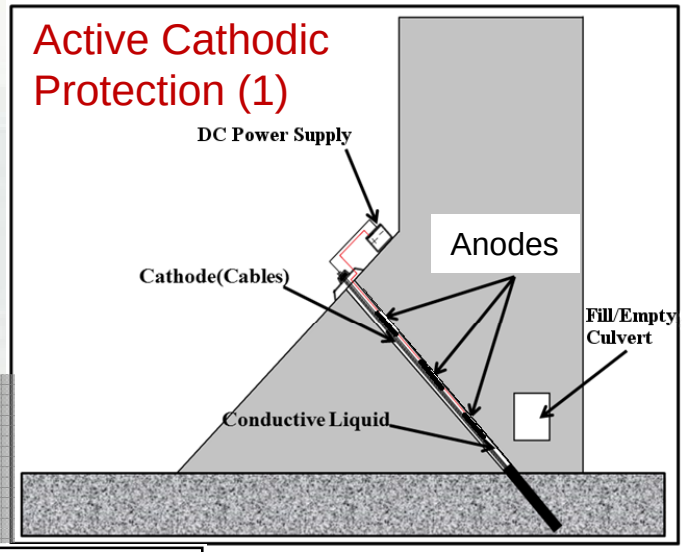


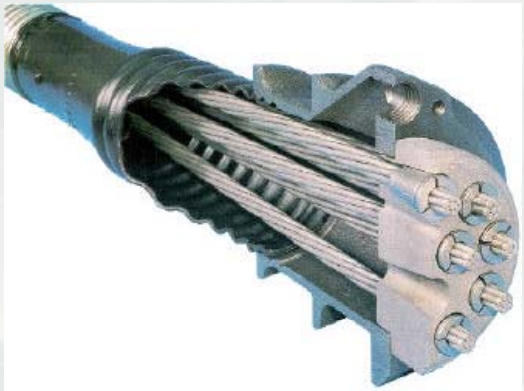
Assessment of Corrosion Mitigation Techniques

Voids in grout allow moisture to collect about cables, starting corrosion. Coating the cables could slow corrosion (7)

Corrosion is an electro-chemical process. This process can be moved from the cable to sacrificial anode metal. (1)

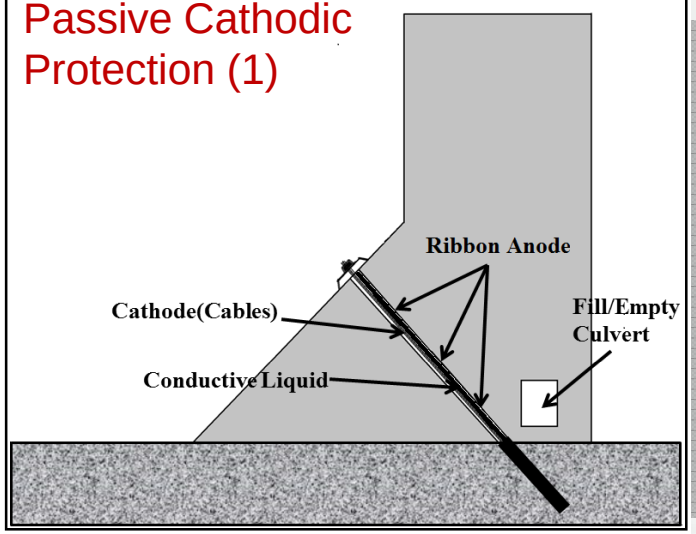
Active Cathodic Protection (1)





The greatest complication with corrosion mitigation and testing is the restricted access. This detail shows the duct and cap region.

Passive Cathodic Protection (1)

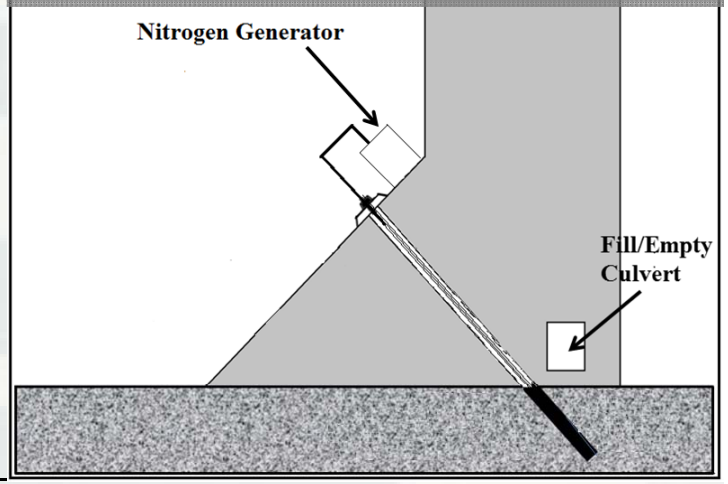


Corrosion Mitigation Techniques:

1. Cathodic protection*
2. Cable drying
3. Regrouting
4. Rust removal
5. Regreasing
6. Increase PH of free space or grout environment
7. Chemical impregnation*
8. Concrete healers and sealers
9. Relief water wells

*Most promising

Because corrosion occurs in the presence of moisture, it may be possible to restrict moisture by keeping the grout tube pressurized, possibly with a neutral gas. (2)



Chemical impregnation is the process where chemicals are introduced along the cables to form a protective barrier about the cables (7)