RECLAMATION
Managing Water in the West

Demonstration Project to Implement Electro-Osmotic Pulse Technology to Stop Water Leaks Through Concrete

Research and Development Office
Science and Technology Program
(Final Report) ST-2018-4553-01, 8540-2018-51

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2018

Mission Statements

The U.S. Department of the Interior protects America’s natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Electro-Osmotic Pulse (EOP) technology has the potential to stop water leaks through concrete, therefore a research program was initiated to test the technology at Trinity Dam. Phase 1 consisted of a feasibility study and project execution planning. Phase 2 involved installing an EOP system in a small test area of the Bonnet Cover Chamber and evaluating the effectiveness of the system to determine if a larger test section with cracks would be appropriate. Based on the results of Phase 2 it was decided to perform Phase 3 of the project. Phase 3 involved the installation of an EOP system in the bottom 40 feet of the headgate shaft as part of the Trinity Dam Intake Gate Shaft Refurbishing (Phase 1) project. This phase of the project involved cleaning a significant buildup of calcite, chemically grouting leaking cracks and joints, and EOP installation. Results of the installations at Trinity Dam to reduce seepage and dry out the concrete walls of the Bonnet Cover Chamber and Headgate shaft show that EOP technology can mitigate many water-related problems from the interior of affected areas. It appears to be an effective tool to consider when attempting to stop water leaks through concrete.

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Demonstration Project to Implement Electro-Osmotic Pulse Technology to Stop Water Leaks Through Concrete

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Acronyms and Abbreviations

A	Amps
A/m^2	Amps per square meter
ASR	Alkali-Silica Reaction
CSE	Copper Copper-Sulfate Reference Electrode
CSV	Comma-separated values
D	diameter
EOP	Electro-Osmotic Pulse
ft	feet
ft^3	cubic feet
h	height
hrs	hours
Hz	Hertz
HTP	Humidity Temperature Probe
I	Current
In.	Inch
lbs	pounds
MMO	Mixed-metal oxide
MPCO	Mid-Pacific Construction Office

NCAO	Northern California Area Office
NEMA	National Electrical Manufacturers Association
PVC	Poly-vinyl chloride
V	Volts
V_{AC}	Alternating current voltage
VCSE	voltage versus a copper copper-sulfate reference electrode
V_{DC}	Direct current voltage
V/m	Voltage per meter
R	Resistance
R	Radius
SD	Scan Disk

$\rho^{\pm}$ = density of the medium of the positive (negative) ions

$z^{\pm}$ = charge of an ion

e_0 = elementary electric charge

$m^{\pm}$ = mass of a positive (negative) ion

$\vec{E}$ = strength of the electric field of the system

Ω	Ohms

Executive Summary

Reclamation has many existing structures which are unique, due to the size and amount of cracks. These structures play a critical role and any type of damage due to water seepage through concrete can cause extensive and lead to expensive repairs. This damage can include, but is not limited to, corrosion from the resultant damp environment affecting the equipment operation (e.g., gate operating motors and pipelines), corrosion of the reinforcing steel causing cracks and potential structural failure, increased maintenance required to mitigate damage to equipment, removal of calcite, and mitigation safety issues. Chemically grouting leaks may only be a temporary fix and often takes a significant amount of time to completely seal the cracks. Grouting does not prevent seepage through the pores and very fine cracks.

Electro-Osmotic Pulse technology has the potential to stop water leaks through concrete, therefore a research program was initiated to test the technology at a Bureau of Reclamation (Reclamation) facility. This Research Office sponsored project involved three phases. Phase 1 consisted of a feasibility study involving site inspections, initial calculations, and project execution planning. Phase 2 involved installing an EOP system in a small test area of the Bonnet Cover Chamber at Trinity Dam and evaluating the effectiveness of the system to determine if a larger test section with cracks would be appropriate. Based on the results of Phase 2 presented in MERL-2012-10 [1] it was decided to perform Phase 3 of the project.

Phase 3 involved the installation of an EOP system in the bottom 40 feet of the headgate shaft at Trinity Dam. An EOP system was installed as part of the Trinity Dam Intake Gate Shaft Refurbishing (Phase 1) project. This phase of the project involved cleaning a significant buildup of calcite off the walls, chemically grouting leaking cracks and joints, and EOP installation.

The system is operating such as to prevent most water from seeping through the concrete walls of the shaft. A number of installation and operation issues became evident during the EOP system installation and evaluation. Some issues still present include the existence of some cracks which were not able to be grouted and continued seepage from the area above the system installation area.

The EOP system has reduced the moisture content of the concrete in the test area. EOP appears to have stopped leaks in some small cracks that were not grouted. Collected data shows that based on the trend in the collected data which shows the resistance has increased over time at a constant voltage and the total current has decreased. Resistance of the concrete between the anode and cathode is inversely related to the moisture in the concrete.

Results of the installations at Trinity Dam to reduce seepage and dry out the concrete walls of the Bonnet Cover Chamber and Headgate shaft show that EOP technology can mitigate many water-related problems from the interior of affected areas. Overall, the EOP system seems to be working as intended as observed by the data showing an increase in the resistance in the concrete. It appears to be an effective tool to consider when attempting to stop water leaks through concrete. This trial was very specific and limited in scope, so we recommend further investigations at other Reclamation facilities to determine the effective limits of the technology. Further investigations are also recommended to determine if this technology can prevent or deter

other common problems due to water intrusion observed at a number of Reclamation facilities (e.g. freeze-thaw and alkali-silica reaction (ASR)). EOP may also be effective in diverting water into a drainage system.

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Background

Test Site

Trinity Dam is near Redding, California, and was chosen as the site for the third phase of the EOP system evaluation. The facility is experiencing water leaks in the headgate shaft, which leads to several maintenance problems in the shaft and bonnet chamber. The leaks are from cracks and joints in the shaft. While the specific cause of the cracks was not determined, it was determined that the cracks are not from a concrete deterioration mechanism and most likely from initial concrete shrinkage. Results from the second phase of the pilot test previously installed in the bonnet chamber were reported in MERL-2012-10 [1] and will be discussed briefly as part of the introduction of this report.

Problem

Due to the seepage, there is standing water in the bonnet chamber, resulting in corrosion of the bonnet cover and air inlet pipe, as shown in Figure 1a and b. Failure of the air inlet pipe would result in complete flooding of the chamber and shaft. This would cause water to run down the tunnel to the powerplant yard if the door was not sealed shut due to both corrosion and calcium carbonate build-up.

Calcium carbonate (calcite) forms when water containing calcium ions reacts with carbon dioxide in the air. In some areas, the seepage over time has resulted in stalactite formation. The walls of the shaft are covered with calcite as shown in Figure 2a - f. While the calcite had an average deposit thickness of 0.5 to 1 inch in the bonnet chamber, in some areas of the shaft it has been reported to be as thick as 6 to 8 inches[2]. The build-up of calcite in the gate shaft prevents removal of the headgate for inspection and maintenance. Prior to this, the upstream face of the gate had not been inspected since installation.

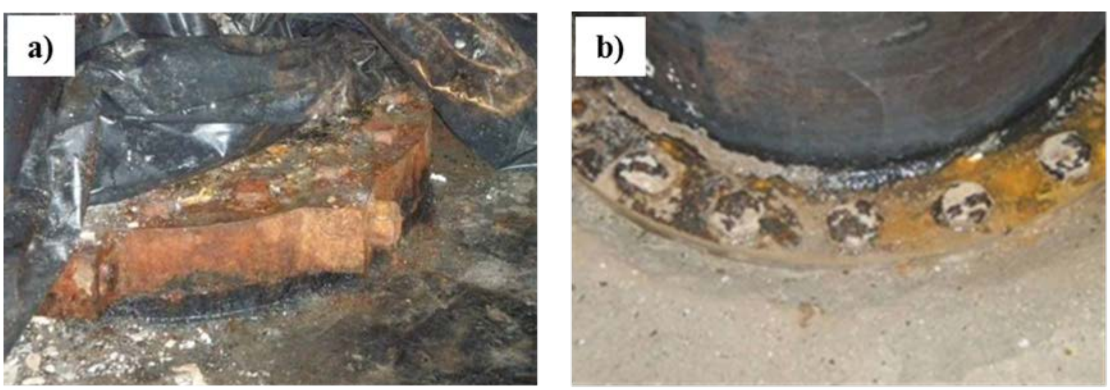

Figure 1. Corrosion of the bonnet cover and air inlet pipe due to the standing water.

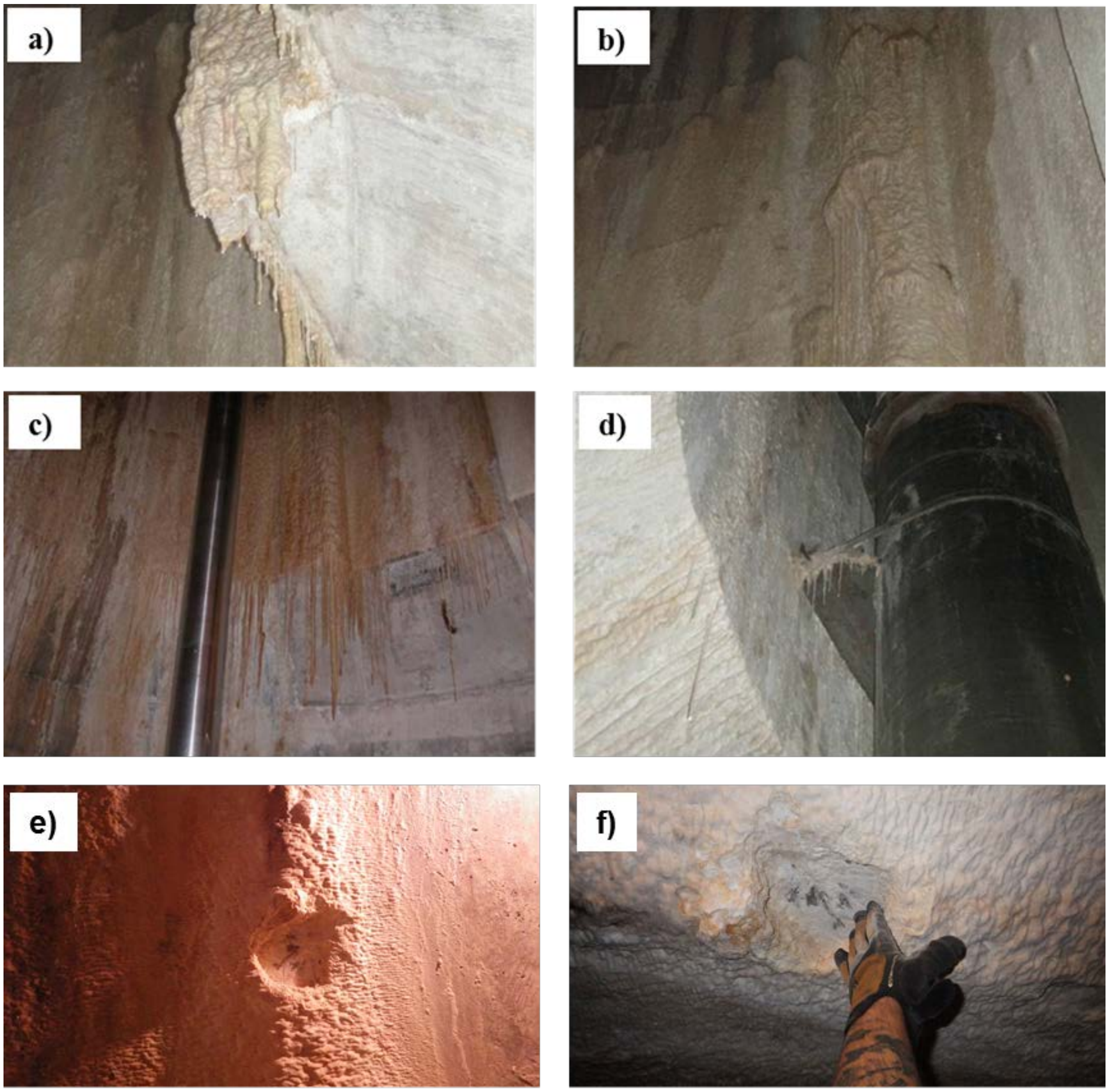

Figure 2. Calcite deposits observed on the walls of the headgate shaft. Excessive seepage over time has resulted in stalactites and corrosion of air vent supports.

Overview of Electro-Osmotic Pulse Technology

Electro-Osmotic Pulse (EOP) is a technology that in conjunction with grouting and concrete repair can potentially be a long lasting solution to water intrusion through concrete. Results from previous installations performed by the U.S. Army Corps of Engineers showed that in some applications, it may have a lower life-cycle cost than conventional methods, such as chemical grouting. One very important benefit of this technology is that excavation of the structure to prevent leaks is not required which can be a major ordeal and lead to accidental damage to the structure.

This technology uses current and electric fields to drive water away from the anode towards the cathode. This results in essentially forming a barrier to water intrusion from the external surface or for thick sections of concrete a barrier in the concrete. The system involves inserting anodes (positive electrodes) into the concrete surface on the side of the structure that needs to be dry and placing cathodes (negative electrodes) in the soil or water directly outside the structure. In the case of thick concrete walls or accessibility issues, the cathodes can be inserted into the concrete to a given depth. Figure 3 shows an illustration of a typical EOP system layout and operation. An illustration of the result of a properly designed system is shown in Figure 4. EOP systems require a minimum 120-volt alternating current (V_{AC}) circuit for the system controller, similar to a typical impressed current cathodic protection system.

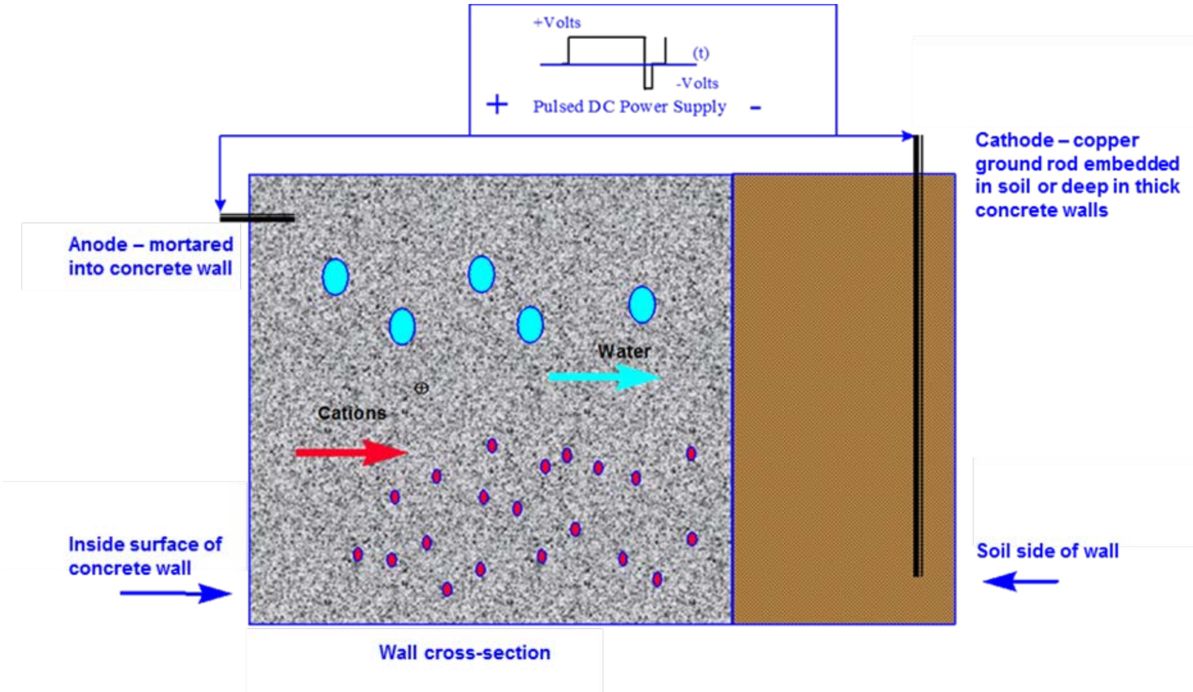

Figure 3. Illustration of cations and water molecules moving from anode to cathode on a macro scale with the application of EOP to dehydrate concrete.

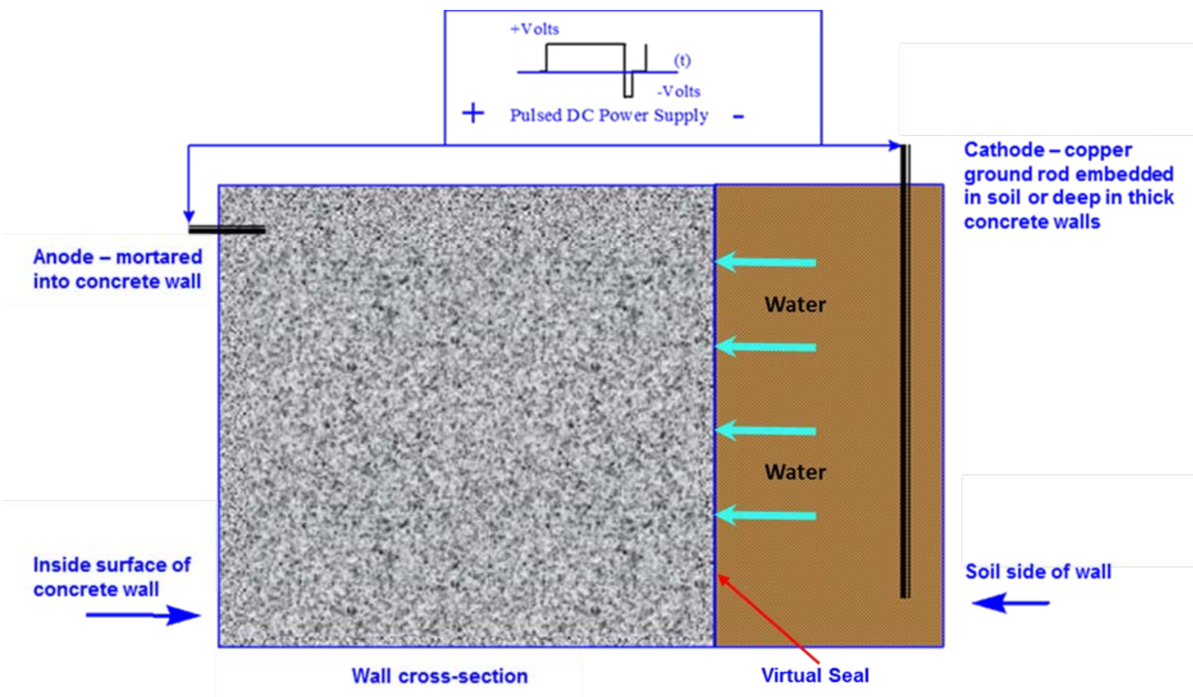

Figure 4. Illustration of the effects of the application of EOP to create a virtual seal or barrier to prevent water from entering the concrete on a macro scale.

The applied waveform is important in the operation and effectiveness of the EOP system. The pulsed voltage waveform includes periods of positive, rest or zero, and negative applied voltages. The critical negative voltage pulse controls the amount of moisture in the concrete to prevent the alteration of the chemical composition of the pore solution due to the application of current. This prevents the system from losing efficiency and helps to avoid any subsequent damage caused by overdrying of the concrete matrix [3]. Figure 5 shows a typical EOP pulse wave form sequence. The signal amplitude for the system is typically on the order of 20 to 40 volts direct current (V_{DC}) [3].

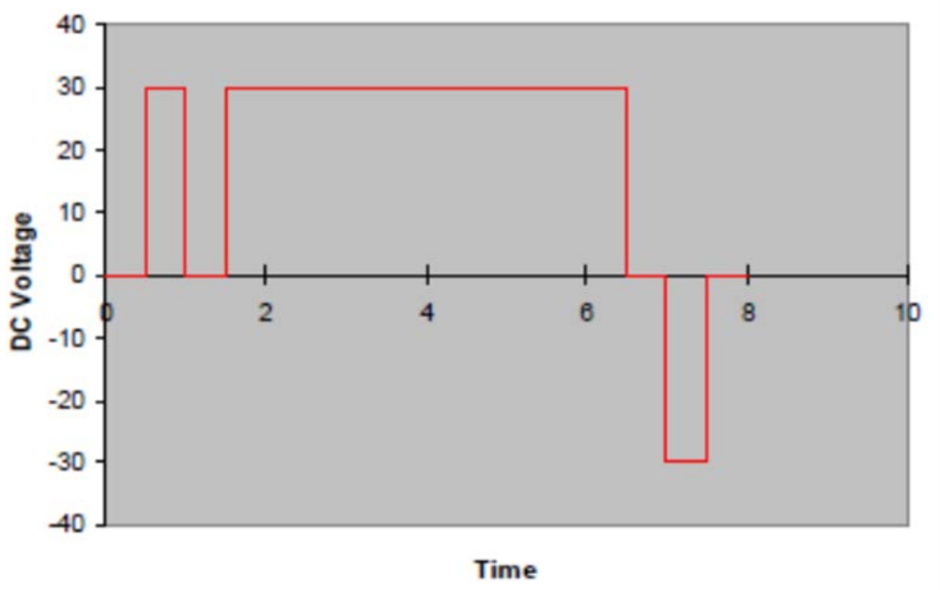

Figure 5.Typical EOP wave form showing the positive pulses, negative pulse, and rest period [4].

The current density of the anode/cathode must be balanced to help prevent the generation of gas and acid at the anodes [3]. The acid will cause degradation of the anode material and the cement paste used to embed the anode into the concrete structure [3]. It is well known that the pH can change dramatically in the vicinity of the electrodes during electro-osmosis [5]. Figure 6 shows a representative plot of the localized anode and cathode pH change versus time in concrete as a result of electro-osmosis [6].

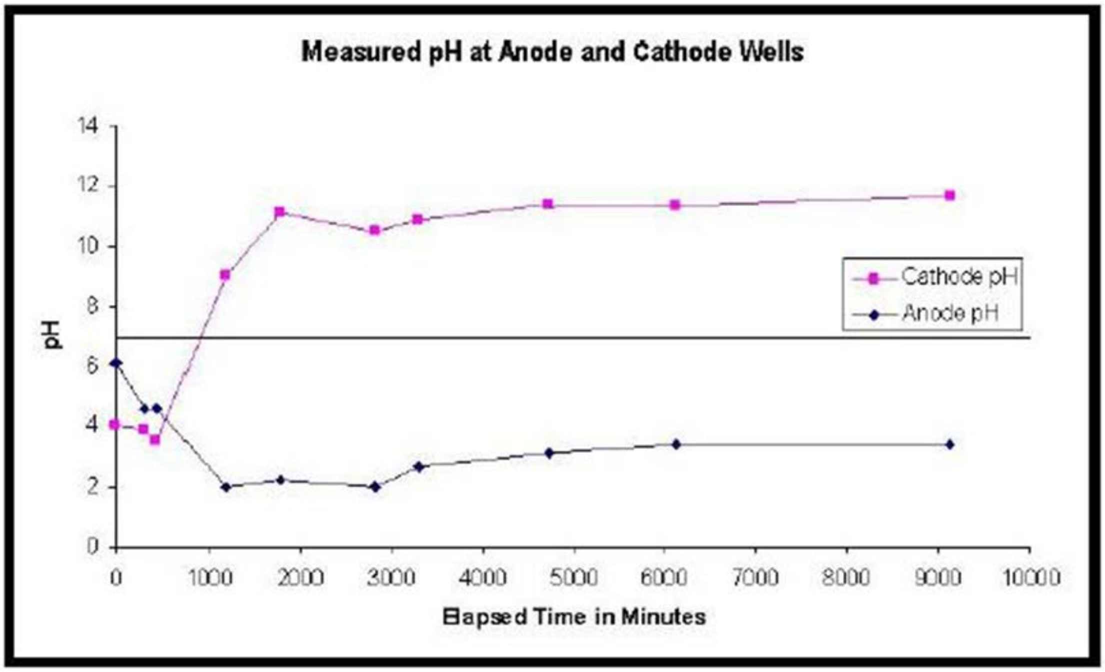

Figure 6. Typical EOP wave form showing the positive pulses, negative pulse, and rest period [4].

Synopsis of Phase 2 Installation and Operation

The following information in this section is a brief synopsis of the previous installation at Trinity Dam and was previously reported in Reclamation report MERL-2012-10.[1]

Installation

The objective of the second phase was to install EOP in a section of the bonnet chamber at Trinity Dam and monitor the EOP system performance in stopping water migration through the concrete at that location. The test section was a wall section approximately 14-foot-wide by 6 ½-foot-high located opposite the personnel entry tunnel. Figure 7 shows a schematic diagram of the installed system.

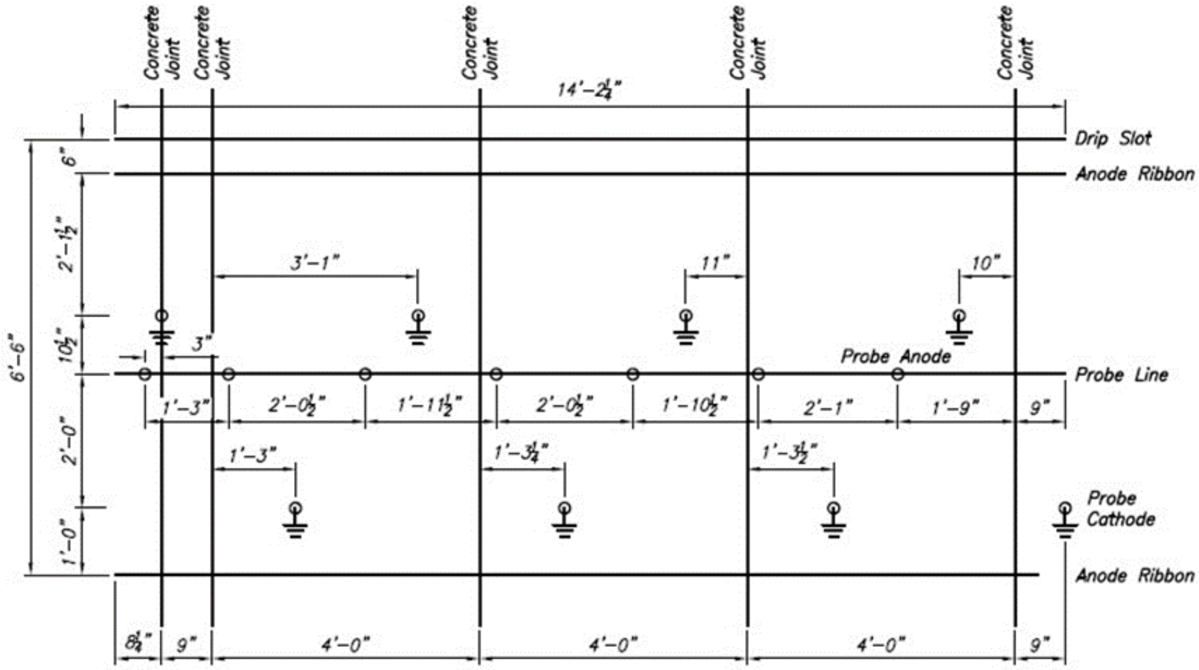

Figure 7. Schematic of installed EOP system in Bonnet Cover Chamber during phase 2.

For the Trinity installation, strip anodes were approximately 7 feet long and ½ inches wide. A red insulated cable was used for the anodes. Figure 8a and b shows anode materials installed on this project. Strip cathodes were approximately 12 inches long and ½ inch wide. A green insulated cable was used for the cathodes. Figure 8c and d shows cathode materials installed on this project. Installation of the anodes and cathodes are shown in Figure 9 and Figure 10.

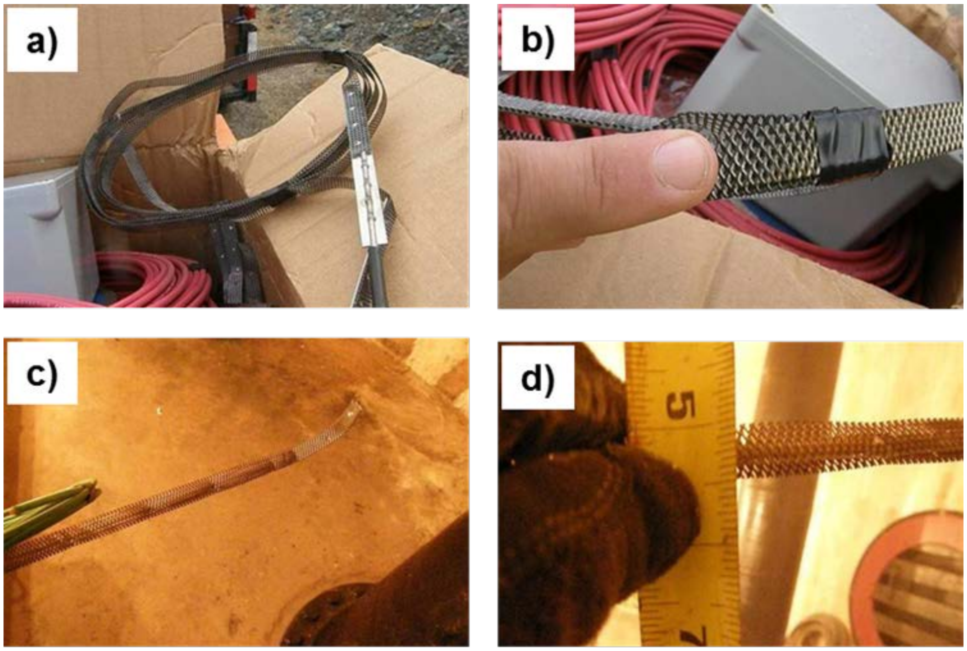

Figure 8. Mixed metal oxide coated titanium mesh strip type anodes (a and b) and cathodes (c and d) installed in the concrete wall.

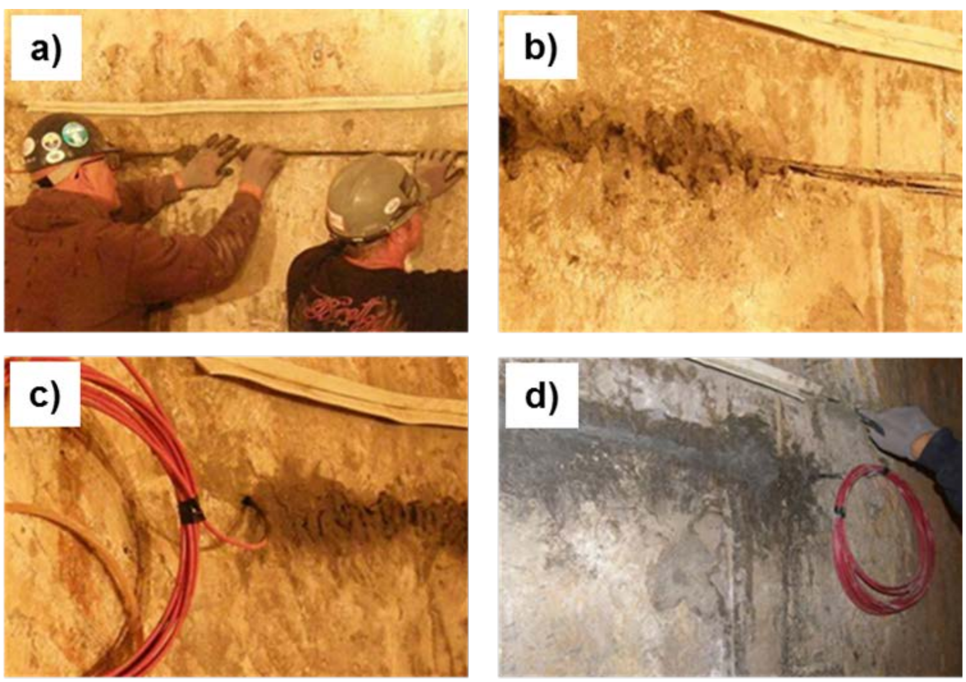

Figure 9. Installation of upper strip anode and hand packing of Portland cement grout into the groove shown in photos a), b) and c). Photo d) shows finished installation of upper anode strips and cable.

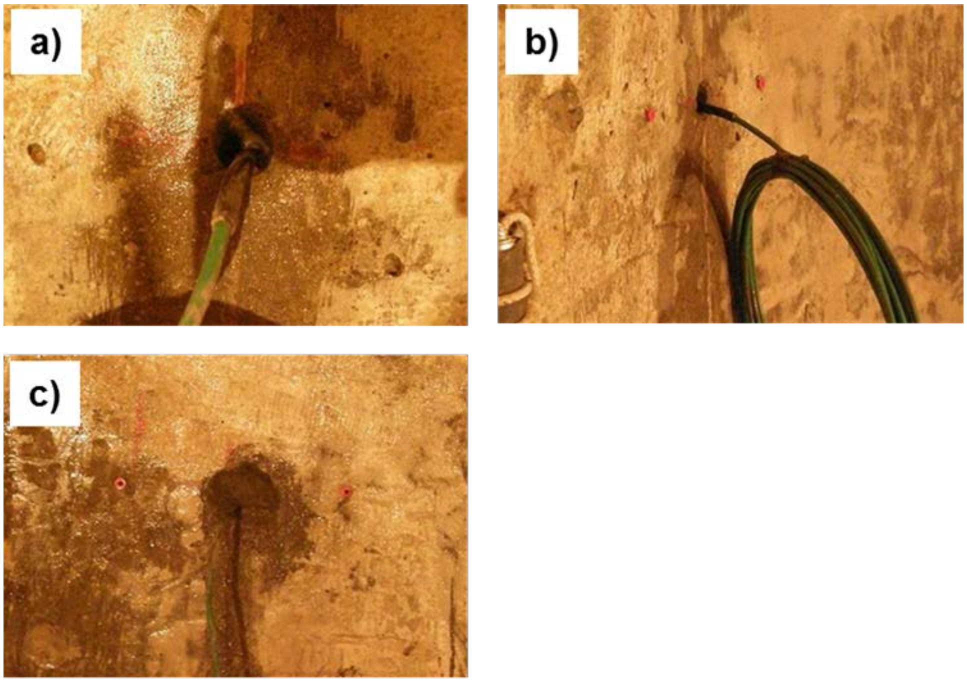

Figure 10. Installation of strip cathodes into holes drill to a depth of ~18 inches shown in a) and b). Portland cement grout was poured in the holes around the cathodes, and the cathodes and cables were grouted in as shown in c).

All the cables were terminated in a main junction box. The cathode cables were connected to a main cathode header cable, all the anode cables were connected to a main anode header cable, and the main header cables and a cable connected to the rebar were run through conduit to the system controller. Figure 11 shows the complete installation of all electrodes and junction boxes.

Figure 11. Completed installation with junction boxes and conduit.

Operational Analysis

The test location on the wall of the chamber showed a saturated or wet concrete, both to sight and touch, as shown in Figure 12a and b. These photos document the visual conditions to determine if the system was operating. Figure 12c and d show dry areas of concrete after 2 weeks of operation. Figure 12d shows the area next to where the system was installed is wet. The tray was not draining, causing water to drip down onto the wall below in some areas.

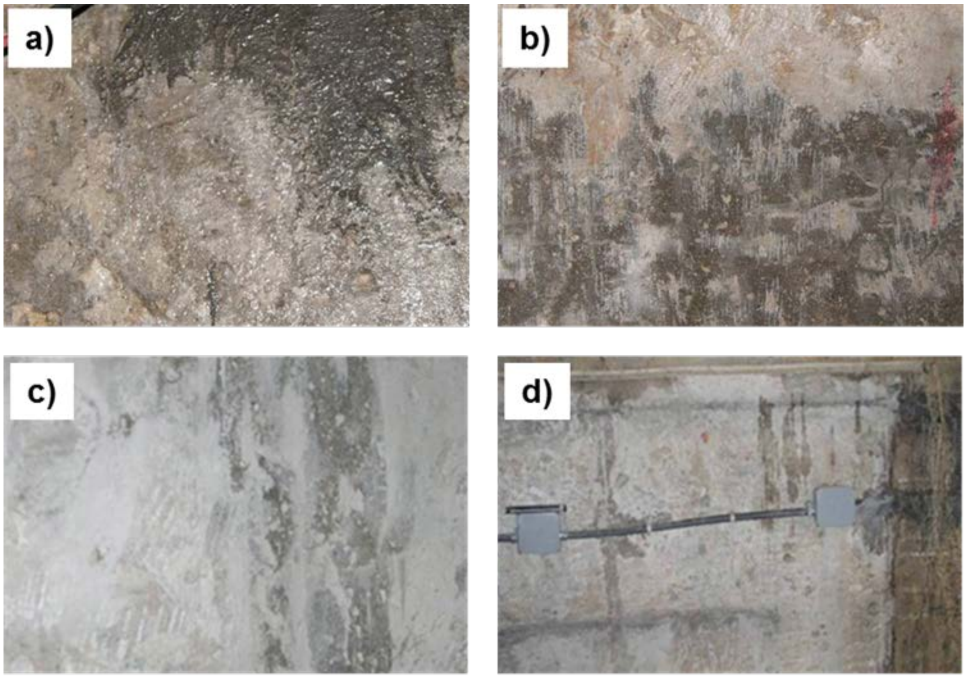

Figure 12. Condition of wall at installation prior to energizing of the system is shown in a) and b). Note the wall was damp to sight and touch. The wall was dry to sight and touch over most of the test section after two weeks of system operation as shown in c

Data collected after 15 weeks of operation was used to evaluate the system operation and the current and resistance trend. The data was analyzed using Ohm's law E = IR, where E is the potential (V), I is the current (A), and the R is resistance (ohms). Over time, at a constant applied potential, the current will decrease and the resistance will increase as the moisture level in the concrete decreases in the wall when the system is operating as designed. Figure 13 shows the analyzed data for total current output and resistance. The continued decrease in current and increase in resistance indicates that the system is still operating and moving water through the concrete towards the cathodes. The resistance calculated after 11 weeks of operation was almost 3 times larger than it was originally.

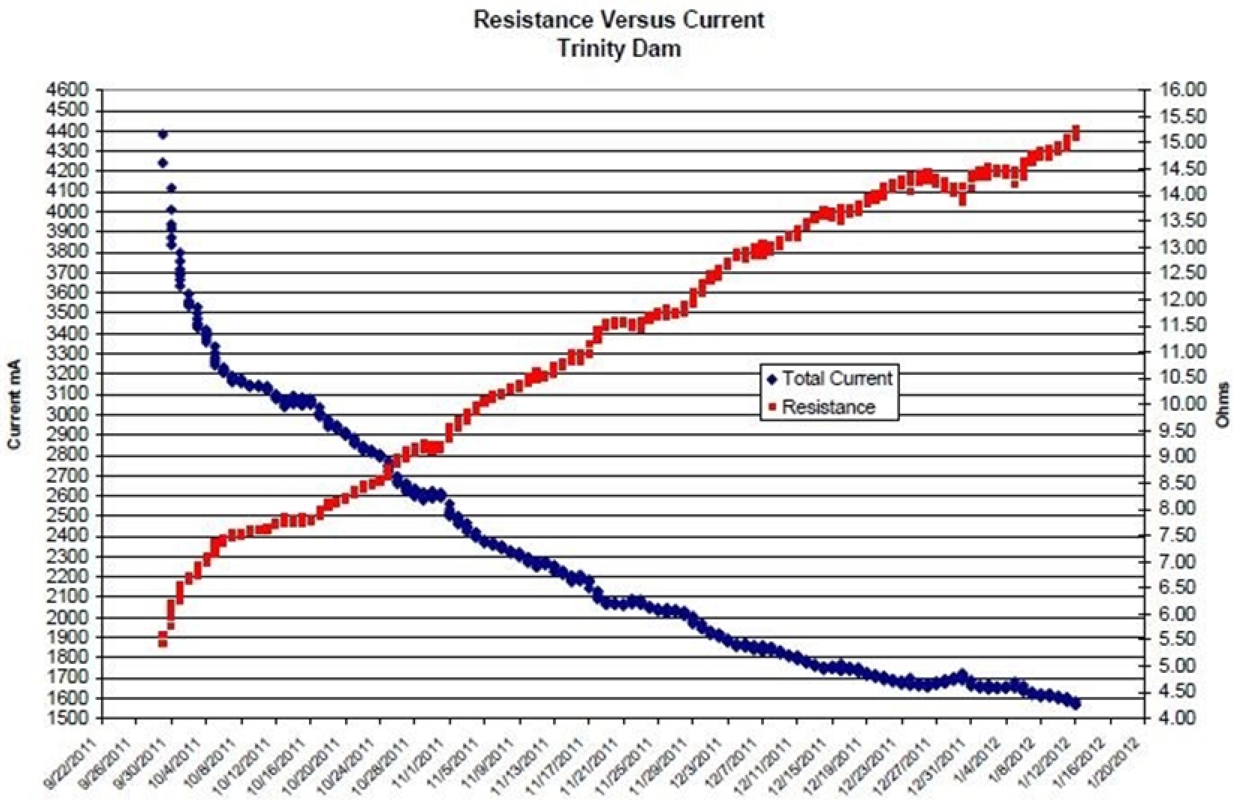

Figure 13. Data from the first 15 weeks of system operation showing the current and resistance over time. The data shows that the moisture content in the concrete is decreasing.

Phase 3 Installation

Introduction

Phase 3 of this research project occurred in conjunction with the Trinity Dam Intake Gate Shaft Refurbishing (Phase 1). Phase 1 of the refurbishing project involved removing the calcite buildup from the concrete walls of the gate shaft, grouting visible cracks, and installing the EOP system. The system was contractor designed, installed, and tested in accordance with the performance specification as part of the Phase 1 project.

Concrete Preparation

Due to the significant number of cracks which were leaking it was necessary to grout them as both part of the Phase 1 project and in order for the EOP system to operate successfully. Figure 14a and b show the extent of water flow from the numerous leaks in the concrete wall of the shaft. A significant amount of grout was injected into the wall in order to seal the cracks. The large number of ports required for the grout injection is shown in Figure 14c and d. This was due to the fact that grouting cracks is often a large undertaking. The length or size of the cracks inside the wall is not always clear and is therefore often referred to as “chasing” cracks. A small number of cracks not grouted were seeping water at a much slower rate and it was believed that the EOP system would decrease or stop the seepage for those cracks.

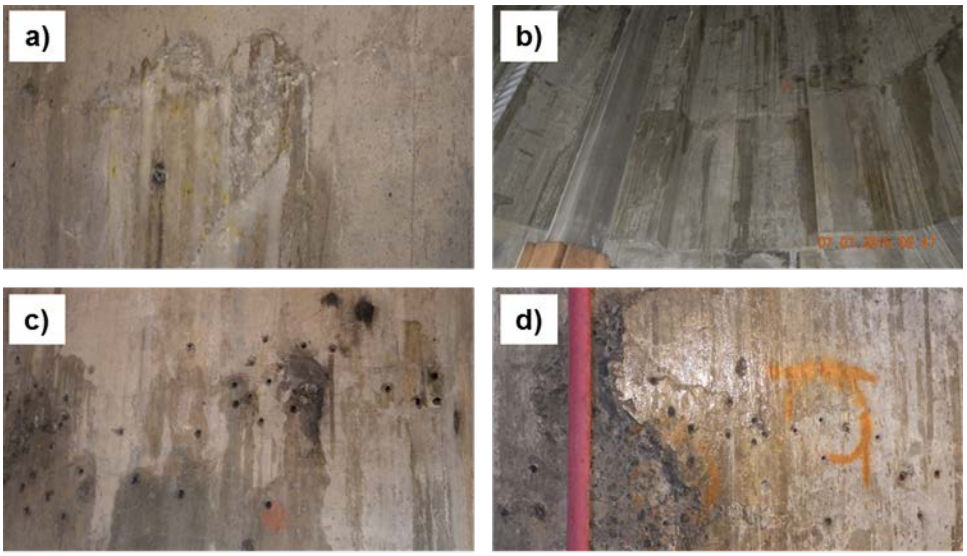

Figure 14. Significant water flow from the cracks is shown in a) and b). The large number of grout ports is shown in both c) and d). The photo in d) also shows concrete spalling due to excessive pressure during grout injection.

EOP Design Calculations

Design assumptions and calculations were performed by contractor:

The first step was to determine the minimum electric field based on water hydraulic pressure and pressure gradient. The dominant force components are generally those due to pressure and electro-osmosis. In applications for preventing water seepage, where the seepage is caused by hydrostatic pressure, the electro-osmotic force must balance or exceed the hydraulic pressure force.[7]

$$+\left(\frac{\rho^{+} z^{+} e_0}{m^{+}}+\frac{\rho^{-} z^{-} e_0}{m^{-}}\right)\vec{E}$$

Where:
$\rho^{\pm}$ = density of the medium of the positive (negative) ions
$z^{\pm}$ = charge of an ion
e_0 = elementary electric charge
$m^{\pm}$ = mass of a positive (negative) ion
$\vec{E}$ = strength of the electric field of the system

This is the general component to compare with the pressure gradient. Due to working with water seepage, the only charges moving will be the positive charges, from the anodes (inside the concrete) to the cathodes (outside of the concrete).

The electric field needed in the worst case, probably the point farther from the anodes, at the edge of the concrete, was calculated to be 14.6 V/m. This is the electric field at the point where the pressure gradient is the maximum value.

If the pressure gradient would have an equation, the electric field could be calculated in several points. When water samples are obtained, the water cation composition can be determined and the equation above adjusted with the total positive charges. The electro-osmotic force must overcome the hydraulic pressure force, because the electro-osmotic force has to move the water in the opposite direction of the water concentration gradient that is favored by the hydraulic pressure. The water needs to move against its natural flow direction, from low concentration inside the concrete to high concentration outside the concrete.

The second step was to determine the potential distribution in the concrete due to the anodes and the calculated electric field to match the electric field needed following step one.

The current density needed for the EOP system was assumed from prior experience and was tested and adjusted after the system was installed and commissioned. The value assumed was 0.35 A/m^2. This would mean the total current needed for water movement was 64.4 A.

The area where the system was to be installed was divided in two hemispheres or zones, and each zone was divided into 5 sub-sections with 7 anode ribbons and 5 cathode rods as shown in Figure 15 and Figure 16. The anodes were installed horizontally approximately 1 inch below the surface of the concrete. The cathodes were installed radially with 1.5 ft of the length coated (part inside the concrete) and 1.5 ft bare (part getting out radially from the concrete, this is the active zone that will collect the current and water from inside the concrete). The anodes used for the calculations were mixed metal oxide (MMO) coated titanium ribbons with the dimensions 0.25 inches high by 0.024 inches thick. The total length of anodes per subsection was determined to be ~189 feet. The cathodes used for the calculations were copper clad steel bars ¾ in diameter and 3 feet long. The first 1.5 feet were to be coated to isolate the portion of the bar close to the anodes. Calculations determined that 5 cathodes would be required for every 7 anode ribbons. A schematic diagram of the finished system is shown in Figure 17.

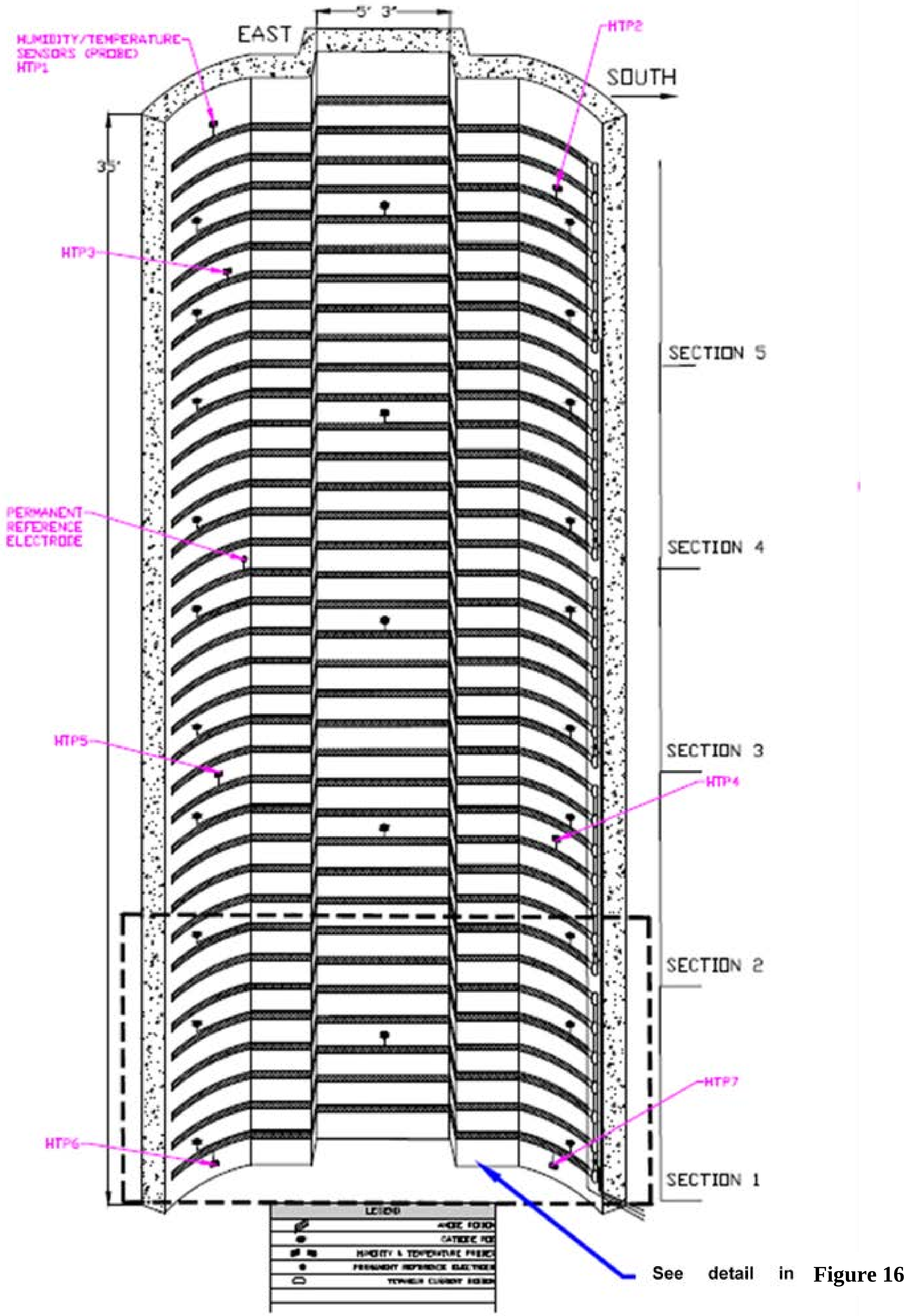

Figure 15. East hemisphere installation indicating location of components and number of sections per segment.

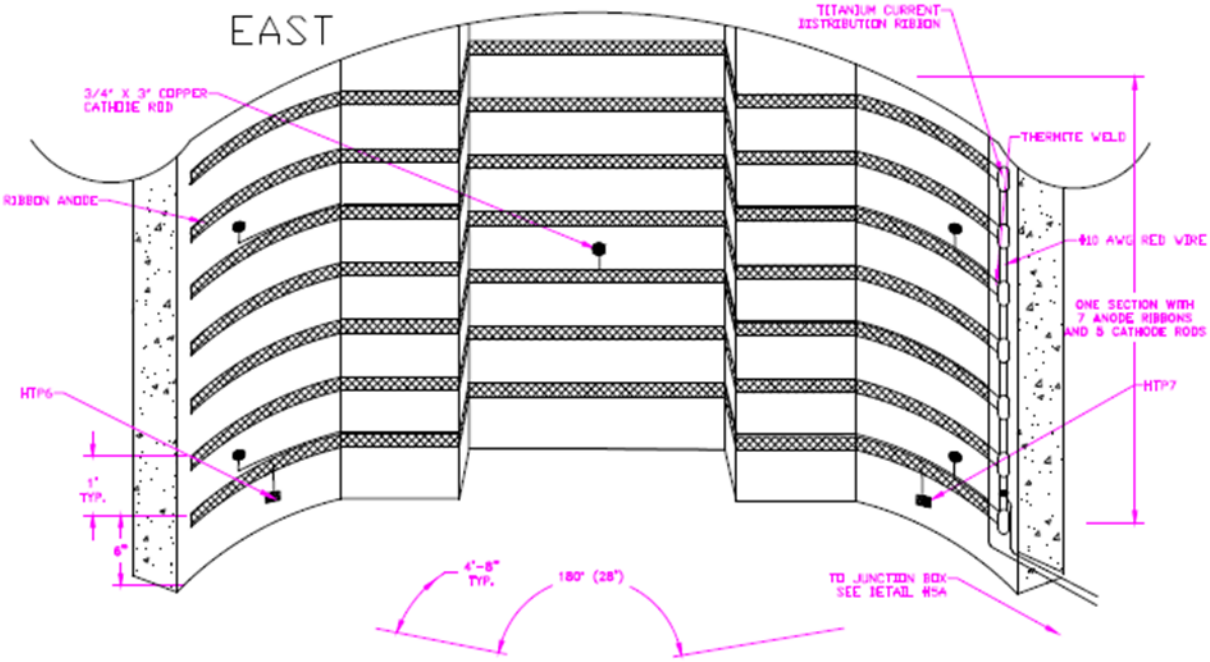

Figure 16. Section of east side segment showing dimension details of component locations.

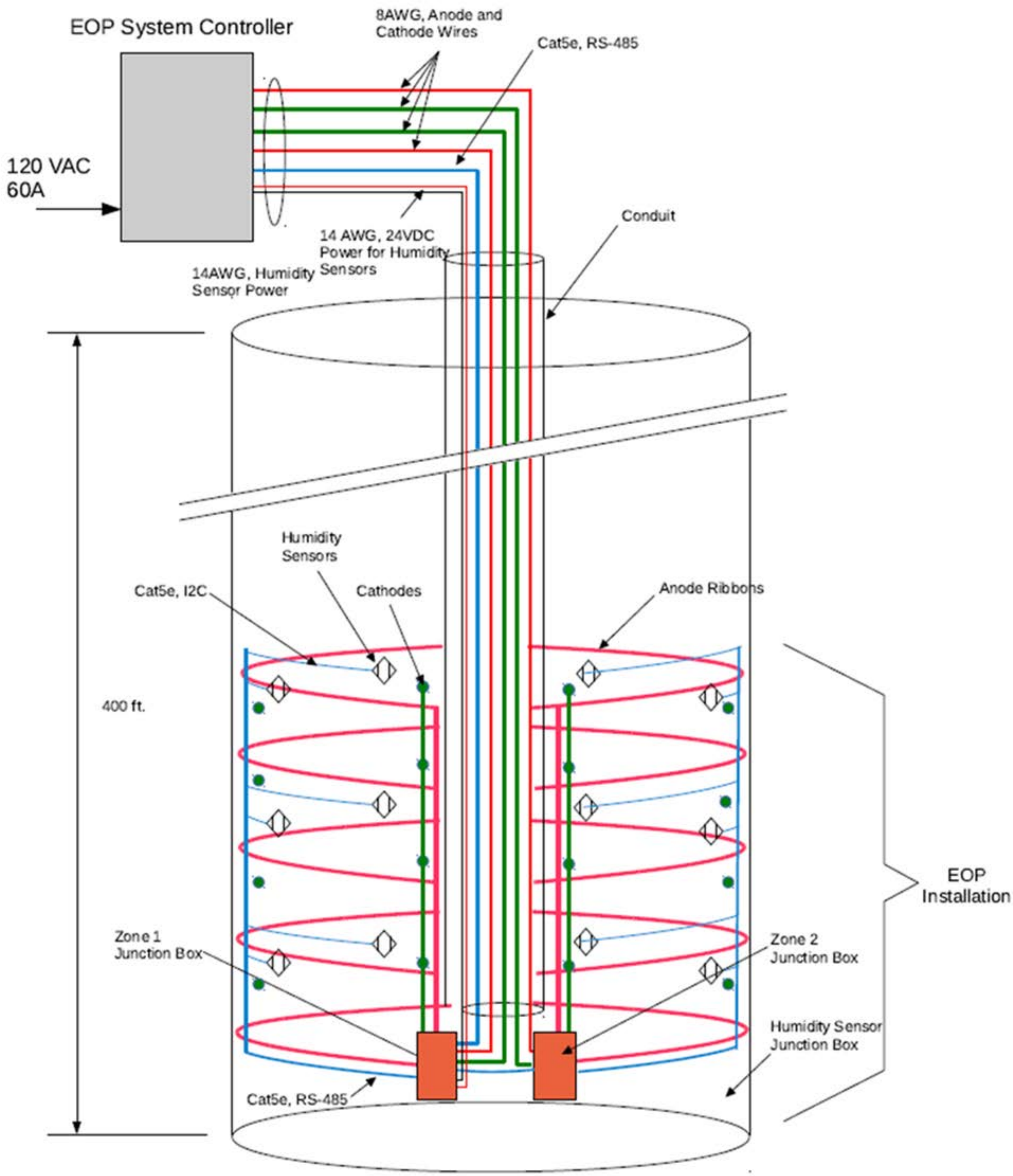

Figure 17. Schematic of the installed system design and component installation locations.

The volume of rebar in the EOP installation area was calculated to determine if it was anticipated that there would be any detrimental effects on the rebar due to the system. The calculations and results are included in Table 1.

Table 1. Rebar volume calculations for EOP installation area.

<table>
<tr><td colspan="2"></td><td>Inner Ring</td><td>Outer Ring</td></tr>
<tr><td colspan="2">Circumference = π*D</td><td>58.2 ft</td><td>67 ft</td></tr>
<tr><td colspan="2">I.D. = 222.5 inch</td><td></td><td></td></tr>
<tr><td colspan="2">O.D. = 256 inch</td><td></td><td></td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="2">35 rings inner (35 ft section) * 58.2 ft =</td><td>2037 ft</td><td></td></tr>
<tr><td colspan="2">35 rings outer (35 ft section) * 67 ft =</td><td></td><td>2345 ft</td></tr>
<tr><td colspan="2">58 vertical rebar inner * 35 ft =</td><td>2030 ft</td><td></td></tr>
<tr><td colspan="2">58 vertical rebar outer * 35 ft =</td><td></td><td>2345 ft</td></tr>
<tr><td colspan="2">Total linear feet of rebar</td><td colspan="2">8757 ft</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Cylinder volume = $\pi*r^2*h$</td><td colspan="3">$\Pi*(0.6\ in/12\ in)^2*1\ ft = 0.00785\ ft^3$</td></tr>
<tr><td>Rebar diameter #8 = 1 in</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>Rebar diameter #11 = 1.4 in</td></tr>
<tr><td>Average rebar diameter = 1.2 in</td></tr>
<tr><td colspan="4">12 in Spacing mat, rebar density = 490lbs/ft^3</td></tr>
<tr><td colspan="2">Volume per 1.2 in diameter rebar per linear ft</td><td colspan="2">0.00785 ft^3</td></tr>
<tr><td rowspan="4"></td><td>x</td><td colspan="2">8757 linear ft</td></tr>
<tr><td>x</td><td colspan="2">490 lbs/ft^3</td></tr>
<tr><td></td><td colspan="2">33683 lbs</td></tr>
<tr><td>or</td><td colspan="2">16.84 tons</td></tr>
</table>

Installation

Contractor Plan

The installation plan that was submitted for the EOP system was as follows:

1. Injection repair of cracks
2. Drip edge would be installed around perimeter to funnel water to floor
3. Identify proposed anode locations on substrate according to design drawing
4. Saw cut with Hilti dual blade concrete saw 1.25 inches wide by 0.75 inches deep channel, then chip out concrete between cuts using chipping hammer

5. Install MMO ribbon in channel and apply mortar
6. Saw cut channel for cable runs to junction box
7. Install cable and grout in

Contractor Sequence of Work

1. Mobilization onto site
2. Outline and mark by temporary marking, lines and positions of cathodes
3. Saw cut all channels and anode lines
4. Drill holes for temperature and humidity probes (different depths)
5. Drill or bore all cathode areas identified
6. Grout anodes in place
7. Grout wires from anodes and cathodes in channel
8. Attach all junction boxes
9. Secure all conduit

Anodes, Cathodes, and Sensor Probes

Due to the nature of the work zone, access was an issue. The contractor installed a temporary traveling platform to move up and down the shaft to the various locations to perform the necessary work. Photos of this platform are shown in Figure 18a-d.

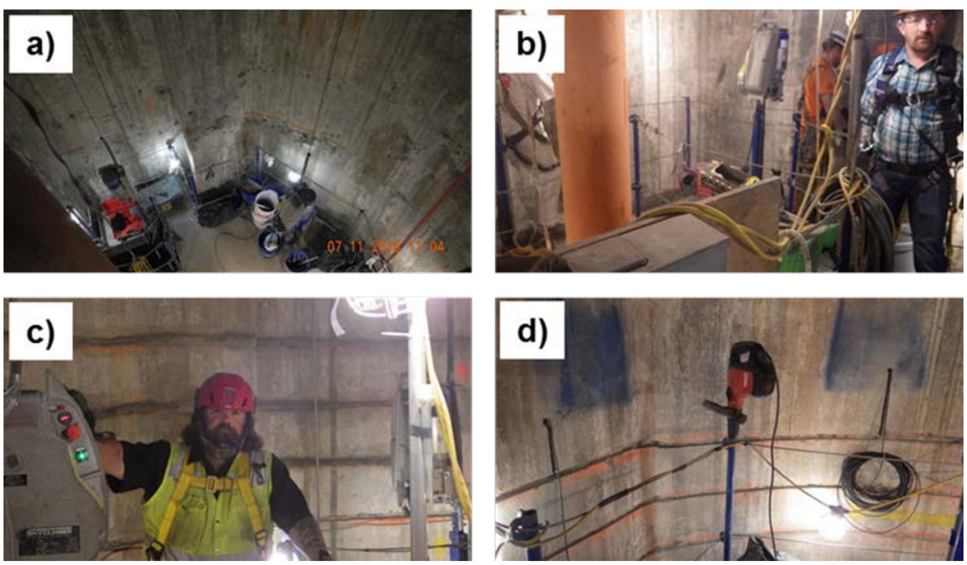

Figure 18. Installation was performed using a traveling platform.

Utilizing the traveling platform the locations of the anodes, cathodes, relative humidity and temperature sensors, and reference electrodes were mapped out on the shaft walls with spray paint. Figure 19 shows photographs of the markups as well as the location of a few of the leaks still exhibiting a degree of seepage. It was indicated by the contractor that a portion of this seepage would be dried out by the EOP system.

Once the locations of the components were mapped out grooves for the anodes were cut along the orange lines as shown in Figure 19. This was accomplished by using a HEPA vac system attached to concrete saws. The contractor made two cuts for each groove (Figure 20a and b), about 1 inch apart, and chipped out the concrete between the cuts to a depth of approximately 1 ⅜ inch. The grooves for the anodes were to be 1 foot apart. The anode grooves were not always 1 foot apart, 1 inch wide, 1 inch deep, or parallel to the floor of the chamber floor as shown in Figure 20c and d. Figure 21a and b show photos of some of the dimensions of the anode groves. Many of the grooves, and therefore the anodes were not spaced a foot apart but rather some were closer and some farther as shown in Figure 21c-f.

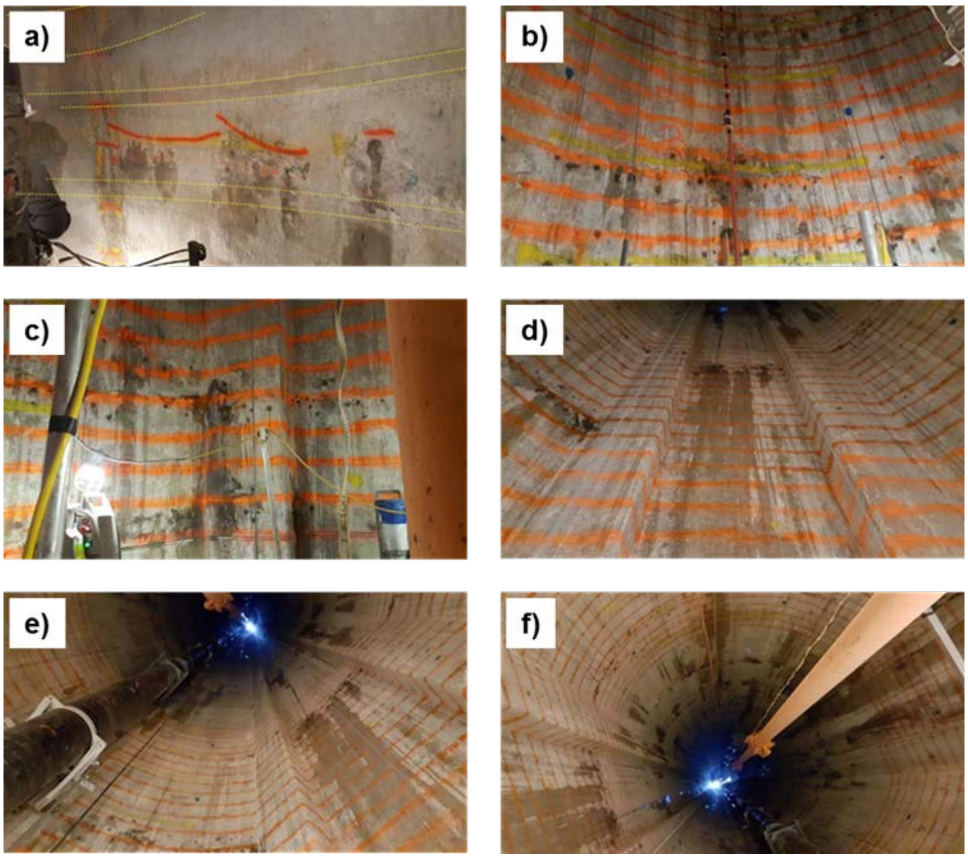

Figure 19. Photos of shaft after marking the walls with paint indicating the location of the anodes. The photos show that some cracks were still leaking however most had been sealed.

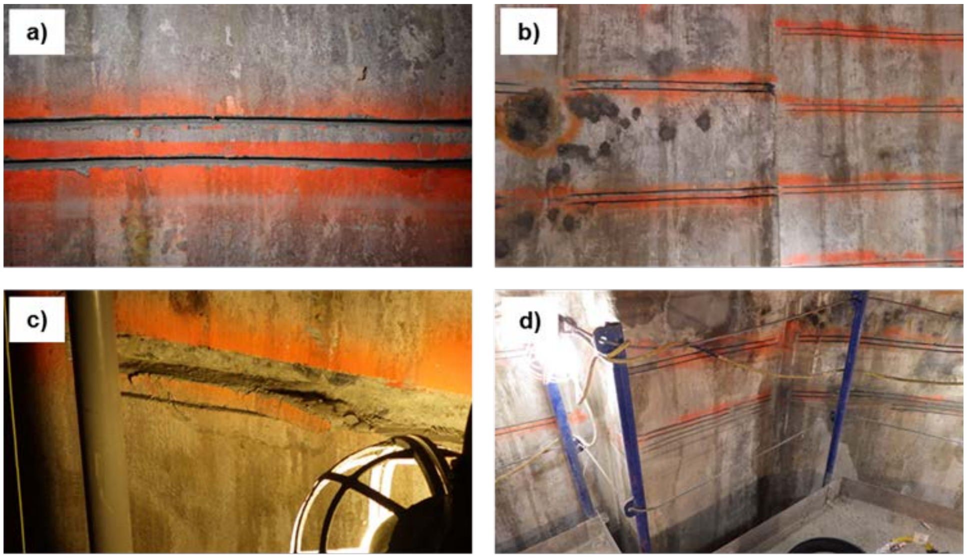

Figure 20. Anode grooves cut into the concrete wall. Photos a), b), and c) show cuts made prior to chipping out the concrete. Photos c) and d) show some chipped concrete and the results of extra cuts due to errors from the marks or labor.

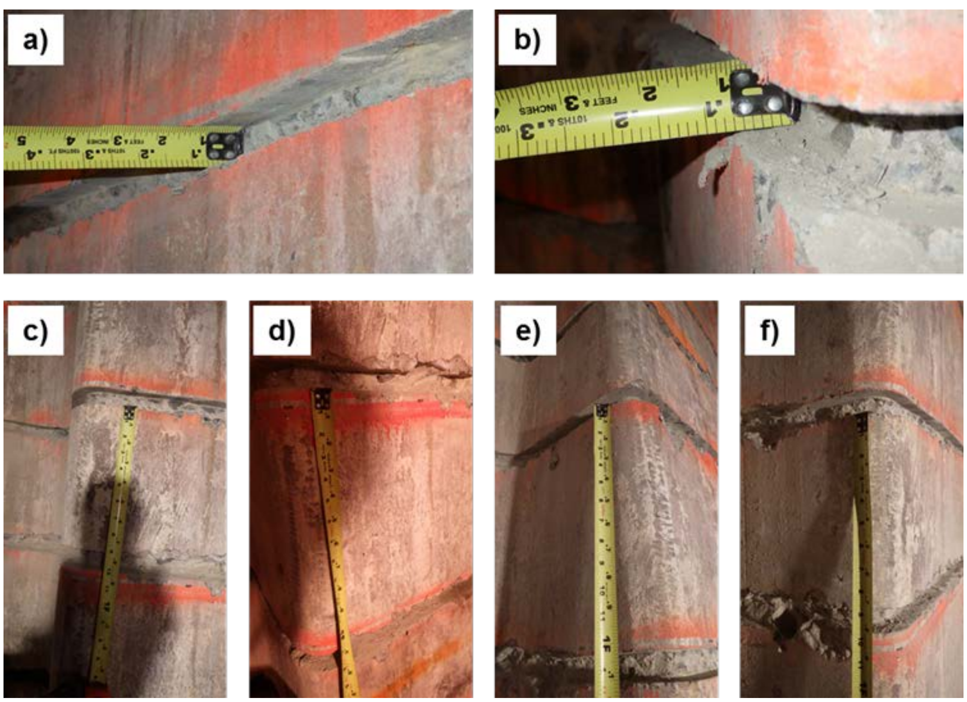

Figure 21. Dimensions of a representative number of anode grooves cut into the walls. These photos indicate that the grooves and therefore the anodes were not always separated by a foot.

MMO coated titanium ribbon anodes were installed in the grooves and held in place using wood dowel until the grooves could be filled with mortar for permanent placement (Figure 22). Connection to an end of all the anode ribbons was made using a copper crimpet to a #10 cable anode header cable with HMWPE insulation as shown in Figure 23a. There was one anode header cable for all 7 anodes in each of the sections in each zone. These cables were collected together and run to the junction box (Figure 23b and c) where they were connected to a titanium current bar.

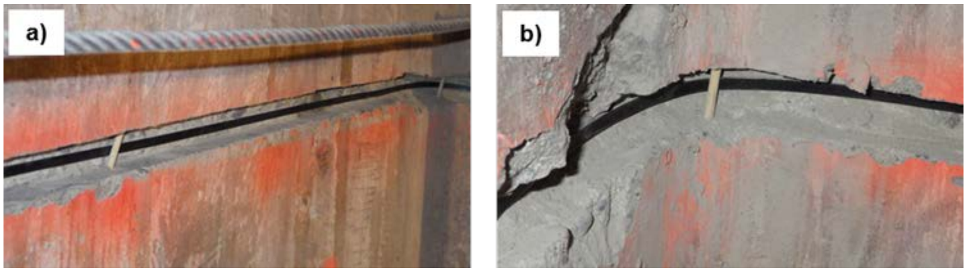

Figure 22. MMO anode ribbons installed in grooves and held in place using wooden dowels.

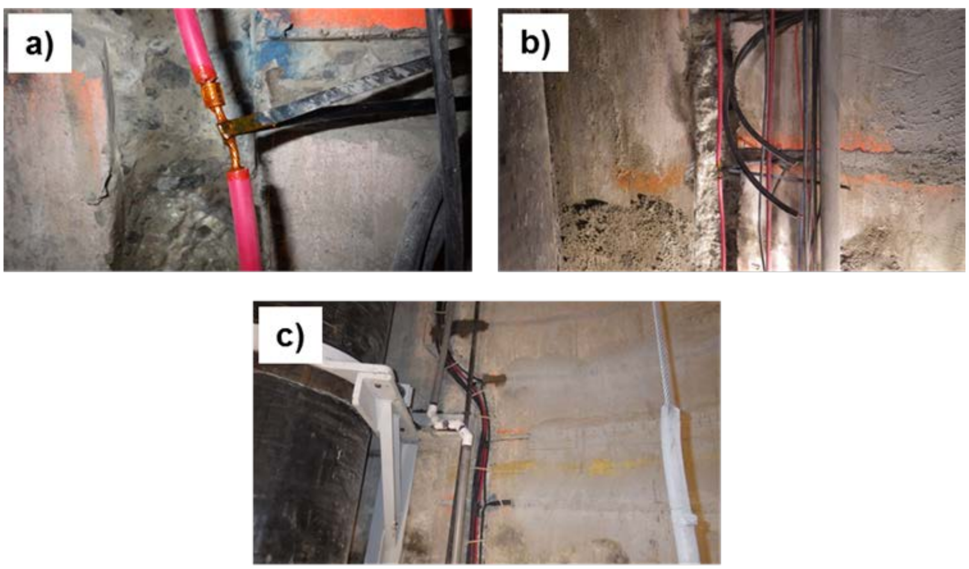

Figure 23. Anode ribbons crimped to a copper cable is shown in a). Photos b) and c) show the cables placed in a groove cut into the wall and running to the junction box.

Holes were drilled into the wall at designated locations for the cathodes and sensor probes. At some locations multiple holes were drilled due to rebar in the concrete wall. Figure 24 is a schematic of the installation of the cathodes, when rebar could not be avoided, in order to isolate the cathode rod from the steel reinforcement. Table 2 is a list of the depths to which the cathodes were embedded. Cathode installation is shown in Figure 25. The number written next to the cathode in Figure 25c) represents the depth of the hole. After installation of the cathode rods and sensor probes the holes were packed with mortar. Table 3 is a list of sensor locations and depths to which the sensors were embedded (6, 12, and 18 inches). After the anodes, cables and sensor probe cables were installed in the grooves (Figure 26a, b, c, d, and e) the grooves were then packed with mortar to encase them in the wall (Figure 26f, g, and h). The anode, cathode, and sensor probe cables were collected in trenches or grooves next to the air vent pipe and run down to the junction boxes. These cable grooves were then packed with mortar as shown in Figure 27.

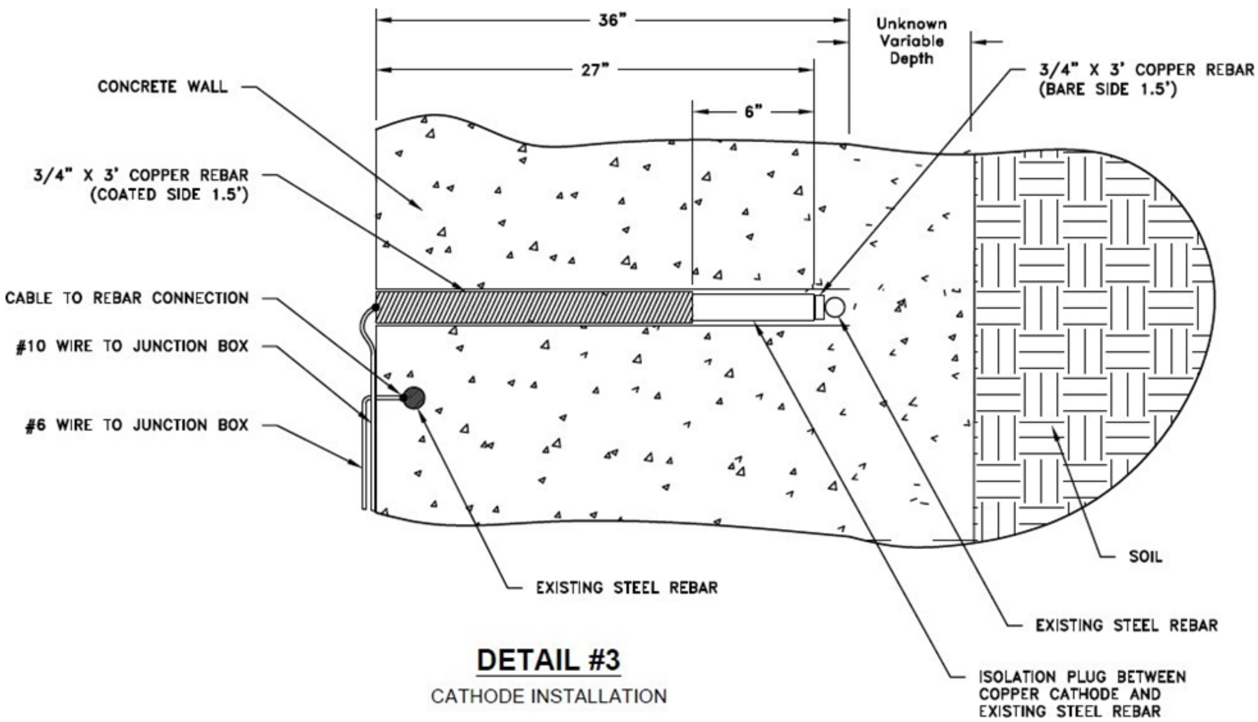

Figure 24. Schematic of cathode installation for isolation from rebar.

Table 2. Cathode rod placement and depth.

CATHODES	Zone 1*	Depth (in)		CATHODES	Zone 2*	Depth (in)
Z1.Sec1.Line2	20”	27		Z2.Sec1.Line2	20”	27
Z1.Sec1.Line2	23’4”’	27		Z2.Sec1.Line2	23’4”’	27
Z1.Sec1.Line4	14’	48**		Z2.Sec1.Line4	14’	27
Z1.Sec1.Line6	20”	27		Z2.Sec1.Line6	20”	27
Z1.Sec1.Line6	23’4”	27		Z2.Sec1.Line6	23’4”	27
Z1.Sec2.Line1	20”	27		Z2.Sec2.Line1	20”	27
Z1.Sec2.Line1	23’4”	27		Z2.Sec2.Line1	23’4”	27
Z1.Sec2.Line3	14’	27		Z2.Sec2.Line3	14’	27
Z1.Sec2.Line5	20”	27		Z2.Sec2.Line5	20”	27
Z1.Sec2.Line5	23’4”	27		Z2.Sec2.Line5	23’4”	27
Z1.Sec3.Line1	20”	27		Z2.Sec3.Line1	20”	27
Z1.Sec3.Line1	23’4”	27		Z2.Sec3.Line1	23’4”	27
Z1.Sec3.Line3	14’	27		Z2.Sec3.Line3	14’	48**
Z1.Sec3.Line5	20”	27		Z2.Sec3.Line5	20”	27
Z1.Sec3.Line5	23’4”	27		Z2.Sec3.Line5	23’4”	27
Z1.Sec4.Line1	20”	27		Z2.Sec4.Line1	20”	27
Z1.Sec4.Line1	23’4”	27		Z2.Sec4.Line1	23’4”	27
Z1.Sec4.Line3	14’	27		Z2.Sec4.Line3	14’	27
Z1.Sec4.Line5	20”	27		Z2.Sec4.Line5	20”	27
Z1.Sec4.Line5	23’4”	27		Z2.Sec4.Line5	23’4”	27
Z1.Sec5.Line1	20”	27		Z2.Sec5.Line1	20”	27
Z1.Sec5.Line1	23’4”	27		Z2.Sec5.Line1	23’4”	27
Z1.Sec5.Line3	14’	48**		Z2.Sec5.Line3	14’	27
Z1.Sec5.Line4	20”	27		Z2.Sec5.Line5	20”	27
Z1.Sec5.Line4	23’4”	27		Z2.Sec5.Line5	23’4”	27
Depths include 6 in. of exposed copper inside hole, with insulators for rebar contact						
*Locations include a tolerance of +/- 5 in. due to rebar blockage encountered						
*Measured from right of center (wire channel) in Zone 1 and left of center in Zone 2						
**Holes reached outer soil, and longer cathodes were used to contact soil						

Table 3. Humidity and Temperature probe sensor location chart.

Z1 East	Depth (in)	Location	Z2 West	Depth (in)	Location(ft)**
HTP1	6	21	HTP8	18	22
HTP2	12	10	HTP9	12	9
HTP3	18	22	HTP10	6	21
Reference Cell	12	24	HTP11	12	10
HTP4	6	9	HTP12	18	22
HTP5	12	21	Reference Cell	12	19
HTP6	18	22	HTP13	6	10
HTP7	12	8	HTP14	12	22
			HTP15	18	9
*Distance from current distribution bar to the right					
**Distance from current distribution bar to the left					

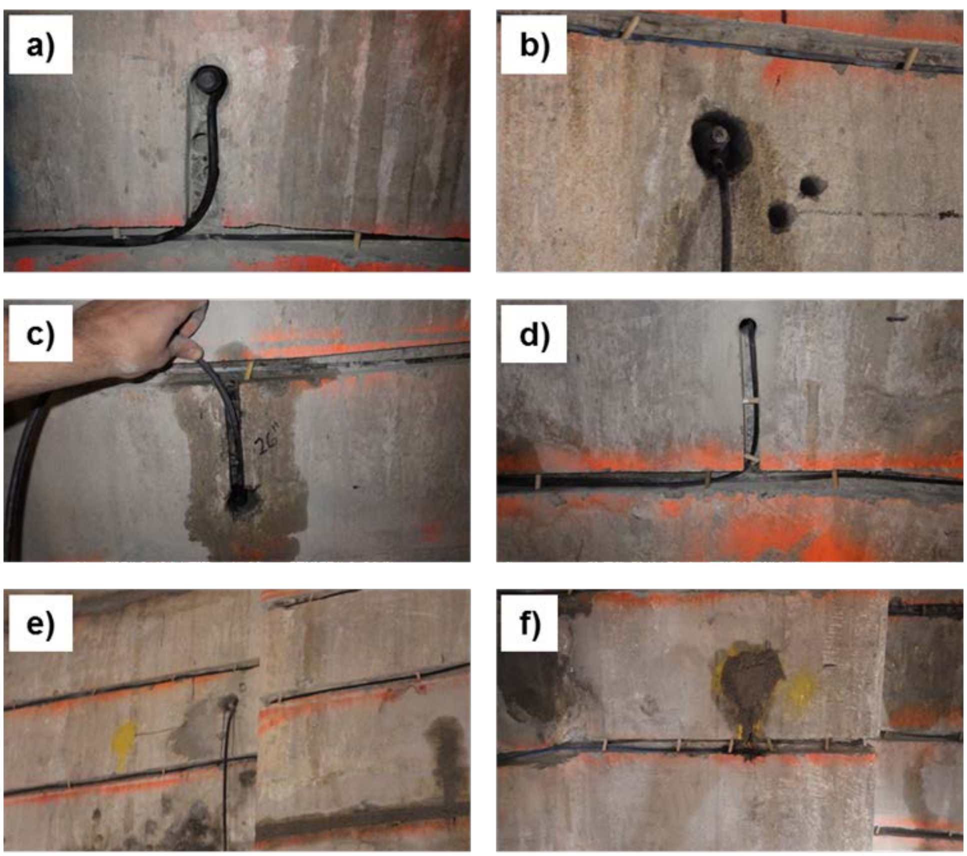

Figure 25. Cathodes installed in holes drilled into the wall of the shaft. Note the cable is run back to the junction box in the same groove as the anode ribbons. The cathode and sensor probe holes were then packed with mortar as seen in f).

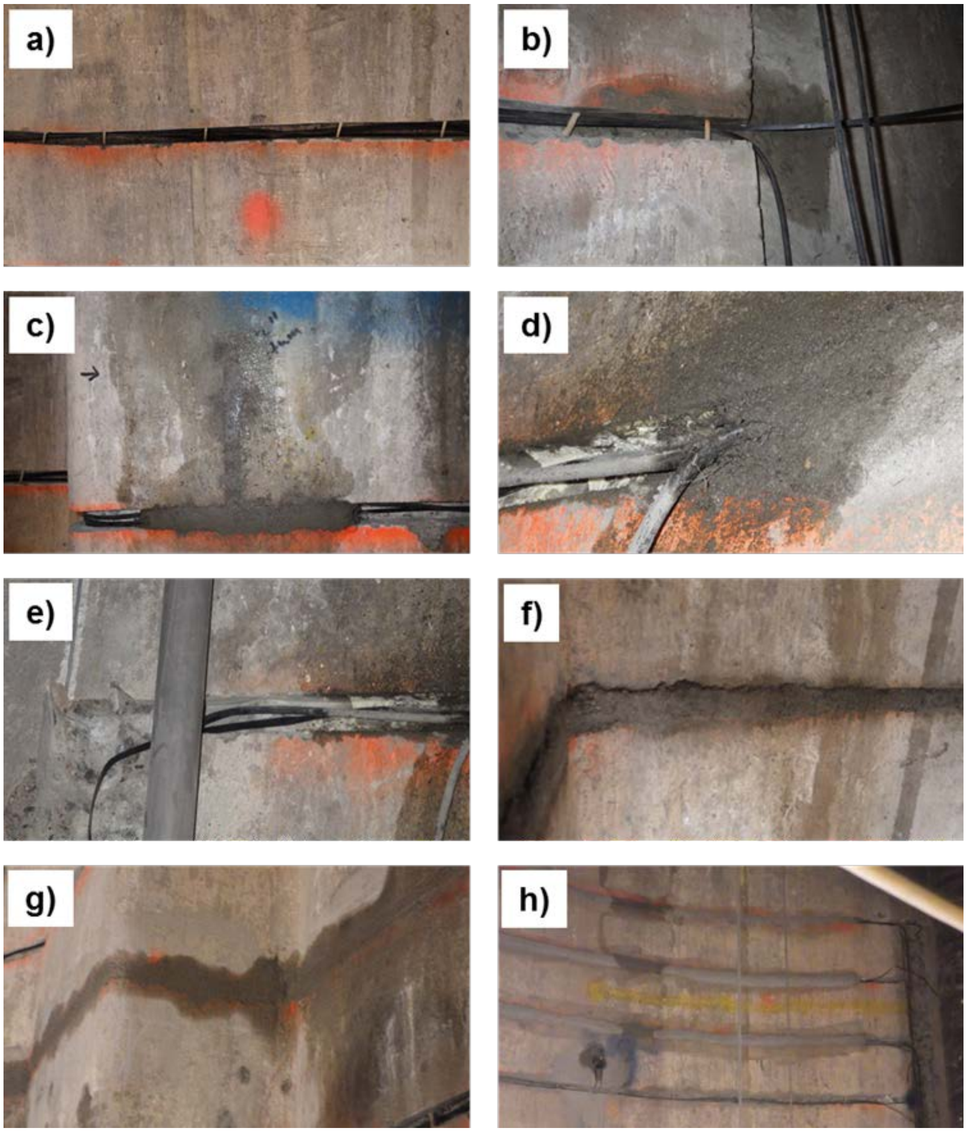

Figure 26. Photos showing cables from cathodes and sensor probes in same grooves as anode ribbons. Grooves were then packed with mortar.

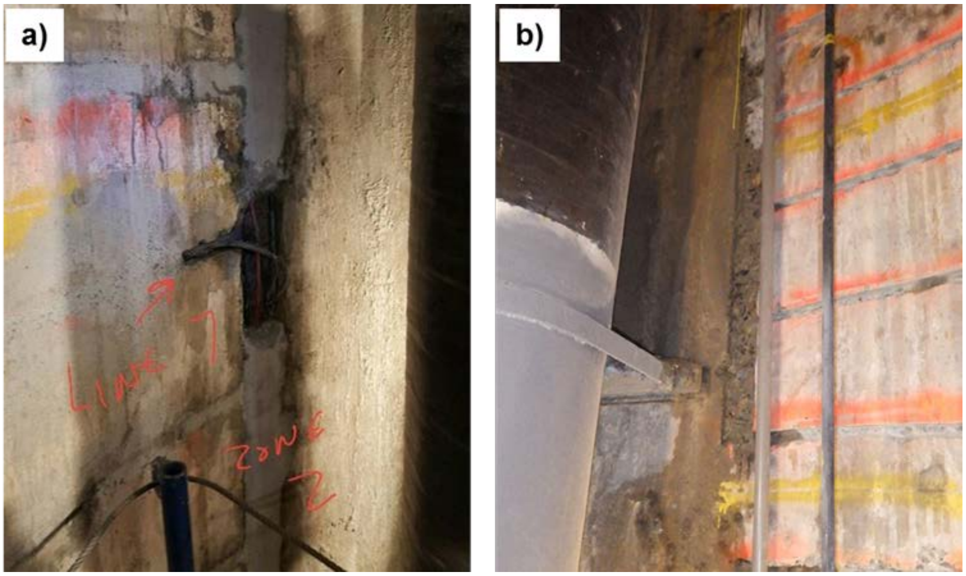

Figure 27. Cable trench for terminating anode ribbons, cathode cables, and sensor probe cables from each section. Trenches were packed with mortar to embed the cables.

Junction boxes are mounted to the top of the bonnet cover chamber where the anode, cathode, and sensor probe cables from the embedded components terminate (Figure 28a and b). These cables are connected to bus bars inside the boxes (Figure 28c and d) and a single cable from each zone is run through conduit to the EOP system controller (Figure 28e). The controller for the EOP system was located at the top of the shaft where it is out of the sun and protected and easily accessed.

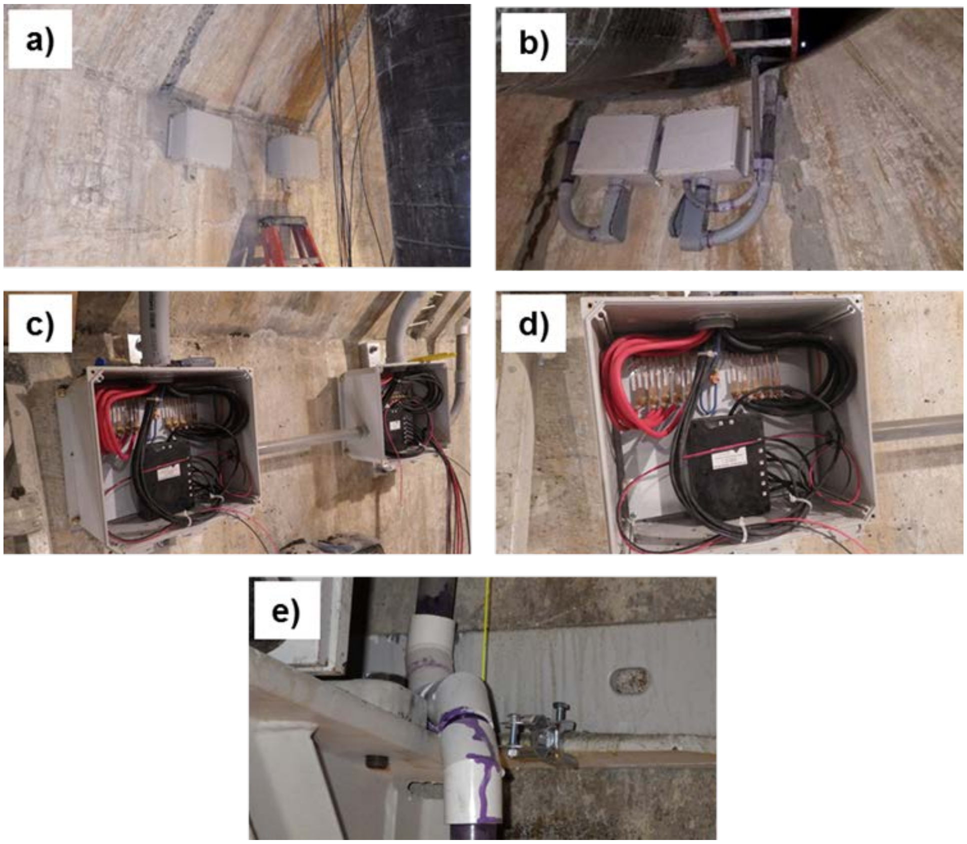

Figure 28. Junction boxes mounted at the top of the bonnet cover chamber, a) and b). Photos c) and d) show the cable connections inside the junction boxes, including cathode and anode cables. Photo e) is the conduit for the cables connecting to the EOP controller.

EOP Controller

Overview

The EOP controller, shown in Figure 29, applies the EOP sequence to the anodes and cathodes, reads the relative humidity and temperature from each sensor, monitors the applied voltage and resulting current, and stores the data on a removable SD card.

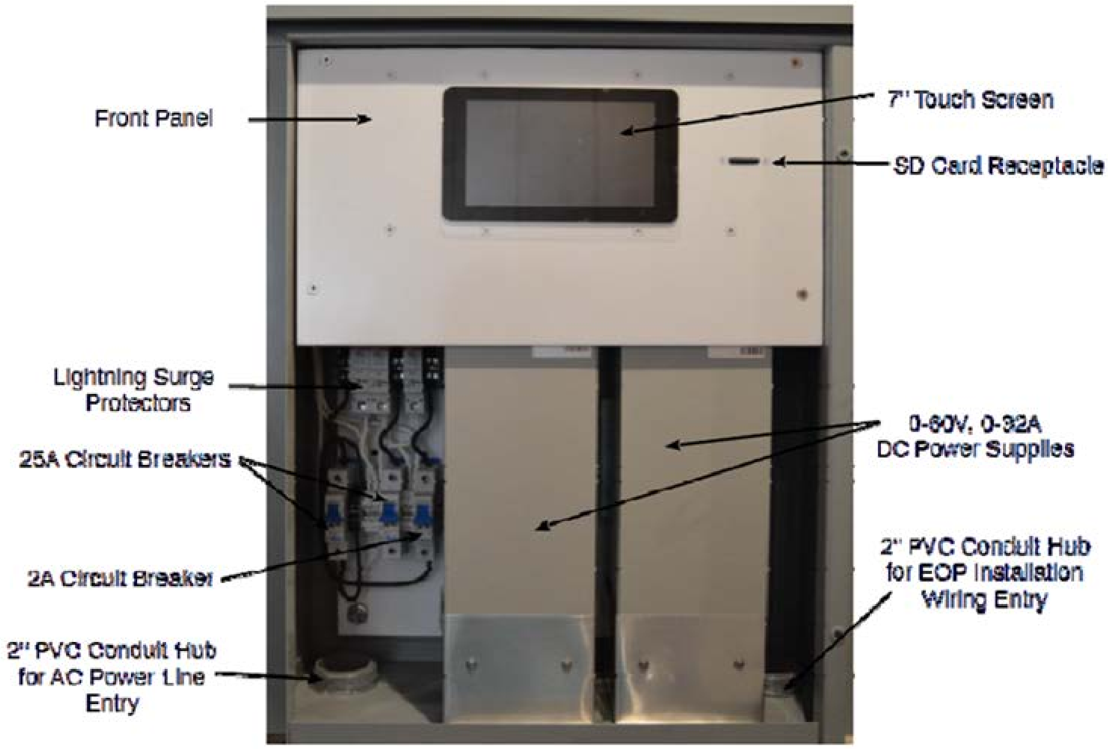

Figure 29. EOP controller for operating the system by applying a pulse sequence to the installation.

Per the two-hemispherical zones anode/cathode arrangement, the system controller has two independent power supplies, each one powering a section of the installation. The EOP sequence or pulse is produced using a microcontroller based H-Bridge circuit. The pulse sequence is configurable with respect to timing and duration of the positive and negative pulse and off (no voltage) cycle. The system allows programming of up to twenty sequential intervals, each of which can be configured as positive, negative, or off. The duration of each interval is programmable in a range of 10 milliseconds to 60 seconds, with a resolution of 10 milliseconds.

Each of the two power supplies feature output voltage adjustment within a range of 0V to 50V and current adjustment within a range of 0A to 32A.

The controller includes a touchscreen used to display the EOP voltage, current, humidity, and temperature measurements and to allow the user to configure the system. The SD card interface is provided to log time stamped data measurements.

Cabinet
The EOP controller is installed in a NEMA 250 type 3R cabinet with a hinged door with a padlock hasp. The enclosure provides protection from any environment exposure conditions such as rain and snow. To avoid these conditions the controller was installed at the top of the shaft of the catwalk inside the top structure. The cabinet requires air circulation through the

enclosure to prevent over-heating of the power supplies and circuits. The installation required a minimum of 12 inches of free space below and on each side of the cabinet. The dimensions of the installed controller are shown in Figure 30.

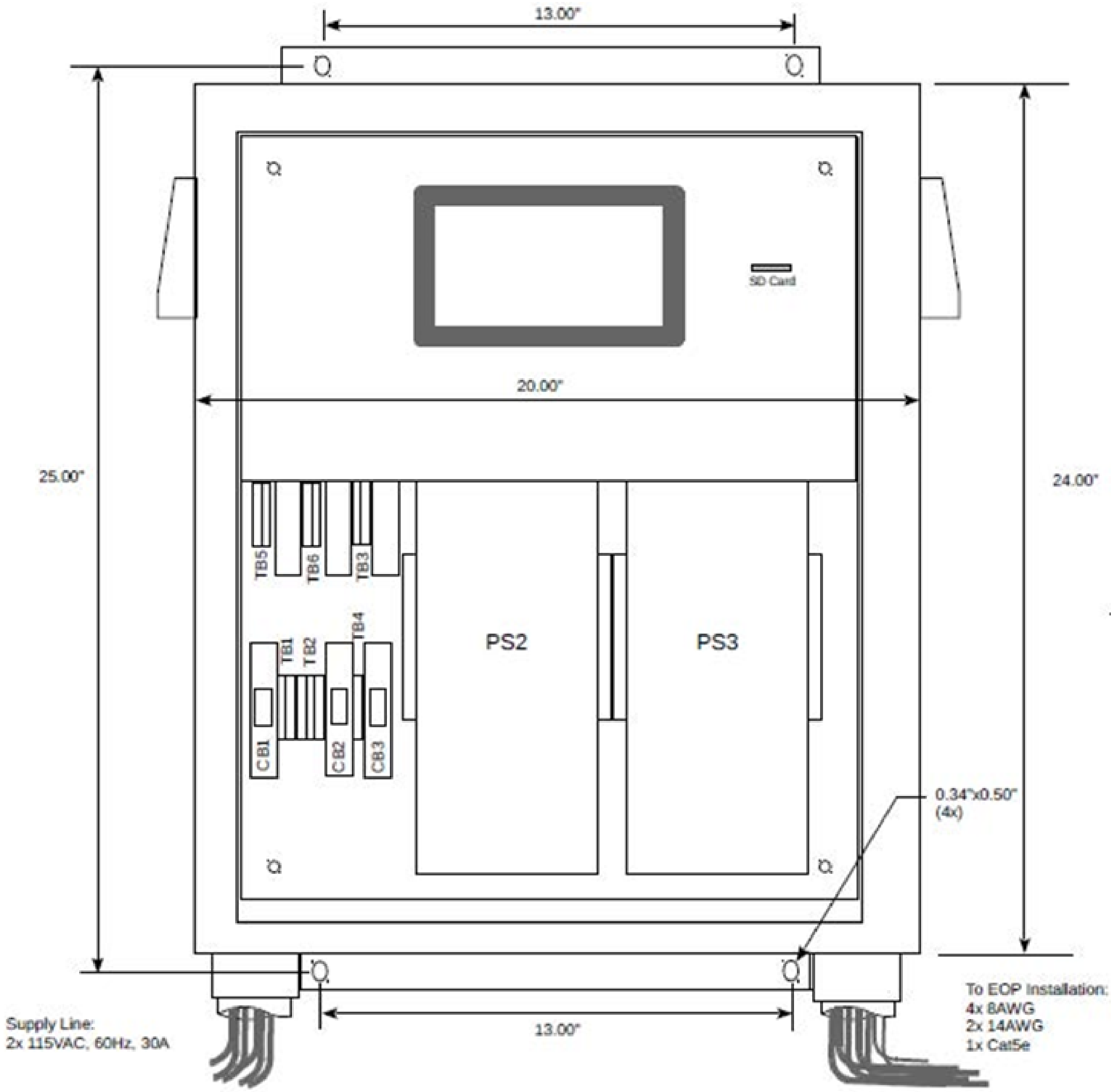

Figure 30. Schematic of controller dimensions and installation requirements.

Power Connections

The controller operates using two independent 115V_{AC}, 60 Hz, 30 A power lines. One supplies the power to the electronic control circuits as well as the zone 1 DC power supply. The other supplies power to the zone 2 DC power supply. The controller includes the following internal circuit breakers:

Power line #1:

1. 2 A breaker to the electronic control circuits
2. 25 A breaker to the zone 1 power supply

Power line #2:

1. 25 A breaker to the zone 2 power supply

The power input circuits are wired as shown in Figure 31. A PVC conduit hub is provided on the bottom left side of the cabinet for entry of the input power lines. The power lines were connected as follows:

1. 115 V_{AC} line (black wire) connected from power line #1 to the open terminal of the black terminal block to the right of the left-most (25 A) circuit breaker.
2. 115 V_{AC} neutral (white wire) connected from power line #1 to the open terminal of the white terminal block immediately to the right of the black terminal block.
3. Earth ground (green wire) connected from power line #1 to the open terminal of the chassis ground block.
4. 115 V_{AC} line (black wire) connected from power line #2 directly to the bottom of the center (25 A) circuit breaker.
5. 115 V_{AC} neutral (white wire) connected from power line #2 to the open terminal of the white terminal block immediately to the right of the center (25 A) circuit breaker.
6. Earth ground (green wire) connected from power line #2 to the open terminal of the chassis ground block.

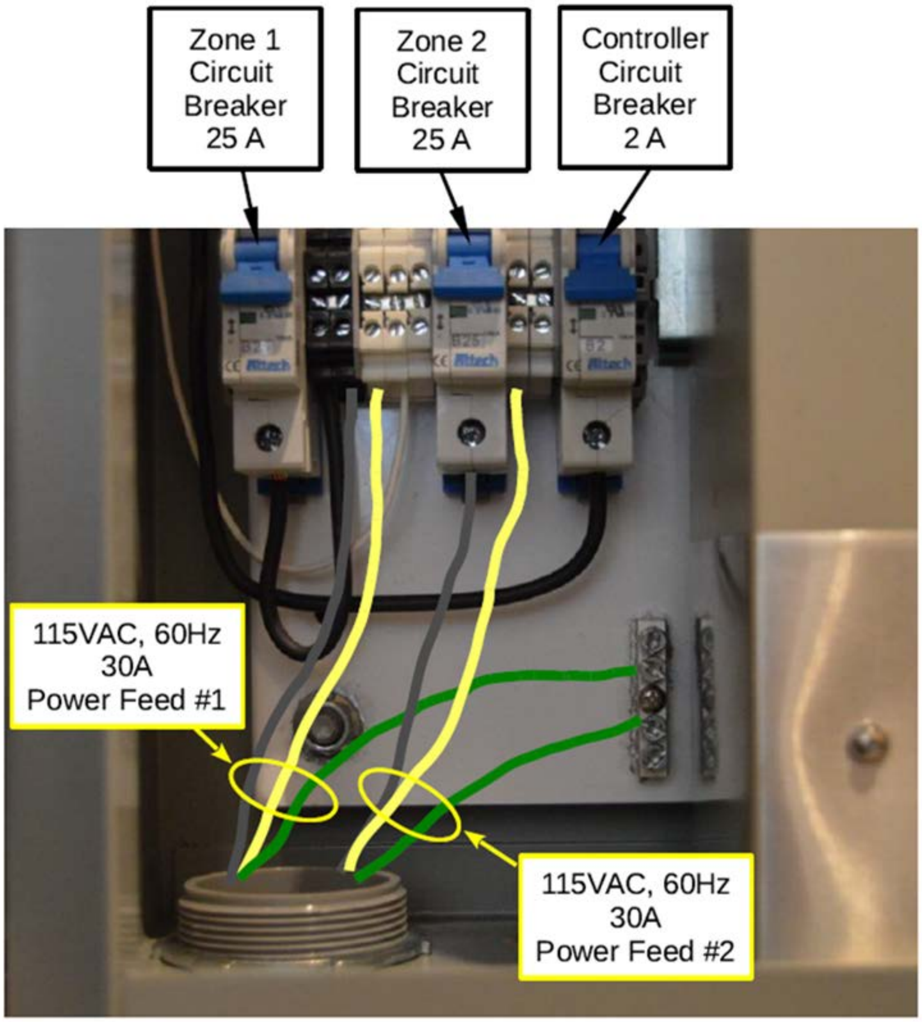

Figure 31. Input power wiring diagram.

Component Cable Connections

The front panel was removed to access the terminals used to connect the following wires:

1. Anode and cathode wires from the installation
2. Humidity sensor power wires from the installation
3. CAT5e cable used to read the humidity sensors

The front panel was removed using the following procedure:

1. Removing the four front panel mounting screws shown in Figure 32
2. Carefully pulled the front panel away from the cabinet revealing the wiring connected behind the front panel display (Figure 33)
3. Removing the two 24 V_{DC} power wires from the rear of the front panel
4. Removing the two RJ11 cables from the rear of the front panel

Figure 32. Controller front panel mounting screws.

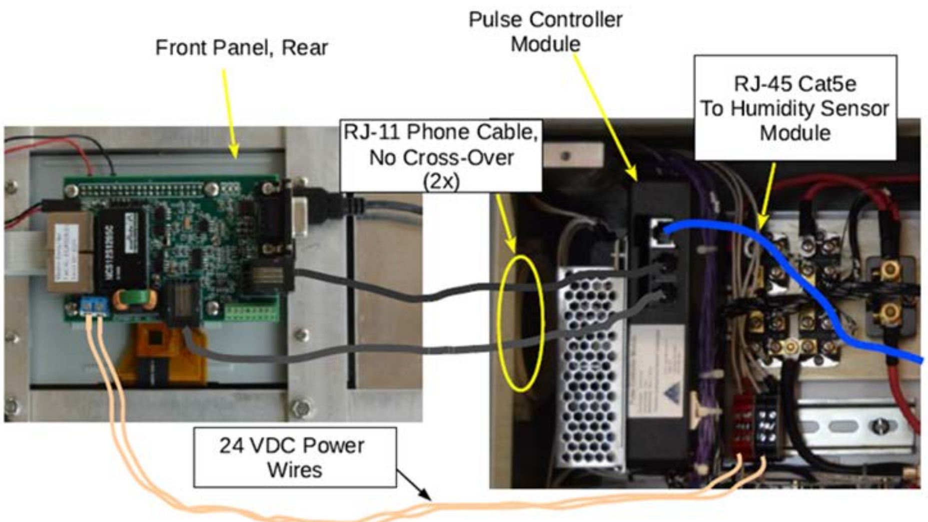

Figure 33. Front panel wiring.

The anodes and cathodes were connected to the terminal blocks located in the upper right corner of the controller, behind the front panel. Independent anode and cathode wire connections were provided for each zone. The wires were routed from the installation through the conduit hub on the lower right of the cabinet and connected as shown in Figure 34.

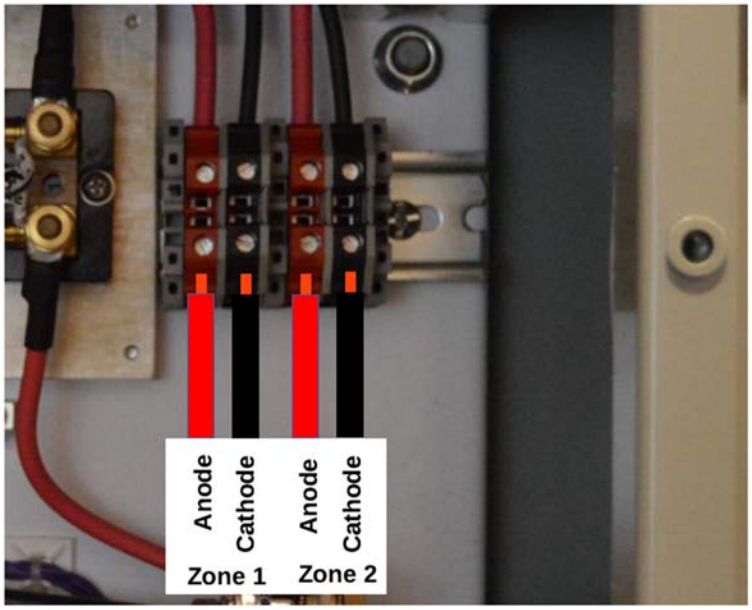

Figure 34. Anode and cathode wire connections inside controller.

The controller included provisions for powering and interfacing to external remote monitoring equipment. The power source provides 24 V_{DC} at up to 1 A to power the equipment. The data interface is provided through an RJ45 connector which provides access to a daisy chained multi-drop RS-485 interface that connects the master controller module to internal and external slave modules.

The humidity sensor power lines were routed through the hub located on the right of the cabinet and connected as shown in Figure 35.

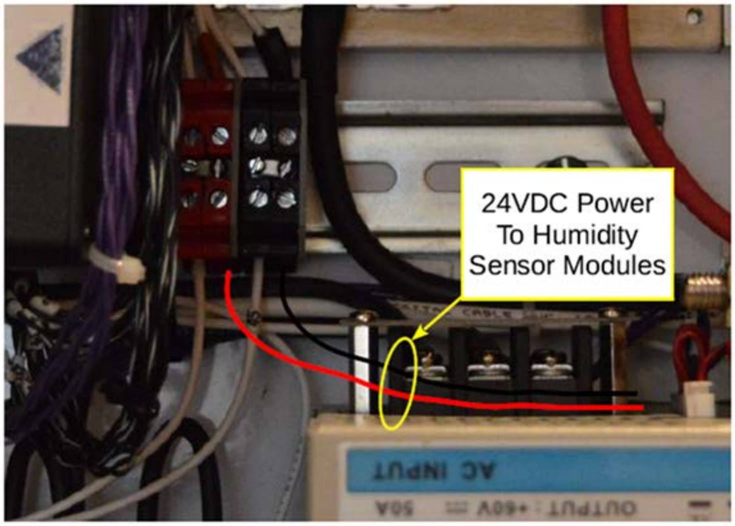

Figure 35. 24 VDC humidity sensor interface power connections.

The CAT5e data interface cable was routed through the conduit hub on the lower right of the cabinet. The upper connector of the pulse controller module was connected as shown in Figure 36.

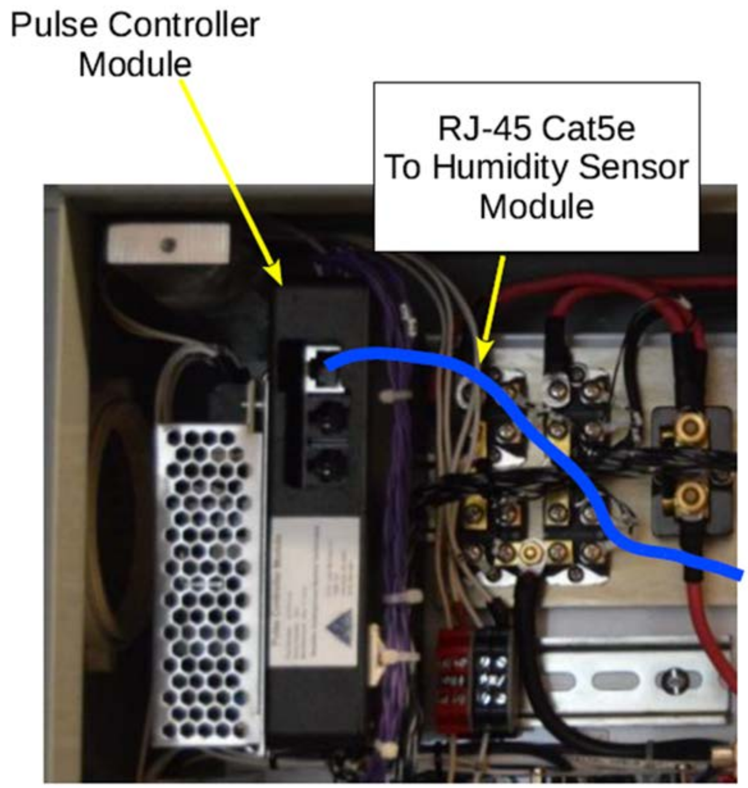

Figure 36. Humidity sensor interface data connection.

Data Results

In order to determine if there were any detrimental or adverse effects on the structural rebar due to the EOP system, the native potential of the rebar was measured and compared to the potential after the system was energized. The native or static potential is the voltage measurement between the rebar encased in concrete and a calibrated reference electrode, in this case a copper/copper sulfate reference electrode (CSE). The static rebar-to-concrete potential was determined prior to energizing EOP system. After the system is energized, another measurement is performed and the “instant OFF” or polarized potential of the rebar is determined. The polarized rebar-to-concrete potential was determined after the EOP system has been energized for a sufficient amount of time, but immediately after the EOP system current is interrupted. The results from these measurements are provided in Table 4.

Table 4. Rebar-to-concrete potential measurement results in each zone before and after the EOP system was installed and energized.

Rebar-to-Concrete Potential vs. Copper/Copper Sulfate Reference Electrode (V)						
Date	Zone 1			Zone 2		
	Native (Before EOP System Installed)	After EOP System Energized		Native (Before EOP System Installed)	After EOP System Energized	
		On	Instant Off		On	Instant Off
4/20/2016	-0.762	N/A	N/A	-0.425	N/A	N/A
10/4/2016	N/A	-1.125	-0.730	N/A		
4/25/2017	N/A		-0.735	N/A	-0.870	-0.450
11/14/2017	N/A	-1.135		N/A	-0.760	-0.430

While the native potentials are more negative than what is typically expected (0.0 V_{CSE} to -0.4 V_{CSE}) the static potentials of rebar can vary significantly with moisture, oxygen, carbonation, chlorides, and amount of concrete coverage. The potential measurements in Table 6 for both Zone 1 and Zone 2 showed only a shift around ± 0.3 V. Therefore the EOP system does not appear to have had a detrimental effect on the rebar.

The EOP system was powered up on September 10, 2016 and initial testing was performed and completed. The system was allowed to operate as initially programmed and the results reported below. The data was collected on the SD card every minute, however, the data reported is shown within a 4-hour window. The data for the initial 24 hr period of operation is presented in Table 5 as well as graphically in Figure 37, although the actual data was collected over a longer period of time. The data shows the desired effect of increasing resistance over time indicating that the water content between the anodes and cathodes is decreasing. The temperature data shown in Figure 38 and Figure 39, in zone 1 and 2 respectively, for the first 24 hrs showed no change over the period of time. The ambient humidity measured during the first 24 hrs after energizing the EOP system (Figure 40) also indicated no change.

Table 5. Initial 24 hrs of data collected after energizing the EOP system.

Area	Zone 1- East Side			Zone 2 West Side		
Date & Time	Voltage (V)	Current (A)	Resistance (Ω)	Voltage (V)	Current (A)	Resistance (Ω)
11/3/2016 21:29	39.9	4.2	9.5	40	4.4	9.090909
11/4/2016 1:29	40	4.4	9.090909	39.9	4.4	9.068182
11/4/2016 5:29	40	3.8	10.52632	40.1	4.1	9.780488
11/4/2016 9:29	50	5.8	8.62069	50.2	6.2	8.096774
11/4/2016 13:03	39.9	3.5	11.4	40	3.8	10.52632
11/4/2016 17:03	39.9	3.5	11.4	39.9	3.6	11.08333
11/4/2016 21:03	40	3.5	11.42857	39.9	3.6	11.08333
11/5/2016 1:03	39.9	3.3	12.09091	40	3.5	11.42857
11/5/2016 5:03	39.9	3.3	12.09091	40	3.5	11.42857
11/5/2016 9:03	39.9	3.4	11.73529	40	3.6	11.11111

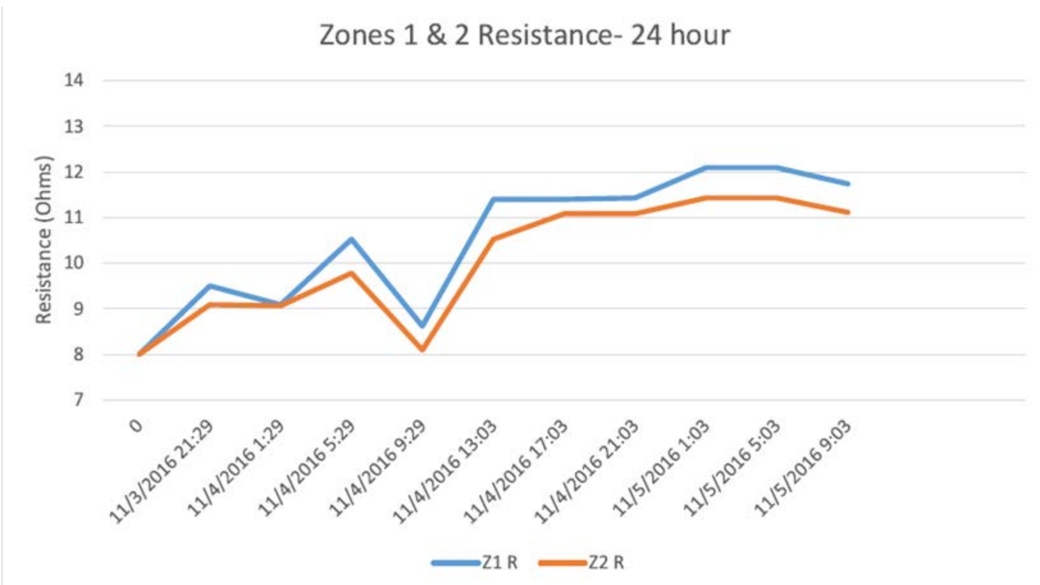

Figure 37. Graph of the initial 24 hrs of data collected after energizing the EOP system. The resistance for each zone is increasing over time indicating that the water is moving away from the surface.

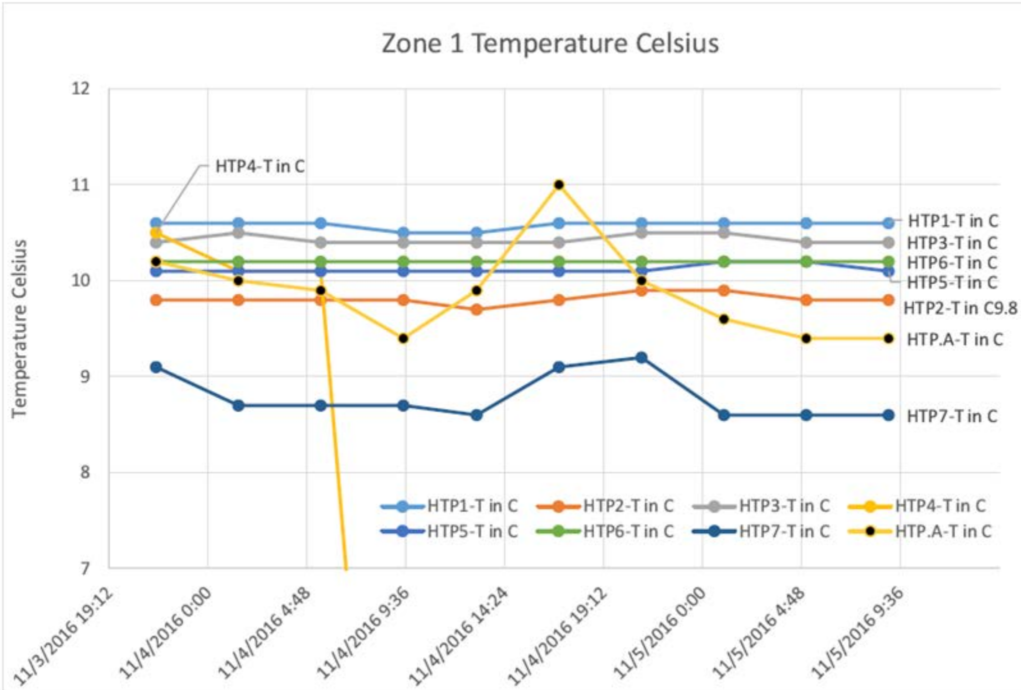

Figure 38. Graph of the first 24 hrs of temperature data collected after energizing the EOP system for Zone 1. There was no real change in temperature observed.

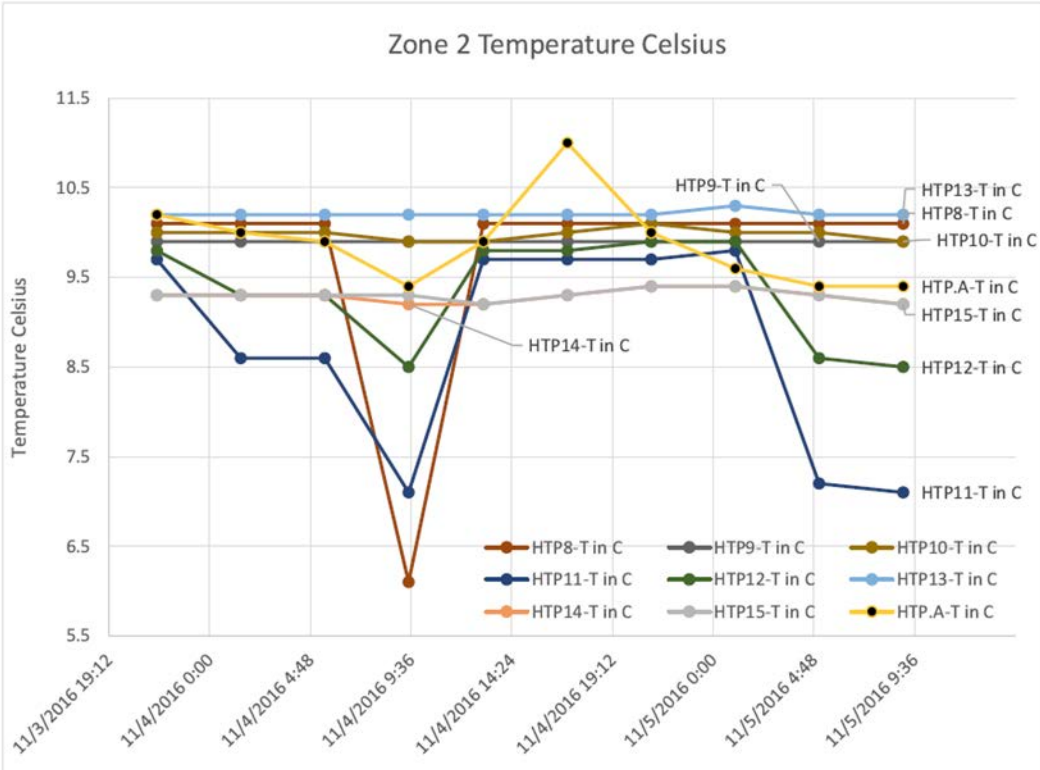

Figure 39. Graph of the first 24 hrs of temperature data collected after energizing the EOP system for Zone 2. There was no real change in temperature observed.

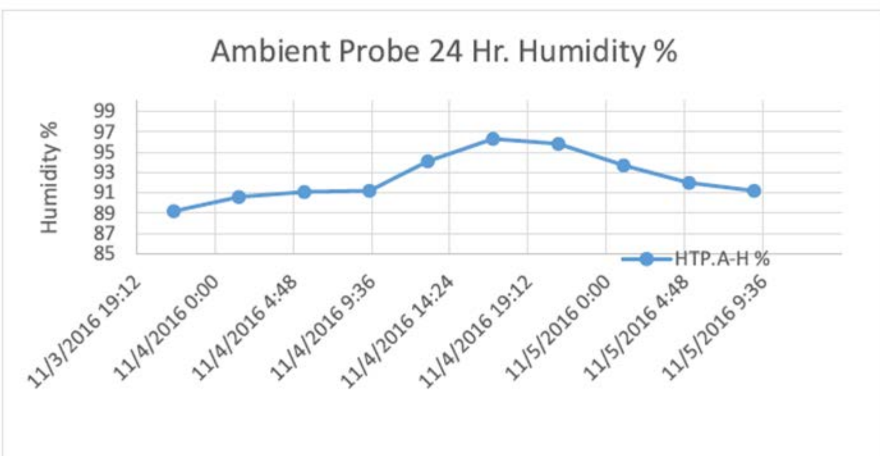

Figure 40. Graph of the first 24 hrs of ambient humidity data collected after energizing the EOP system.

Shorts were discovered in the system and were repaired on November 4, 2016. After the shorts were repaired the potential of the rebar was compared to the potential of the cathode, as shown in Table 6. The potential difference was large, indicating that the shorts were fixed.

Table 6. Potential measurements of rebar and cathodes for determining potential electrical shorts.

	Zone 1	Zone 2	Remark
Potential of Rebar Mat to Reference (V)	1.135	0.760	
Potential of EOP Cathode to Reference (V)	5.920	2.563	
Potential Difference between EOP System and Rebar Mat (V)	4.785	1.803	High potential difference, No Shorts

On November 11, 2016, data was pulled from the system for evaluation of the first 7 days of operation (Table 7). The system was performing as designed. The resistance values continued to rise as desired, indicating the system was drying the concrete. This is shown graphically in Figure 41. The temperature measured in zone 1 (Figure 42), zone 2 (Figure 43), and the ambient humidity (Figure 44) indicated no change during this period of time.

Table 7. Initial 7 days of data collected after energizing the EOP system.

Area	Zone 1- East Side			Zone 2 West Side		
Date & Time	Voltage (V)	Current (A)	Resistance (Ω)	Voltage (V)	Current (A)	Resistance (Ω)
11/4/2016 13:03	39.9	3.5	11.40	40	3.8	10.53
11/5/2016 13:03	39.9	3.3	12.09	39.8	3.5	11.37
11/6/2016 13:03	40	3.4	11.76	40.1	3.6	11.14
11/7/2016 13:03	40	3.3	12.12	40	3.5	11.43
11/8/2016 13:03	40	3.3	12.12	40	3.5	11.43
11/9/2016 13:03	40	3.2	12.50	40	3.5	11.43
11/10/2016 13:03	40	3.3	12.12	40	3.6	11.11
11/11/2016 13:03	39.9	3	13.30	40	3.5	11.43

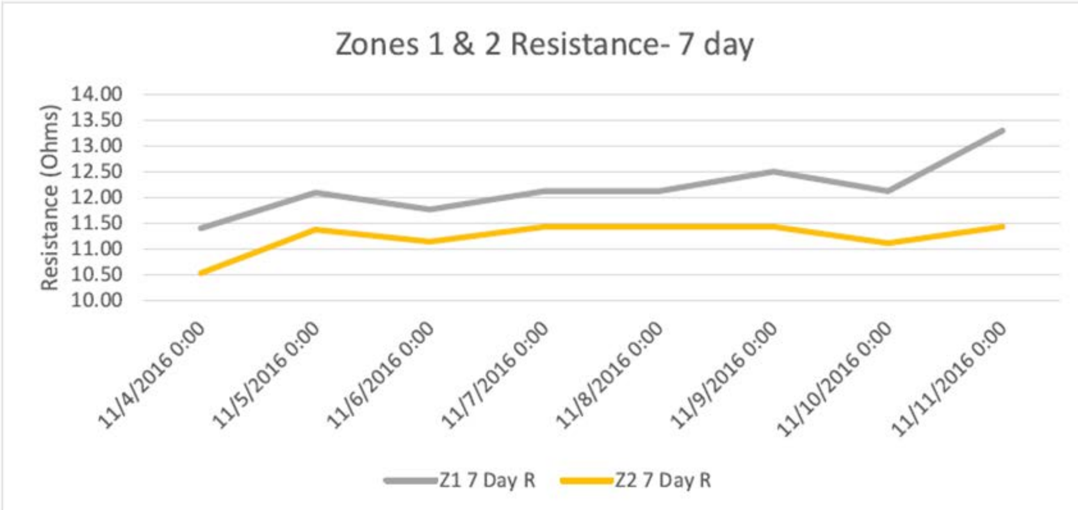

Figure 41. Graph of the first 7 days of data collected after energizing the EOP system. The resistance for each zone is increasing over time indicating that the water is moving away from the surface.

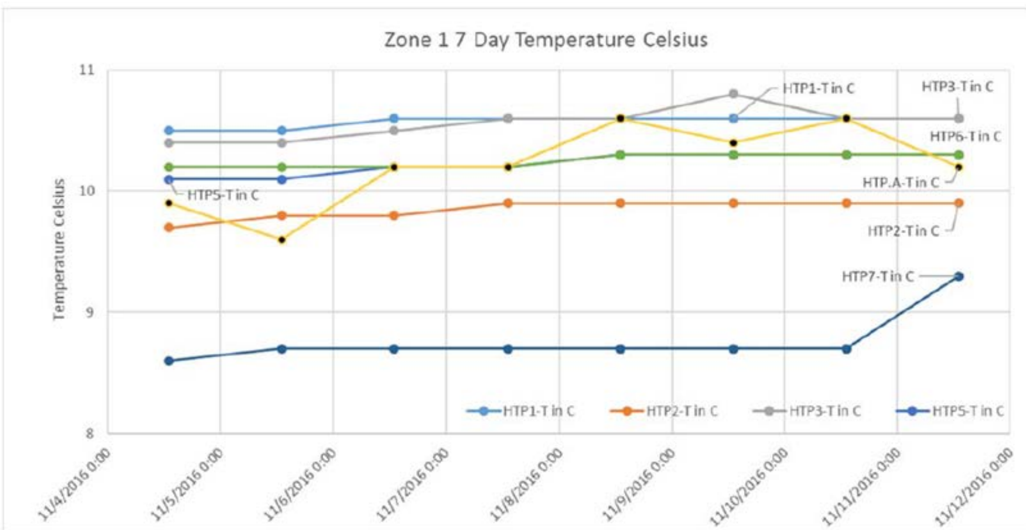

Figure 42. Graph of the first 7 days of temperature data collected after energizing the EOP system for Zone 1. There was no real change in temperature observed.

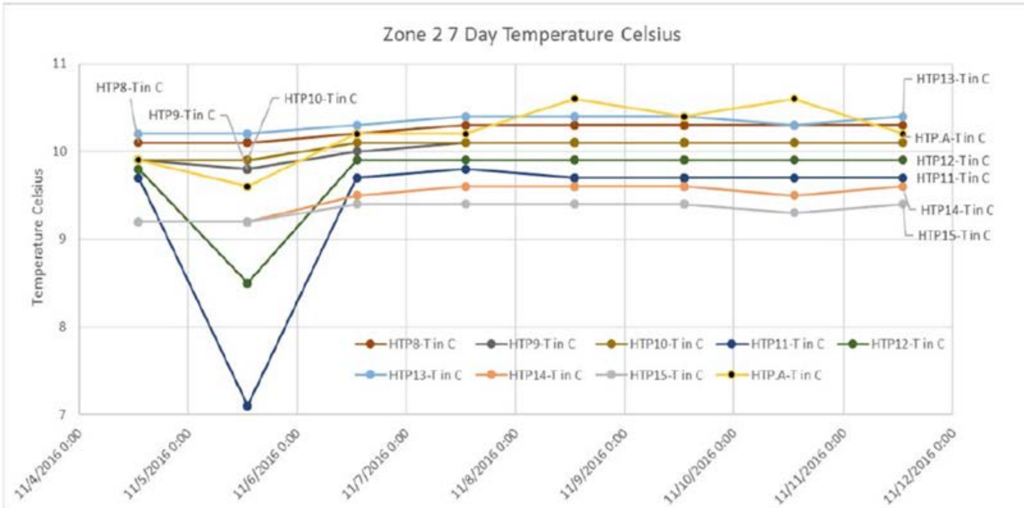

Figure 43. Graph of the first 7 days of temperature data collected after energizing the EOP system for Zone 2. There was no real change in temperature observed.

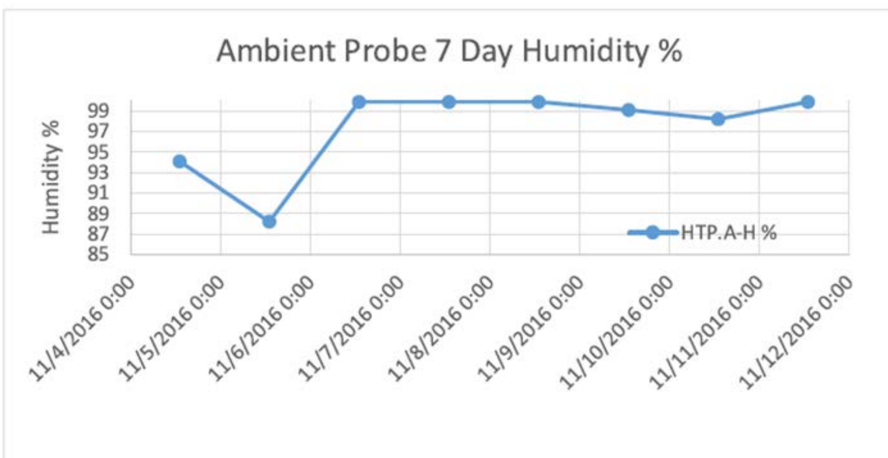

Figure 44. Graph of the first 7 days of ambient humidity data collected after energizing the EOP system.

Table 8 shows data from the first 30 days of operation. The system was still performing as designed. The resistance values continued to rise, indicating the system was drying the concrete. This is shown graphically in Figure 45. The temperature measured in zone 1, zone 2, and the ambient humidity indicated no change during this period of time.

Table 8. Initial 30 days of data collected after energizing the EOP system.

Area	Zone 1- East Side			Zone 2 West Side		
Date & Time	Voltage (V)	Current (A)	Resistance (Ω)	Voltage (V)	Current (A)	Resistance (Ω)
11/4/2016 13:03	39.9	3.5	11.40	40	3.8	10.53
11/5/2016 13:03	39.9	3.3	12.09	39.8	3.5	11.37
11/6/2016 13:03	40	3.4	11.76	40.1	3.6	11.14
11/7/2016 13:03	40	3.3	12.12	40	3.5	11.43
11/8/2016 13:03	40	3.3	12.12	40	3.5	11.43
11/9/2016 13:03	40	3.2	12.50	40	3.5	11.43
11/10/2016 13:03	40	3.3	12.12	40	3.6	11.11
11/11/2016 13:03	39.9	3	13.30	40	3.5	11.43
11/12/2016 13:03	40	3.2	12.50	40	3.6	11.11
11/13/2016 13:03	40	3.2	12.50	40	3.6	11.11
11/14/2016 13:03	40	3.2	12.50	40	3.6	11.11
11/15/2016 13:03	40	15.2	2.63	40	15.3	2.61
11/16/2016 13:03	40	18.5	2.16	40	19.7	2.03
11/17/2016 13:03	40	19.5	2.05	39.9	21	1.90
11/18/2016 13:03	39.9	19.2	2.08	40	20.9	1.91
11/19/2016 13:03	40	20	2.00	40	20.5	1.95
11/20/2016 13:03	40	19.9	2.01	40	20.9	1.91
11/21/2016 14:28	20	9.9	2.02	20	11.1	1.80
11/22/2016 13:15	40	19.1	2.09	40	21	1.90
11/23/2016 13:15	40	19.2	2.08	39.8	20.5	1.94
11/24/2016 13:15	40	18.8	2.13	40	20.5	1.95
11/25/2016 13:15	39.9	18.7	2.13	39.9	20.6	1.94
11/26/2016 13:15	40	19	2.11	39.9	20.5	1.95
11/27/2016 13:15	40	18.9	2.12	39.9	20.4	1.96
11/28/2016 13:15	40	18.8	2.13	40	20.5	1.95
11/29/2016 13:02	19.9	9.1	2.19	19.9	10.2	1.95
11/30/2016 13:02	40	18.4	2.17	40	20.4	1.96
12/1/2016 13:02	39.9	18	2.22	40	20.3	1.97
12/2/2016 13:02	39.8	18	2.21	39.8	20.1	1.98
12/3/2016 13:02	39.8	17.9	2.22	39.9	20.1	1.99

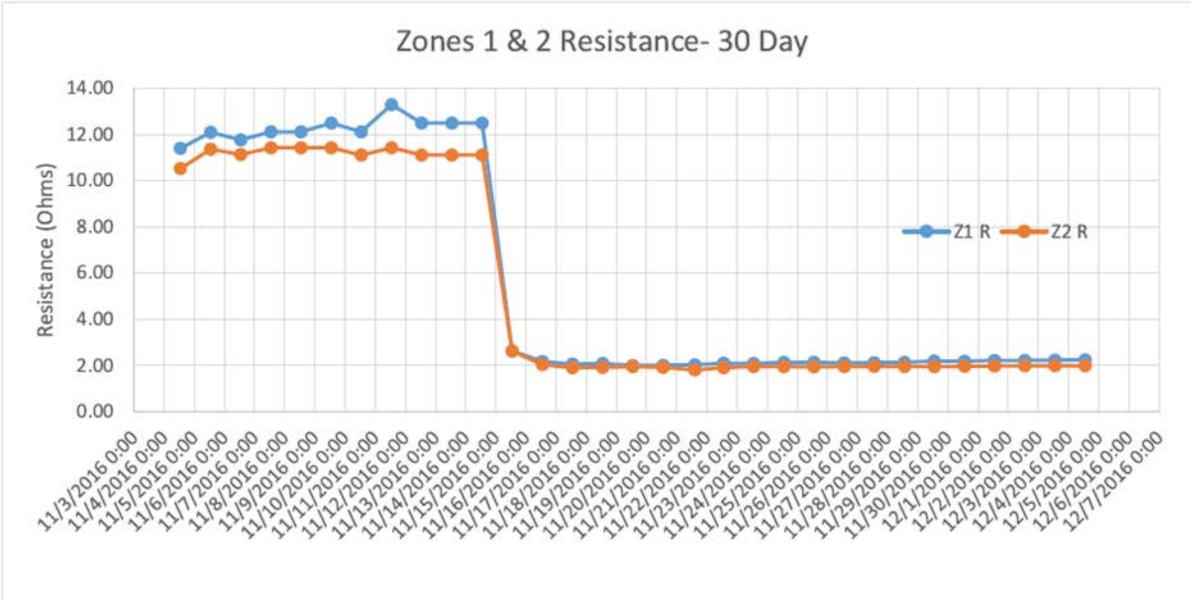

Figure 45. Graph of the first 30 days of data collected after energizing the EOP system. The resistance for each zone is increasing over time indicating that the water is moving away from the surface. A dramatic decrease in the measured resistance was observed on November 15, 2016 due to to an apperant short or other undetermined failure in the system.

Increased current drops and resistance values are the desired effect of the EOP system. As shown in the data, the resistance values are increasing over the first 30 days. This is further indicated by the graph in Figure 46 which shows the data gathered for the first 12 months. This indicates the effect of moisture leaving the structure. As the electrolyte (water) leaves the concrete, this makes it more difficult for electrical current to flow, which results in higher resistance. The collected data was analyzed using Ohm's law.

$$E = I * R$$

Where: E= Potential in Volts (V), I= Current in Amps (A), and R= Resistance in Ohms (Ω)

At a constant applied potential over time the current decreases and the resistance increases as the moisture level in the concrete decreases in the zones. The data trend shown indicates that the system is operating as designed.

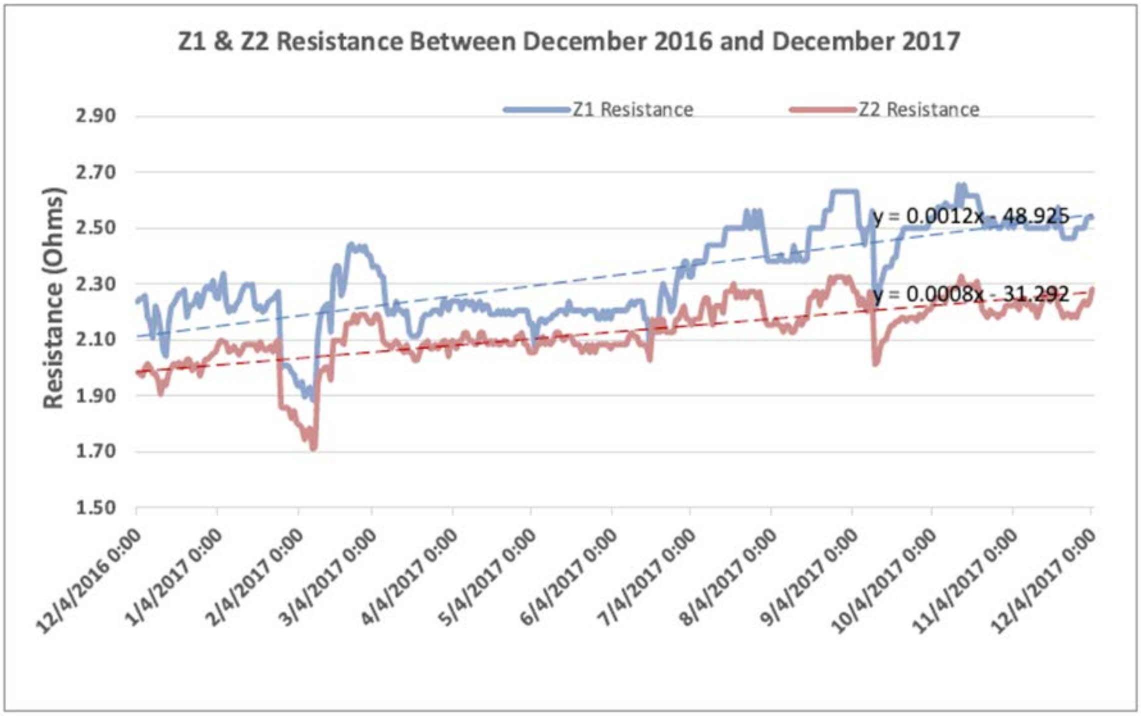

Figure 46. Graph of the first 12 months of data collected after energizing the EOP system. The resistance for each zone is increasing over time indicating that the water is moving away from the surface and the system is still operating as designed.

The temperature for both zones indicated that there was no change and no change in the ambient humidity. This indicates that the ambient humidity and temperature inside the concrete are effected by the environment present in the shaft which has a steady flow of air through the shaft.

The initial potential was set to 40 Volts after repairs on 11/3/16. This produced a resistance increase of approximately 2 ohms over the first 24 hour period. As shown in Table 9, the applied voltage was adjusted over the course of the first 12 months of operation and reflected in the graphs indicating the change in resistance. Three adjustments were made during this time period. These adjustments were performed because the applied voltage was needed to establish an electric field gradient between the anode and cathode to maintain a force against the flow of water. This system will eventually reach an equilibrium point due to the electrochemical reactions from the system. Therefore a steady state will be achieved and the system will stop pushing the desired water and the resistance will stop changing. Adjusting the voltage essentially “jump starts” the effect of the system and the resistance increases again as desired.

Table 9. EOP system applied potential adjustments.

#	Adjustment Date	Voltage (V)	Remark
1	11/3/2016	40	Initial Potential Set
2	2/17/2017	15	First Adjustment
3	6/19/2017	10	Second Adjustment
4	9/12/2017	17	Third Adjustment

The schematic shown in Figure 47 indicates what the ideal system should look like. Information provided by the installation company stated that during installation foreign metal and additional reinforcement was encountered, as shown in the schematics in Figure 48 and Figure 49. The close proximity or direct contact creates an alternative path for the current, altering the electric field gradient, causing the system to operate less effectively. A schematic of what happens when there is an alternative path for the current to take is shown in Figure 50. These shorts will diminish the effectiveness of the EOP system.

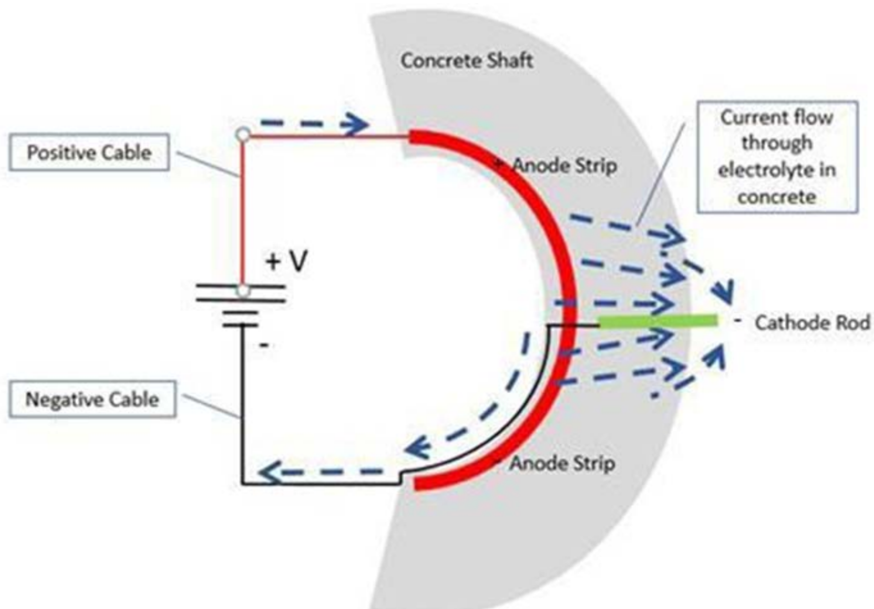

Figure 47. Schematic of a properly installed system without any shorts.

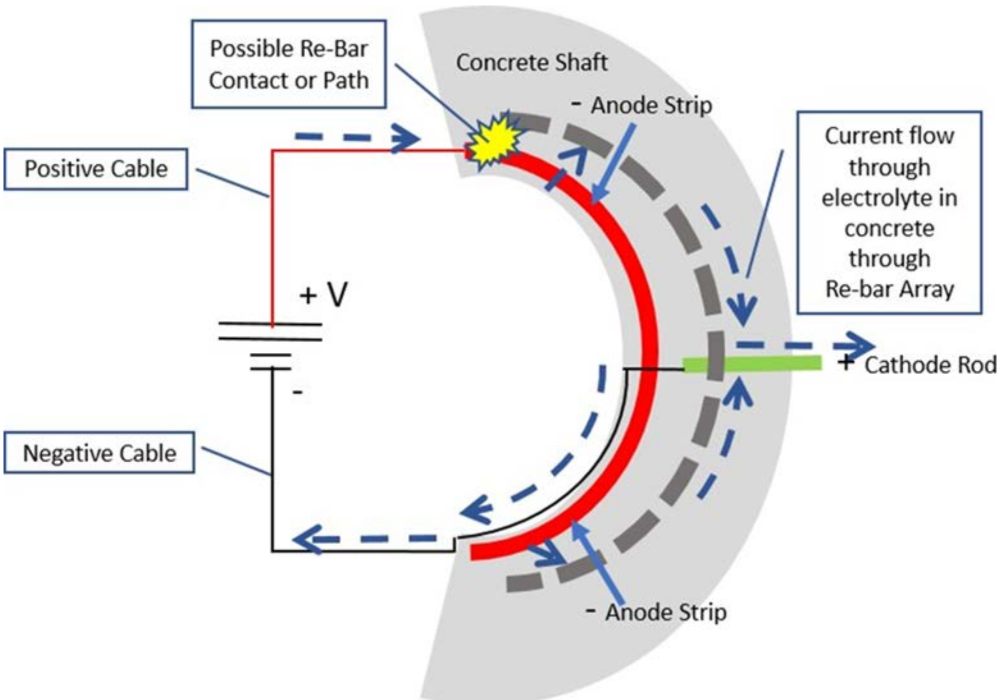

Figure 48. Schematic of a system where contact or close vicinity of the rebar to the anode would cause a short and alternative path for the current.

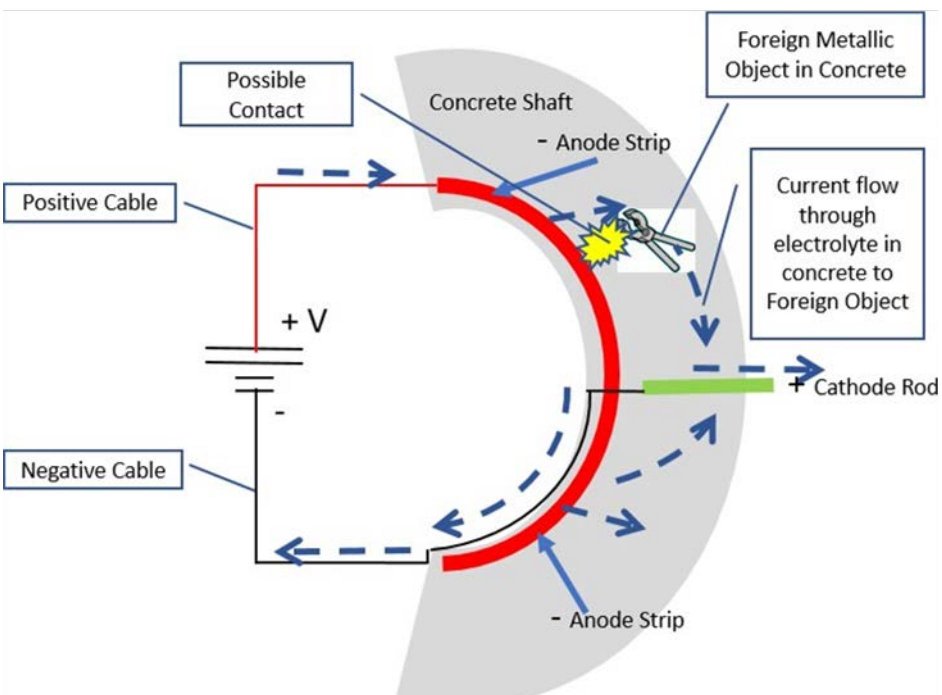

Figure 49. Schematic of a system where contact or close vicinity of the foreign metal to the anode would cause a short and alternative path for the current.

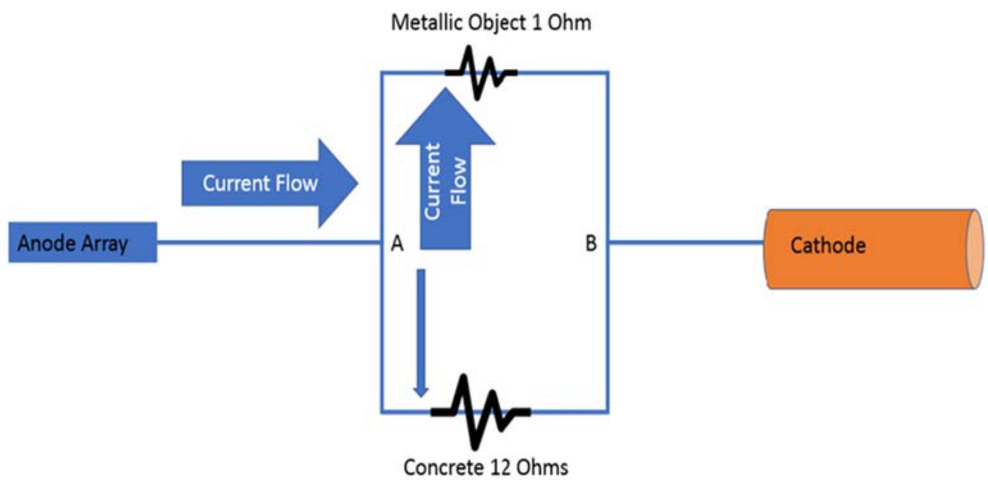

Figure 50. Schematic showing how current can flow through an alternative path through rebar and foreign metal.

Visual Inspection

A visual inspection was performed on September 13, 2017 by the Reclamation climb team. The photos shown in Figure 51 indicate the continued presence of cracks with water seepage outside of the EOP installation. These photos show locations where leaks were grouted and are still leaking, along with areas of cracks that were not grouted. It is highly likely some of the cracks which were small and not initially observed.

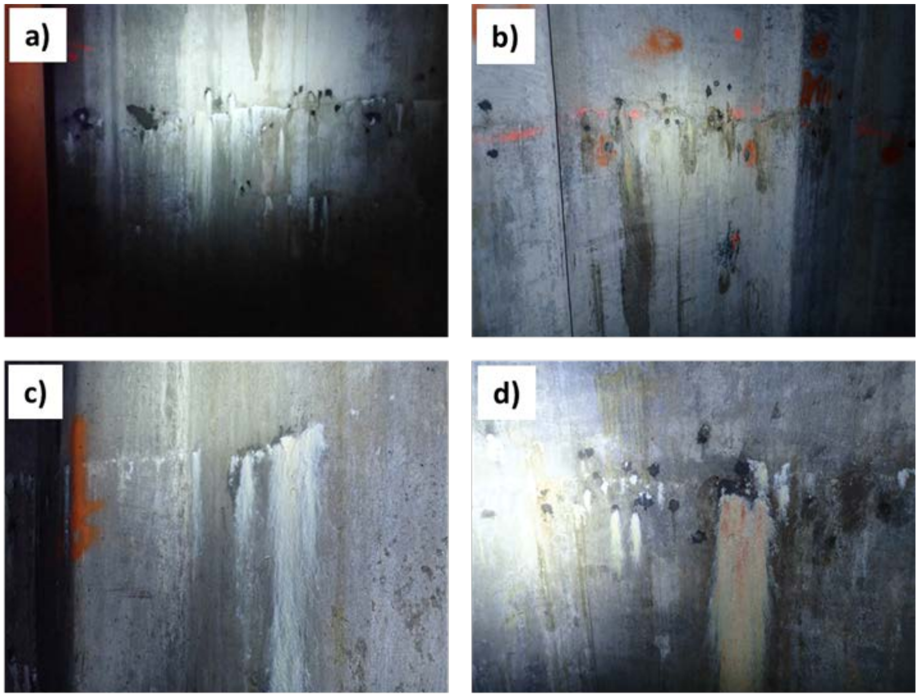

Figure 51. Photos of areas above the EOP installation zones. Photos show locations where grouting was performed which are still leaking and areas of cracks which were not grouted.

Photos from the EOP zone indicated that water is still coming from above the EOP installation zone causing calcite to build up on the drip tray which was installed (Figure 52a). Cracks which were not successfully grouted in the EOP zone are shown in Figure 52b, c, and d.

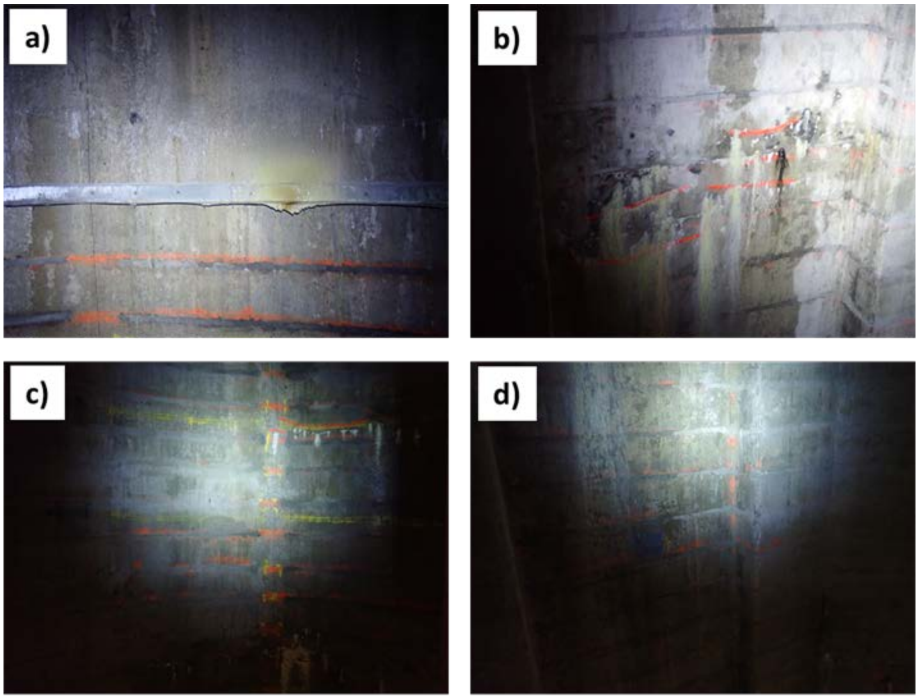

Figure 52. Photos from the EOP zone indicating water coming from above and from cracks in the EOP zone. The photo in a) shows the calcite building up on the drip tray which was installed. The photos in b), c), and d) shows calcite build up due to seepage from cracks which were not successfully grouted.

Photos of the EOP zone, shown in Figure 53, Figure 54, and Figure 55 clearly show moisture on the surface of the walls and new calcite formed over the last 12 months. Photos were taken of the shaft in various areas in the EOP installation zone. The calcite shown in the figures is clearly coming from cracks, grout ports, and anode and cathode locations. The would imply that in addition to cracks that were not grouted, the installation of some of the anodes and cathodes possibly intersected existing cracks, creating a new path for the water to reach the surface.

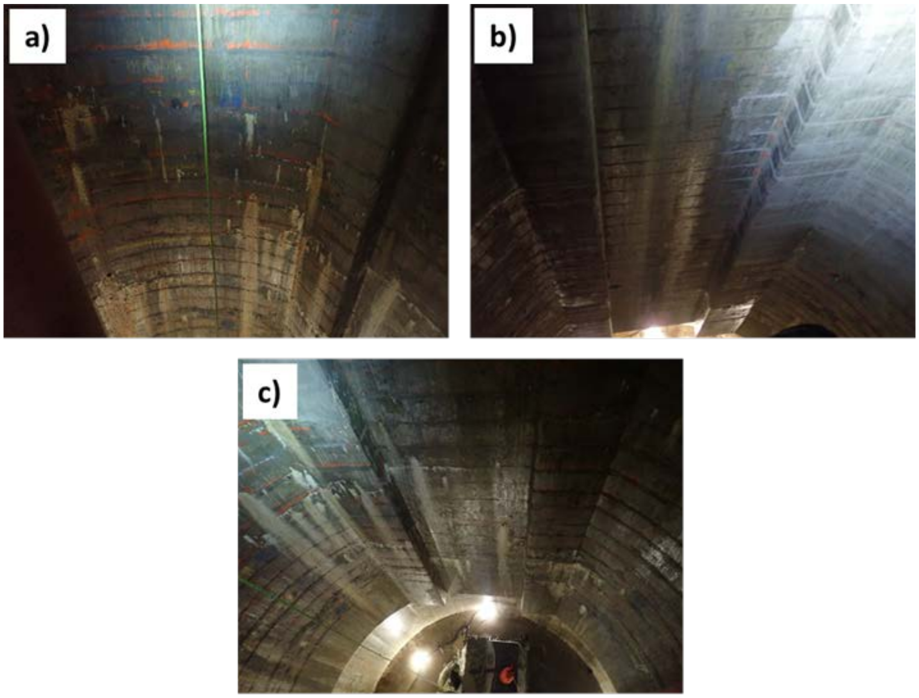

Figure 53. Photos were taken looking down the shaft from above. The photos in a), b), and c) all show new calcite formation over the first 12 months.

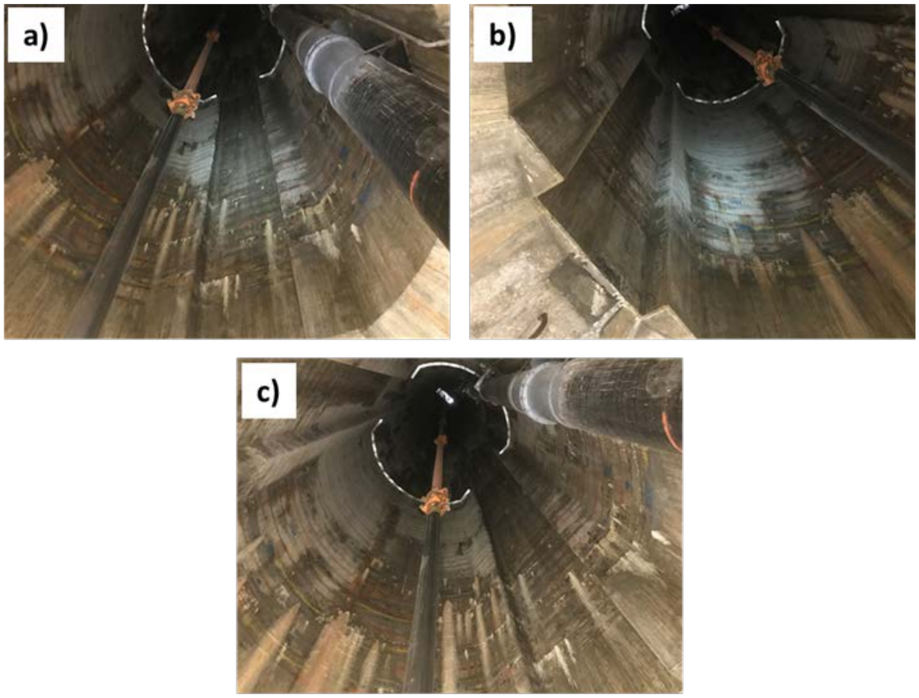

Figure 54. Photos were taken looking up from the bottom of the shaft. The photos in a), b), and c) all show new calcite formation over the first 12 months.

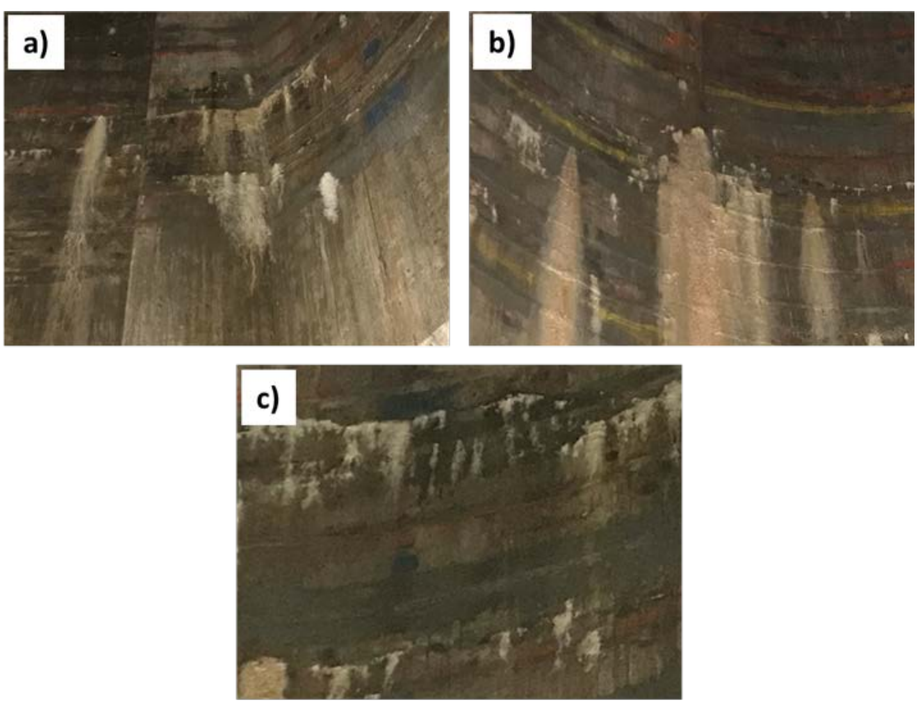

Figure 55. Photos were taken of the shaft in various areas in the EOP installation zone. The photos in a), b), and c) all show new calcite formation over the first 12 months.

Problems and Solutions

Common Concrete Issues

Typical issues found in concrete structures include variations in rebar spacing, tie wires protruding from connection, shifted rebar mats, and variation of concrete wall thickness. Issues and explanations can include the following:

1. Drawings, including as-built drawings, may not be completely accurate.
2. Varying thickness of the concrete is common for certain structures. For a concrete wall, a jagged (not straight) line on a drawing indicates varying thickness.
3. Rebar spacing design not guaranteed. Some variation may occur.
4. Tie wires are almost always encountered when a structure is reinforced and should be anticipated.
5. Grouting all cracks present in a concrete wall is an issue since as easier water paths are plugged with the grout, the water may begin leaking out the next easiest path, commonly referred to as "chasing cracks". Sometimes this may take several days to occur. There are also cracks that are a combination of small enough with sufficient water leakage that is nearly impossible with current technology to effectively seal the leaks with grout. Using excessively high grout pressures to inject grout can also damage the concrete.

Installation Personnel Issues

The following problems with construction and installation were encountered:

1. Experience: EOP installation is highly specialized. It is important that the company performing the installation has experience performing all aspects of the work.
2. Drawings: All drawings should be provided and requested when working on an existing structure. Drawing will help during the design and implementation of the EOP system.
3. Specifications should be well written and enforced during the installation including the following provisions:
    a. Personnel performing the work should be experienced in the installation process.
    b. The supervisor should have adequate experience and be on-site at all times during the job.
        i. A request for change should be submitted if the supervisor is required to be changed out and the credentials of the new supervisor provided.

System Installation Issues

It was reported that there were issues encountered during construction. Some of these issues are reported below:

1. Foreign metal was encountered during installation. While this is possible, measures were proposed by the submittals which would prevent any shorts. One such method was shown earlier in Figure 24.
2. Pre-design and installation investigations should always be performed in order to adequately design the EOP system and anticipate any possible issues or concerns.
3. Figure 26 showed that the cathode and sensor cables were in the same channel as the anode ribbons. This should never be done since the insulation on the cables will shield some of the current making the anodes less efficient. Also, due to the possibility of high

operating voltages and resulting electrochemical reactions, the anode can generate acid and lower the pH in the surrounding mortar. This may damage the other cables and any damage to the insulation on the cables will cause failure of the system.

Conclusions

1. Overall, the EOP system seems to be working as intended as observed by the data showing an increase in the resistance in the concrete.
2. Continued leaks and calcite buildup in areas with EOP are likely the result of:
    a. Anode trenches and drill holes intersecting existing cracks which were not chemically grouted
    b. Small cracks which were not observed previously
    c. Poor repair of drill holes and anode trenches
3. EOP appears to have stopped leaks in some small cracks that were not grouted.
4. The relationship between crack size, water flow, pressure head, and EOP effectiveness has not been determined. Further work will be needed to quantify this relationship.
5. Several shorts were encountered during installation which impaired system performance. These were repaired and system performance was restored.

While the system may have deficiencies and it is unclear how long the system will last due to the potential for damage to the cathode cable insulation from acidification of the mortar. Shielding of the anodes due to the cathode and sensor cables in the anode trenches may also limit the effectiveness of the system.

Future Work

Further work has been proposed and is underway to determine the effectiveness of EOP at higher water pressures and to determine what the critical crack size is which requires grouting. EOP is also be considered as a solution to another common problem observed at numerous dams. Water is collecting lift lines and exiting the dam downstream face rather than the drains as intended. It has been proposed to utilize EOP to direct water to these drains as was originally designed to do.

References

[1] MERL-2012-10, Electro-Osmotic Pulse Leak Repair Method: Evaluation in Trinity Dam Bonnet Chamber, 2012.

[2] BOR Travel Report dated Nov 21, 2005 – Rope inspection.

[3] Hock, V.F., M.K. McInerney, and E. Kirstein, "Demonstration of Electro-Osmotic Pulse Technology for Groundwater Intrusion Control in Concrete Structures," FEAP Technical Report 98/68, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, 1998.

[4] Marshall, O.S., S. Morefield, M. McInerney, and V.F. Hock, "Electro-Osmotic Pulse Technology for Corrosion Prevention and Control of Water Intrusion in Below Grade Concrete Structures," Tri-Service Corrosion Conference, Denver, Colorado, 2007.

[5] Nemec, T.H., "Environmental pH Changes in Electrochemical Cell During Electro-Osmotic Stabilization of Soils," *Studia Geotechnica et Mechanica*, Vol. V, No. 1 (1983), 1988, pp. 13-38.

[6] Morefield, S.W., M.K. McInerney, V.F. Hock, O.S. Marshall, P.G. Malone, and C.A. Weiss, "Interface Modeling for Electro-Osmosis in Subgrade Structures," 24th Army Science Conference, Orlando, Florida, U.S. Army Corps of Engineers, Engineer Research and Development Center, 2005.

[7] Marshall, O.S., S. Morefield, M. McInerney, and V.F. Hock, "Electro-Osmotic Pulse Technology for Corrosion Prevention and Control of Water Intrusion in Below Grade Concrete Structures," Tri-Service Corrosion Conference, Denver, Colorado, 2007.

Appendix A – Controller Operation Procedures

When power is applied to the system, the EOP controller will perform power-on initialization and begin normal operation. The front panel display, shown in Figure A-1, provides the current EOP system status. The display shows the status, voltage, and current of each of the zones, as well as the most recent relative humidity and temperature reading.

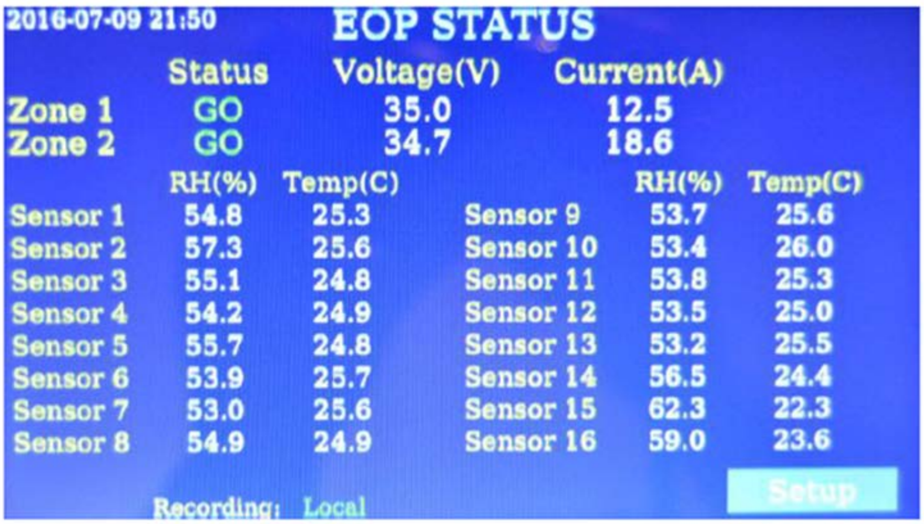

Figure A-1. EOP controller status display.

Data Recording

During operation, data is periodically recorded either to the controller's internal file system or to a removable SD card inserted into the front panel receptacle. When no SD card is present or the SD card recording has not been enabled, data is automatically recorded internally. When SD card recording is initially enabled, this internally recorded data is automatically transferred to the SD card, provided the SD card does not already have previously recorded data.

To log the EOP data to an inserted SD card, perform the following steps:

1. Insert the SD card into the front panel card slot with the label side up. An audible click will indicate when the card is properly engaged
2. Shortly after the card is inserted, the "Log" tough button will appear in the lower left corner of the EOP STATUS display as shown for Condition 2 in Table A-1
3. Press the "Log" button. The following dialog box will appear (Figure A-2):

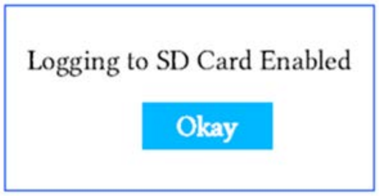

Figure A-2. Logging dialog box for SD card enable.

4. Press “Okay”. The log status will indicate logging to the SD card as indicated for condition 3 in Table A-1.

To prevent data loss, the EOP controller must be notified that the SD card is to be removed before it is removed from the receptacle. The removal procedure is as follows:

1. Press the “Eject” button on the lower left corner of the EOP STATUS display. The following dialog box will appear (Figure A-3):

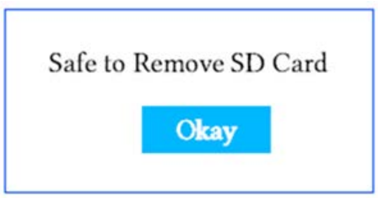

Figure A-3. Safe to remove SD card dialog box.

2. Verify the recording status indicator indicates “Recording: Local” as shown for condition 1 in Table A-1. If not, wait for this condition before removing the SD card
3. Remove the SD card by pressing and then releasing the card. An audible click will be heard and the SD card will protrude slightly from the slot, allowing it to be removed

The removal procedure provided should always be followed to prevent loss of internally buffered data when the SD card is removed unexpectedly. The data recording status is provided on the lower left of the EOP STATUS display. This status field will vary depending on the recording status as shown in Table A-1.

Table A-1. Data recording status display on controller.

Condition		Recording Status
1	SD card not installed	Recording: Local
2	SD card installed, recording locally	Log Recording: Local
3	SD card installed, recording to SD card	Eject Recording: SD Card

Data Recording Format

The EOP controller records the data shown in Table A-2 to the file “eop_data.csv” in a Comma Separated Values (CSV) format that can be read natively by common spreadsheet programs (e.g. Excel). Whenever a new file is created, a header is written as the first line to help identify each column when viewing as a spreadsheet. Subsequent data is then appended to the file as it is recorded. In addition to the EOP data, SD card insertion and removal events are also recorded. An example data file as viewed with a spreadsheet program is shown in Figure A-4.

Table A-2. EOP data format for csv file.

Column	Column Heading	Description
A	Time	The date and time the log entry was recorded
B	Type	The type of log entry. The remaining items of this table are only recorded for log type EOP_log.SD_Card_Removed and SD_Card_Inserted are used to record the time of SD card events.
C	V(Z1)	Zone 1 EOP output voltage, volts direct current (VDC)
D	I(Z1)	Zone 1 EOP output current, amperes
E	S(Z1)	Zone 1 EOP pulse controller status. A value other than ‘0’ indicates a problem with the pulse controller module or power supply hardware.
F	V(Z2)	Zone 2 EOP output voltage, volts direct current (VDC)
G	I(Z2)	Zone 2 EOP output current, amperes
H	S(Z2)	Zone 2 EOP pulse controller status. A value other than ‘0’ indicates a problem with the pulse controller module or power supply hardware.
I	RH1	Relative humidity reading from sensor #1, %
J	T1	Temperature reading from sensor #1, °C
K	RH2	Relative humidity reading from sensor #2, %

L	T2	Temperature reading from sensor #2, °C
M	RH3	Relative humidity reading from sensor #3, %
N	T3	Temperature reading from sensor #3, °C
O	RH4	Relative humidity reading from sensor #4, %
P	T4	Temperature reading from sensor #4, °C
Q	RH5	Relative humidity reading from sensor #5, %
R	T5	Temperature reading from sensor #5, °C
S	RH6	Relative humidity reading from sensor #6, %
T	T6	Temperature reading from sensor #6, °C
U	RH7	Relative humidity reading from sensor #7, %
V	T7	Temperature reading from sensor #7, °C
W	RH8	Relative humidity reading from sensor #8, %
X	T8	Temperature reading from sensor #8, °C
Y	RH9	Relative humidity reading from sensor #9, %
Z	T9	Temperature reading from sensor #9, °C
AA	RH10	Relative humidity reading from sensor #10, %
AB	T10	Temperature reading from sensor #10, °C
AC	RH11	Relative humidity reading from sensor #11, %
AD	T11	Temperature reading from sensor #11, °C
AE	RH12	Relative humidity reading from sensor #12, %
AF	T12	Temperature reading from sensor #12, °C
AG	RH13	Relative humidity reading from sensor #13, %
AH	T13	Temperature reading from sensor #13, °C
AI	RH14	Relative humidity reading from sensor #14, %
AJ	T14	Temperature reading from sensor #14, °C
AK	RH15	Relative humidity reading from sensor #15, %
AL	T15	Temperature reading from sensor #15, °C
AM	RH16	Relative humidity reading from sensor #16, %
AN	T16	Temperature reading from sensor #16, °C

	A	B	C	D	E	F	G	H	I	J
1	Time	Type	V(Z1)	I(Z1)	S(Z1)	V(Z2)	I(Z2)	S(Z2)	RH1	T1
2	7/10/2016 12:49	SD_Card_Removed								
3	7/10/2016 12:49	EOP_log	35	12.4	0	35	18.9	0	46	27.
4	7/10/2016 12:50	EOP_log	35	12.4	0	35	18.9	0	45.5	27.
5	7/10/2016 12:51	EOP_log	35	12.4	0	34.9	18.9	0	45.7	27.
6	7/10/2016 12:52	EOP_log	35	12.4	0	35	18.9	0	46.1	27.
7	7/10/2016 12:52	SD_Card_Inserted								
8	7/10/2016 12:52	EOP_log	35	12.4	0	35	18.9	0	46.5	27.
9	7/10/2016 12:53	EOP_log	35	12.4	0	34.9	18.8	0	46.5	27.
10	7/10/2016 12:54	EOP_log	35	12.4	0	35	18.8	0	46.7	27.
11	7/10/2016 12:55	EOP_log	35	12.4	0	34.9	18.9	0	46.6	27.
12	7/10/2016 12:56	EOP_log	35	12.4	0	35	18.9	0	46.8	27.
13	7/10/2016 12:57	EOP_log	35	12.4	0	34.9	18.9	0	46.2	27.
14	7/10/2016 12:58	EOP_log	35	12.4	0	34.9	18.8	0	45.8	27.
15	7/10/2016 12:59	EOP_log	35	12.4	0	34.9	18.8	0	45.5	27.
16	7/10/2016 13:00	EOP_log	35	12.4	0	35	18.9	0	45.8	27.

Figure A-4. EOP data file example as shown in a spreadsheet.

Controller Configuration

Configuration menus are accessed by touching the Setup button on the lower right of the EOP STATUS display, which will bring up the EOP SETUP display shown in Figure A-5.

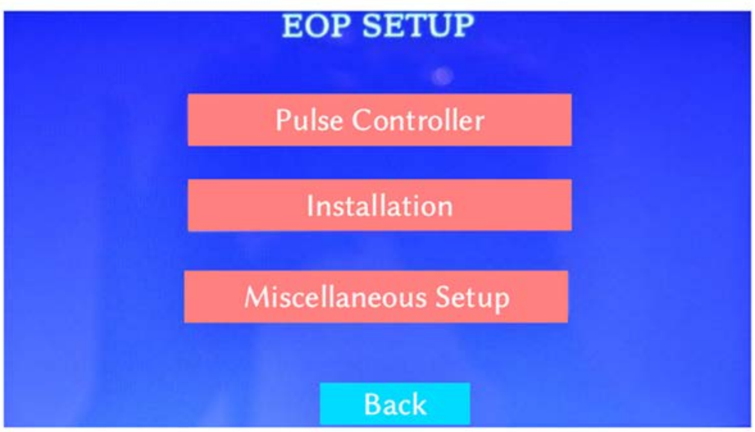

Figure A-5. EOP SETUP display on controller.

The EOP SETUP display provides access to the following configuration menus:

> **Pulse Controller –** Used to configure the EOP sequence that is applied to the zone 1 and zone 2 anodes with respect to the cathodes.

Installation - Used to set the EOP output voltage and current, the time interval between successive reads of the remote humidity sensors, and to selectively enable or disable each of the external remote humidity sensors.

Miscellaneous Setup – Used to set the system date and time and to set the data recording interval value.

The PULSE CONTROLLER SETUP menu is shown in Figure A-6. White data fields can be edited by touching the field, then entering the desired value via the numeric or list selection popup. The menu allows definition of the EOP sequence using up to 20 sequentially executed intervals. Each interval can be programmed with respect to duration in seconds and pulse type.

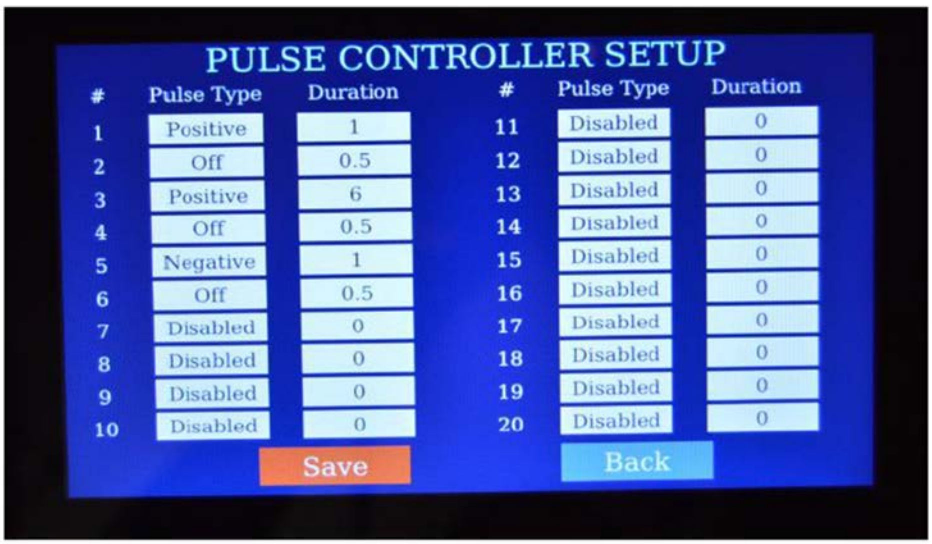

Figure A-6. PULSE CONTROLLER SETUP menu for changing controller configuration.

The EOP sequence is generated by executing the intervals in sequence starting with interval #1 and ending with the first disabled interval. The time value is entered as a decimal number of seconds, and has an allowable range of 0.0 to 60.0. The minimum resolution is 10 milliseconds (0.01 seconds).

The pulse type options are:

Off – No voltage is applied to the anodes with respect to the cathodes during the interval.

Positive – A positive voltage is applied to the anodes with respect to the cathodes during the interval.

Negative - A negative voltage is applied to the anodes with respect to the cathodes during the interval.

Disabled – Denotes the end of the sequence. When the EOP controller encounters an interval with this pulse type, the sequence restarts at interval #1. The interval time value is ignored.

Configure the applicable intervals for the desired sequence, then touch the "Save" button on the bottom of the screen. The EOP sequence information will be written to the Pulse Controller module. This process will take several seconds. A dialog box will appear indicating the results of the save operation. Touch "Okay" to remove the dialog box.

Press "Back" to return to the previous menu.

The INSTALLATION SETUP menu, shown in Figure A-7, is used to set EOP system voltage and current, as well as to selectively enable or disable the humidity sensors and to select the interval of time between humidity sensor read operations.

Figure A-7. INSTALLATION SETUP menu for changing controller configuration.

White data fields can be edited by touching the field, then entering the desired value via the numeric or list selection popup. The installation menu includes the following settings:

Max Voltage – Sets the power supply voltage applied to the EOP sequence in volts. The EOP controller will output this voltage unless the Max Current value is exceeded. If the Max Current value is exceeded, the EOP controller reduces the voltage to the value necessary to maintain the Max Current setting.

Max Current – Sets the maximum power supply output current in amperes that will be applied to the EOP anodes/cathodes. Typically this value is greater than the expected operating current, resulting in the Max Voltage value being continuously applied.

Baud Rate – Sets the data rate of the RS-455 communication interface between the EOP controller and its internal pulse controller module and the external humidity sensor interface modules. This value must be set to 115200 as shown in Figure 62.

CAUTION – changing the baud rate to a value other than 115200 will cause the EOP controller to lose communication with the Pulse Controller module and the external humidity sensor module. This will render the EOP Controller unable to read the EOP system status.

Parity – Sets the parity used for the RS-422 communication interface. This value must be set to "None" as shown in Figure 62.

CAUTION – changing the parity to a value other than "None" will cause the EOP controller to lose communication with the Pulse Controller module and the external humidity sensor module. This will render the EOP Controller unable to read the EOP system status.

RH Read Interval – Sets the interval of time in minutes between each read of the remote humidity sensors.

Snsr 1…Snsr 16 – Enables or disables the remote humidity sensors. When set to "Off", the corresponding humidity sensor is not powered or read by the system. When set to "On", the corresponding humidity sensor is powered and read at the interval specified by "RH Read Interval".

Touch the "Save" button on the bottom of the screen to write the displayed information to the pulse controller and humidity sensor modules. This process will take several seconds. A dialog box will appear indicating the results of the save operation. Touch "Okay" to remove the dialog box.

Press "Back" to return to the previous menu.

The MISC SETUP (miscellaneous) menu, shown in Figure A-8, is used to set the system time and to set the interval of time between successive writes of EOP data to the log file.

Figure A-8. MISC SETUP menu for changing controller configuration.

White data fields can be edited by touching the field, then entering the desired value via the numeric or list selection popup. The installation menu includes the following settings:

Time – Sets the time of day in hours : minutes. Hour values range from 0 to 23, minutes from 0 to 59.

Date – Sets the month, day, and year.

Log File – This field is reserved for future growth to allow operator entry of the log file name. The default log file name "eop_data.csv" is always displayed.

Log Device – This field can be used to select from the available logging devices (currently the local file system and the SD card), however it is recommended to control logging as described previously.

Log Interval – The time interval in minutes between successive writes to the log file. The controller can be set up to record data at intervals ranging from 1 minute to 1440 minutes (24 hours).

Touch the "Save" button on the bottom of the screen to save the displayed information. This process will take several seconds. A dialog box will appear indicating the results of the save operation. Touch "Okay" to remove the dialog box.

Press "Back" to return to the previous menu.