

Electro-Osmotic Pulse Leak Repair Method: Evaluation in Trinity Dam Bonnet Chamber - Central Valley Project, Trinity River Division – California

Daryl A. Little

Materials Engineer, Bureau of Reclamation, Technical Services Center, Materials Engineering and Research Lab, Denver, CO, United States.

Kurt F. von Fay

Civil Engineer, Bureau of Reclamation, Technical Services Center, Materials Engineering and Research Lab, Denver, CO, United States.

Abstract

Electro-Osmotic Pulse (EOP) is a technology that uses current and electric fields to prevent water from leaking through concrete. It is potentially a long lasting solution to water intrusion through concrete. Results from previous installations performed by the U.S. Army Corps of Engineers show it can have a lower life-cycle cost when compared to grouting or concrete repair alone.

Potential benefits of installing an EOP system to dry out a concrete structure include; lower costs due to negative side installation, minimal maintenance costs, and avoids future costs such as disruption and lost productivity associated with continued repairs. In addition, it helps prevent structural degradation of rebar from water penetration.

Because of EOP's potential to stop water leaks through concrete, a research program was initiated to test the technology at a Bureau of Reclamation (Reclamation) facility. EOP was installed in a small area of the gate chamber at Trinity Dam that was leaking water which was damaging equipment.

The EOP system is operating as designed and has significantly reduced the moisture content of the concrete in the test area. The collected data shows the resistance has increased over time at a constant voltage and the total current has decreased. Resistance of the concrete is directly related to the moisture content. More moisture in the concrete lowers its resistance and more current passes between the electrodes.

The success of the test indicates that this technology does work in this type of application and may have application at a number of other Reclamation structures as well.

Introduction

Electro-Osmotic Pulse (EOP) is a technology that uses current and electric fields to prevent water from leaking through concrete. It is potentially a long lasting solution to water intrusion through concrete. Results from previous installations performed by the U.S. Army Corps of Engineers shows that it can have a lower life-cycle cost when compared to grouting or concrete repair alone.

The following are potential benefits of installing an EOP system to dry out a concrete structure:

1. New cracks within the EOP zone of influence do not compromise the system
2. Performance monitored “24-7”
3. Lower cost
 - a. Negative side installation (buried or submerged side)
 - b. Nondegradable, extremely durable
 - c. Minimal maintenance
 - d. Avoids costs of disruption and lost productivity
4. Highest return
 - a. Prevents structural degradation of rebar from water penetrations

Because of EOP’s potential to stop water leaks through concrete, a research program was initiated to test the technology at a Bureau of Reclamation (Reclamation) facility.

This report describes Phase 2 of a research effort to determine the applicability to Reclamation facilities. It also proposes a Phase 3 effort if results from Phase 2 are promising. Phase 1 consisted of a feasibility study involving site inspections, initial calculations, and project execution planning.

For Phase 2, EOP was installed in a small area of the gate chamber at Trinity Dam that was leaking water which was damaging equipment. This test area was selected to evaluate EOP on a small scale to determine if a larger scale test would be appropriate.

Conclusion

The EOP pilot test is operating as designed and has significantly reduced the moisture content of the concrete in the test area. This is based on the trend in the collected data that shows the resistance has increased over time at a constant voltage and the total current has decreased. Resistance of the concrete is directly related to the moisture content where the more moisture in the concrete the less resistance there is to current passed between the anode and cathode.

The success of the pilot test indicates that this technology does work in this type of application. However, the test section was small. A larger installation should be tested to more fully evaluate

the technology. For the larger test section, EOP should be installed in the bottom 10 feet of the shaft, around its entire circumference. For this test, leaking cracks would be included in the test section. If the technology works for this larger test, it would likely work for the entire area of the gate shaft.

The technology may have application at a number of other Reclamation structures as well.

Test Location

Trinity Dam is near Redding, California, and was chosen as the site for the pilot test. The facility is experiencing water leaks through the bonnet chamber shaft, which leads to several maintenance problems in the shaft and bonnet chamber.

The walls of the shaft and bonnet chamber are covered with calcite as shown in figures 1a-1h. Calcite forms when water containing calcium ions reacts with carbon dioxide to form calcium carbonate. In some areas, the seepage over time has resulted in stalactite formation. The calcite has an average deposit thickness of 0.5 to 1 inch as shown in figures 2a-2d. Calcite has been measured as thick as 6 inches in the location shown in figures 1b and 1c. Due to the seepage, there is approximately 1 to 2 inches of standing water in some locations on the bonnet chamber floor, and corrosion of the air inlet pipe and bonnet cover has occurred, as shown in figures 3a-3d.

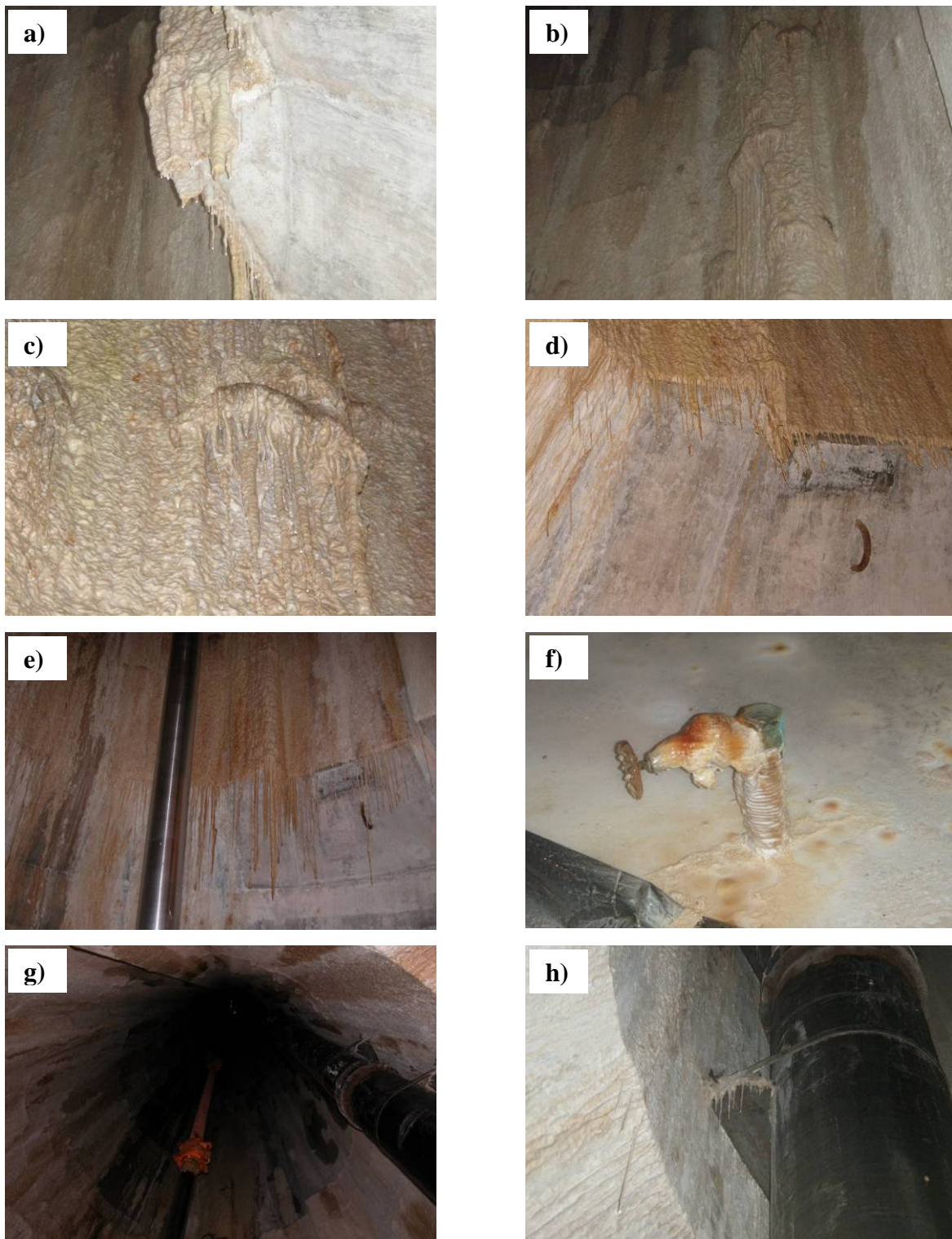


Figure 1. Calcite deposits observed on the walls of the bonnet chamber. Excessive seepage over time has resulted in stalactites and encasement of valves.

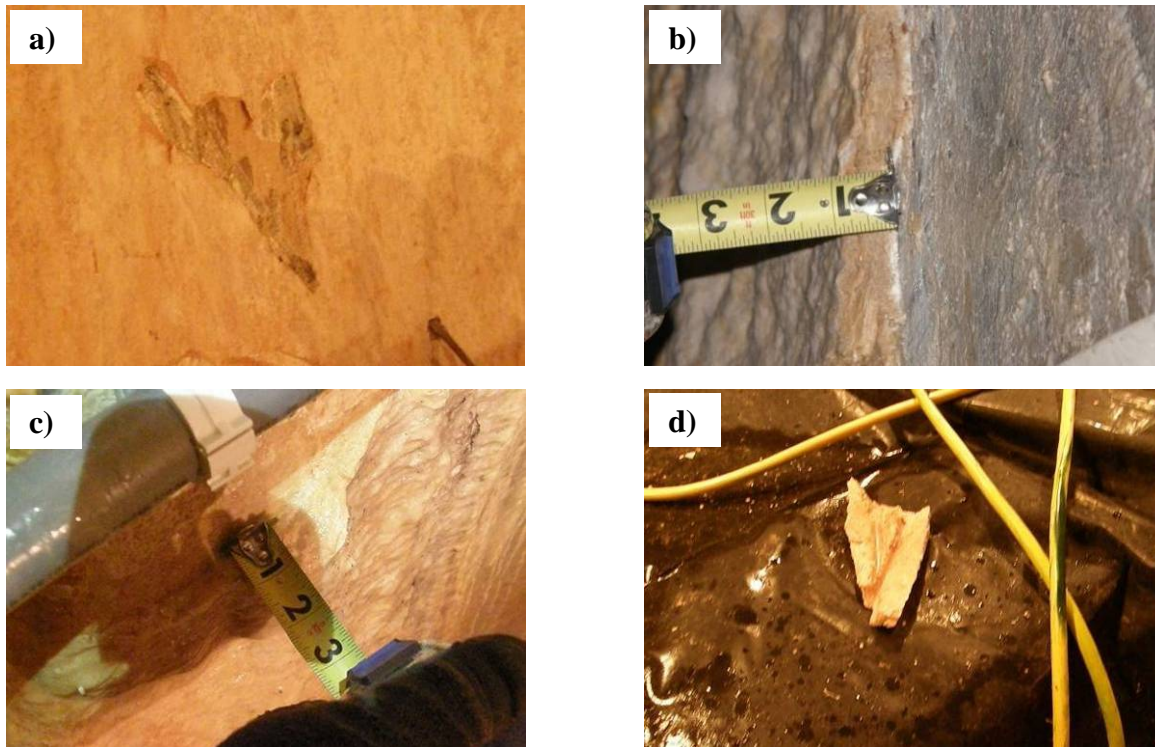


Figure 2. Calcite from the walls indicates an average thickness of 0.5 to 1 inch.

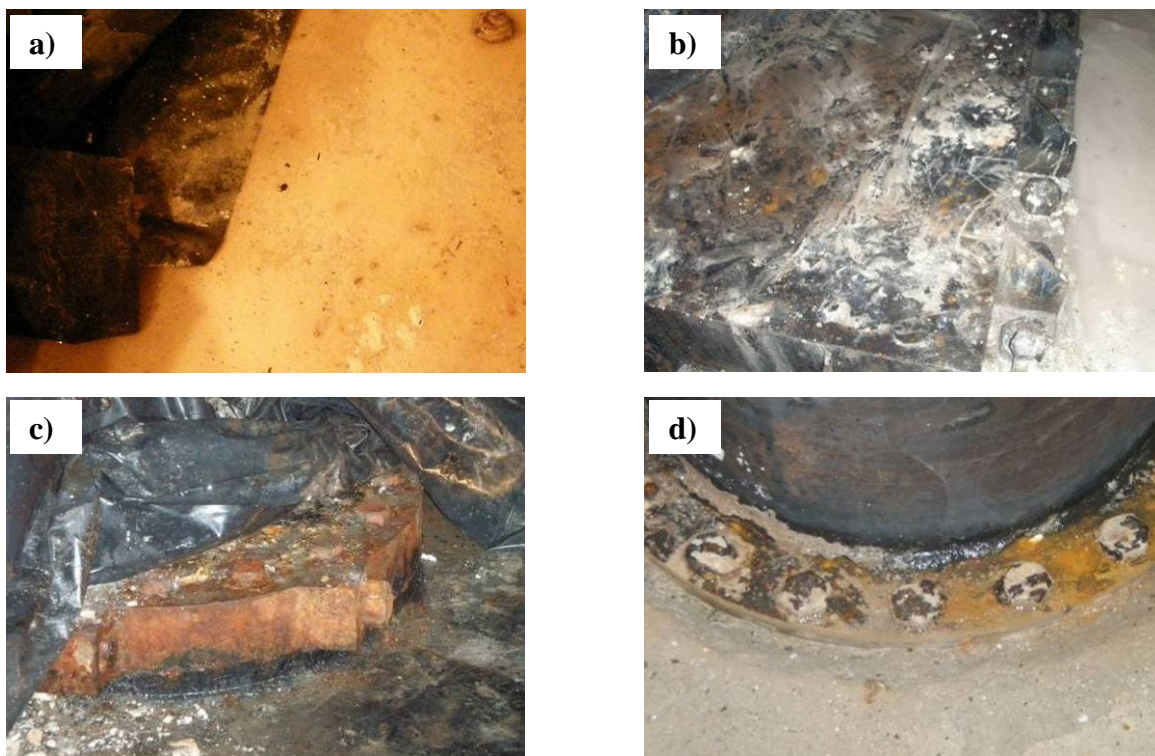


Figure 3. Standing water from the seepage has caused corrosion of the air inlet pipe and bonnet cover.

Objective and Approach

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 4 shows a schematic diagram of the installed system.

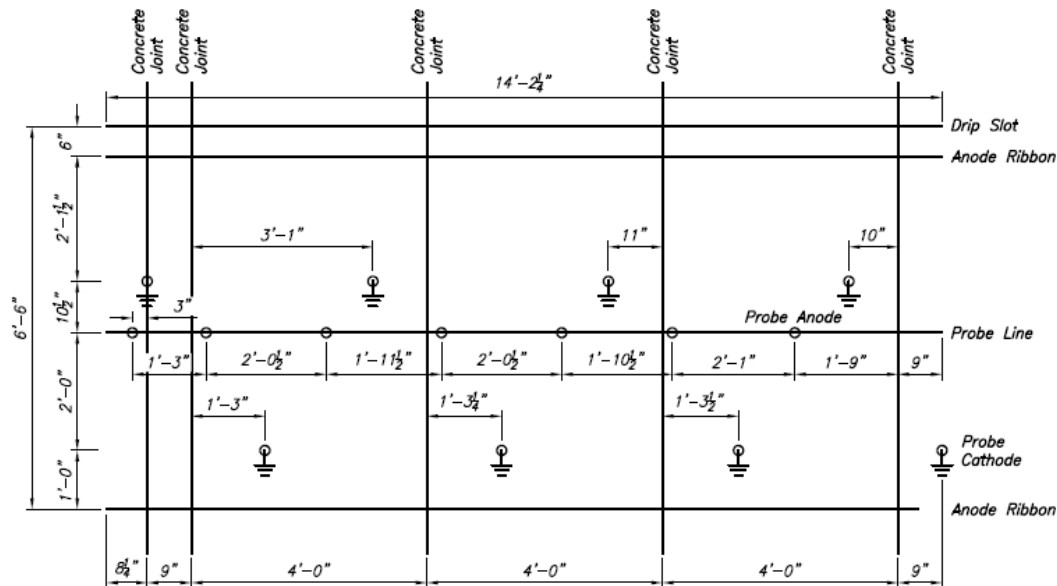


Figure 4. Schematic of installed system.

If measurements determine that the second phase is working to dry out the concrete, then a recommendation will be made to install EOP in a larger test area. We currently envision using performance data to develop an expanded test area for an EOP system to address water intrusion through a 10 foot high section at the bottom of the gate shaft above the bonnet chamber around the entire circumference. The next phase test section will include concrete that contains leaking cracks.

Background

Damage caused by water seeping through concrete or leaks through cracks in a concrete structure can be extensive and expensive to repair. Figure 5 shows sources of water in concrete structures. Corrosion of equipment inside the structure due to the resultant damp environment affects the operation of the equipment (e.g., gate operating motors and pipelines). Maintenance is required to mitigate the corrosion damage to the equipment, remove calcite deposits, and mitigate safety issues due to inoperable equipment and poor air quality. EOP technology can mitigate many water-related problems from the interior of affected areas without the cost of excavation. Corrosion and water/moisture related damage to equipment can be mitigated along with reducing humidity.

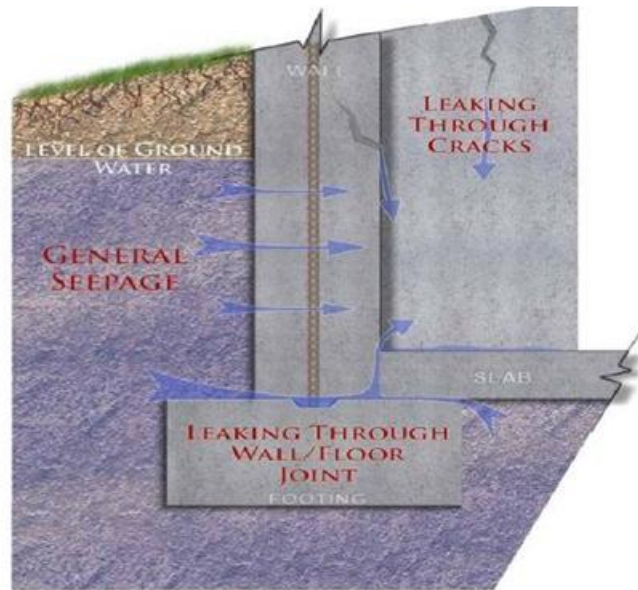


Figure 5. Sources of water and seepage [1, 2].

An EOP system involves inserting anodes (positive electrodes) into the concrete wall or floor on the inside of the structure and placing cathodes (negative electrodes) in the soil directly outside the structure. In the case of thick concrete walls or accessibility issues, the cathodes can be inserted into the wall to a given depth. Initial resistivity tests of the concrete and soil are utilized to determine the density of the anode and cathode placement. Figure 6 shows a typical EOP system layout and operation. EOP systems require a 120-volt alternating current (V_{AC}) circuit for the system controller. The total power requirement for a 2,000-square-foot (ft^2) basement is about the same as that for a 100-watt incandescent light bulb [3].

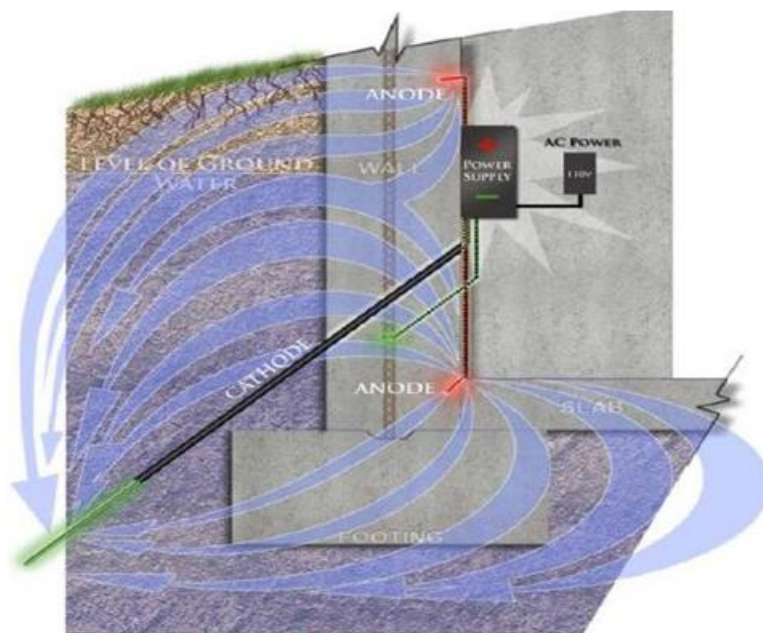


Figure 6. Typical EOP system layout and operation [1, 2].

Principles of Electro-Osmotic Pulse Operation

An experiment conducted by F.F. Reuss in 1809 [11] showed that when an electric field was applied to the soil, water could be forced to flow through a clay-water system. Flow is initiated using the movement of positively charged ions (cations) in the pore fluid within a porous media like clay or concrete. The water surrounding the cations moves with them. This process is defined as electro-osmosis. The basic physics and chemistry of electro osmosis can be found in several textbooks and treatises [12-14]. Electro osmotic systems for waterproofing masonry walls were introduced in the 1960s by the Europeans [15].

The movement of the solution in concrete with a capillary pore system, as described by Tikhomolova [14], contains several forces. These force components include: the forces due to gravity, pressure, viscosity, electro-osmotic force and temperature. The forces due to pressure and electro-osmosis are generally the more dominant components, and to prevent water seepage caused by hydrostatic pressure, the force due to electro-osmosis must balance or exceed the pressure force [14]. The suitability and effectiveness of electro-osmosis is dependent on the presence of capillary pores, the concrete having fixed surface charges, saturation of the structure, and the solution in the pores must be a dilute electrolyte. If the pore size is too small or too large, it is not economically workable for the application of EOP.

Based on this information, observations are made regarding how to maximize the effectiveness of electro-osmosis [16]:

1. Maximizing the potential through use of a porous material
2. Reducing the contamination of the ground water
3. Maintaining a saturated material
4. Limiting the hydrostatic pressure force
5. Minimizing the spacing between electrodes
6. Using nonpolarizing electrodes or a pulsed reversing system (EOP) in order to reduce the resistance in the vicinity of the electrodes

However, not all of these factors can be controlled with regard to existing structures in the field.

In the electrolyte, the positive ions tend to be solvated, and the negative ions tend to be unsolvated [17-19]. Solvation is defined as the process of attraction and association of molecules of a solvent with molecules or ions of a solute, so as ions dissolve in a solvent, they will spread out and are surrounded by solvent molecules. Thus, as the positive ions move through the pores, the water molecules will move with them and are dependent on the concentration of ions, type of material, and magnitude of the applied current [17-19]. The negative charge on the pore walls of the concrete sets up a capillary with an electrical double layer of cations dissolved in the pore fluid (figure 7). The application of a direct current (DC) electric field across the capillary causes the positive ions and the solution to move from the anode to the cathode as shown in figure 8a. The current must be applied to minimize alteration of the pore solution. Figure 8b is a sketch depicting EOP action in a pore.

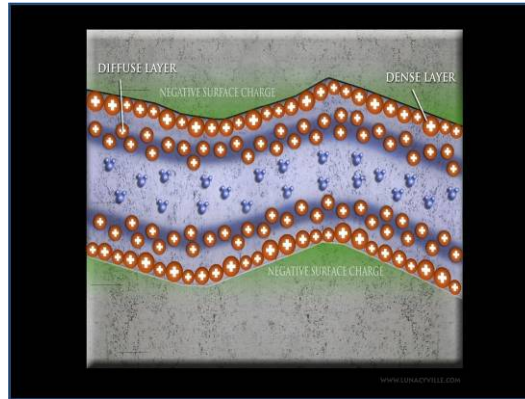


Figure 7. Illustration of concrete pore structures showing the electrical double layer of cations [1].

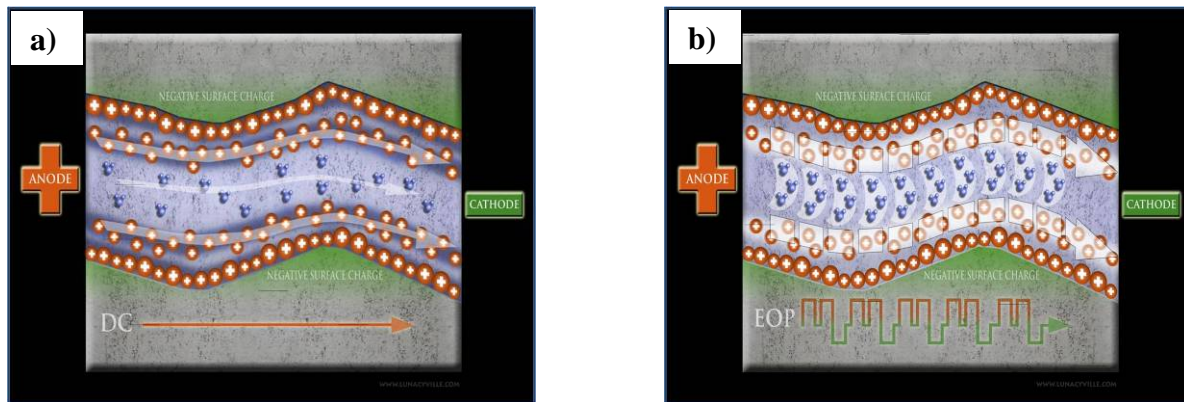


Figure 8. Illustration of concrete pore structures showing the application of DC voltage to move the cations and water (a) and the effect of EOP action in the pore (b) [1, 2].

However, new applications for this technology are still being developed. The electrical pulse causes cations (e.g., Ca^{++}) and the associated water molecules they are dissolved in to move from the anode, installed on the dry side, towards the cathode, installed on the wet side as shown in figure 9. This will create a type of barrier and prevent water molecules from entering the concrete structure as illustrated in figure 10. In the case of thick concrete, cathodes can be placed deep in the concrete section, such that the current and electric field pushes against the direction of flow induced by the hydraulic gradient, preventing water penetration through buried concrete structures. In order to overcome the force exerted on the water molecules by the hydraulic gradient a certain current density is required, creating sufficient electric field strength in the concrete.

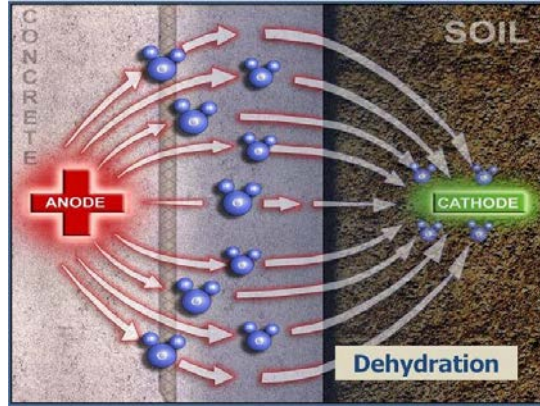


Figure 9. Illustration of cations and water molecules moving from anode to cathode on a macro scale with the application of EOP to dehydrate concrete [1].

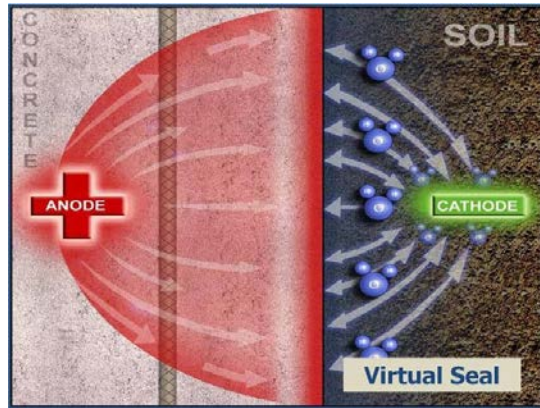
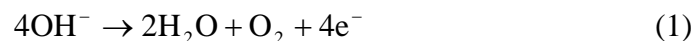


Figure 10. Illustration of the effects of the application of EOP to create a virtual seal or barrier to prevent water from entering the concrete on a macro scale [1].

A commercial system was developed, based on a Polish patent, to apply EOP technology using the application of a pulsating direct electric field, combined with an off period, to reverse the flow of water seepage. The pulse sequence consists of a pulse of positive voltage (as seen from the dry side of the concrete wall), a period of rest when no voltage is applied, another positive pulse, and then a pulse of negative voltage. The voltage pulse prevents the alteration of the chemical composition of the pore solution due to the application of the current [20]. Retaining some moisture in the interior helps to maintain the chemistry of the pore solution [20].

A balance of the anode/cathode current density must be maintained to control the water seepage without generating gas and acid at the anodes [20]. The generation of acid causes degradation of the anode material, as well as the cement paste adjacent to the anode [20]. It is well known that the pH can change dramatically in the vicinity of the electrodes during electro-osmosis [21]. The typical anodic reaction of oxidation of hydroxyl ions, shown in equation 1, begins with producing water molecules, oxygen, and electrons.



These are transferred to the cathode via the system metallic path. The process uses up hydroxyl ions at the anode and, therefore, the concentration of hydrogen ions increases, which often drops the pH of the concrete around the anode to values lower than 5 [20]. Figure 11 shows a representative plot of the pH evolution at the anode and cathode for concrete and montmorillonite cell [22].

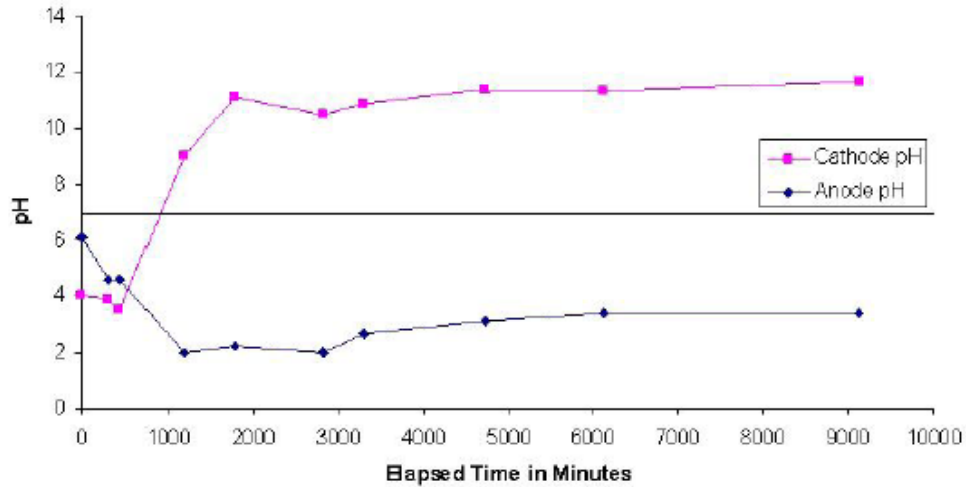


Figure 11. A representative plot of the measured pH at anode and cathode wells for concrete and sodium montmorillonite cell [22].

The amount of moisture in the concrete is controlled by the negative voltage pulse to prevent overdrying of the concrete matrix and subsequent degradation [20]. A pulse sequence consists of a pulse of positive voltage (as seen from the dry side of the concrete wall) for 0.5 second, a period of rest when no voltage is applied, another positive pulse, typically 6 seconds in duration, and then a pulse of negative voltage lasting 0.5 second [20]. The amplitude of the signal is typically on the order of 20 to 40 volts direct current (V_{DC}) [20]. Figure 12 shows a typical EOP pulse wave form sequence.

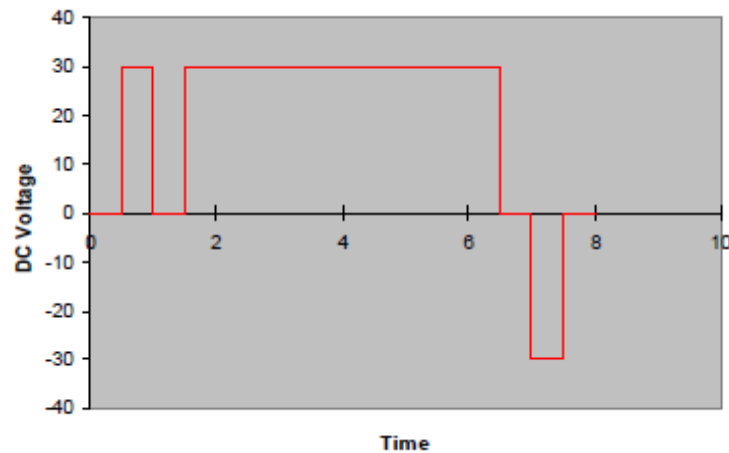


Figure 12. Typical EOP wave form showing the positive pulses, negative pulse, and rest period [2].

Cost/Benefit Analysis

As stated earlier, damage due to water seepage through concrete can cause extensive and expensive damage. Necessary repair work can include excavation, trenching, grouting, coating, major concrete repair for rebar corrosion issues, etc. An analysis can be made to determine the cost/benefit of installing an EOP system. This is a fairly simple method for approximating any cost savings and does not include the cost of any compounded degradation issues. In addition, it may not account for all costs due to disruption and lost productivity. The percent savings calculated using equation 2 is based on the capital costs and, in simple terms, is the comparison between the cost of repair and installing an EOP system [20, 23].

$$\% \text{ first cost saved} = 100 \times \left(1 - \frac{\text{EOP per linear foot}}{\text{Repair per linear foot}} \right) \quad (2)$$

Another important calculation would be that of payback or the time it takes to recoup the investment based on the overall reduction in cost for repair and maintenance. There are two different methods used for determining this: Payback Upon Price Comparison (P_{PC}) and Payback Over Time (P_{OT}) [20, 23]. The price comparison method shown in equation 3 is used to determine the length of time to save the investment for the EOP installation compared to the cost of repair [20, 23]. The overtime method shown in equation 4 is more involved and is a comparison between the EOP installation cost and the sum of all annual costs avoided over a specified length of time due to the EOP system [20, 23].

$$P_{PC} = \frac{1}{\frac{\text{Repair per linear foot} - \text{EOP per linear foot}}{\text{EOP per linear foot}}} \quad (3)$$

$$P_{OT} = \frac{\text{Total Installation Cost}}{\text{Sum of Annual Cost Avoidances}} \quad (4)$$

It is important to understand that these are only approximations. However, they can be used to determine the effectiveness of the installation of EOP compared to the required continual maintenance.

EOP Installation

Components

Strip Type Anodes and Cathodes

Mixed metal oxide coated titanium mesh material is used for the strip anode and cathode material. The mesh is spot or resistance welded to a titanium bar, and the bar is welded to a titanium rod. The lead wire is attached to the titanium rod using a crimp type connection and is encased in shrink wrap tubing. Figure 13 shows a schematic of an electrode.

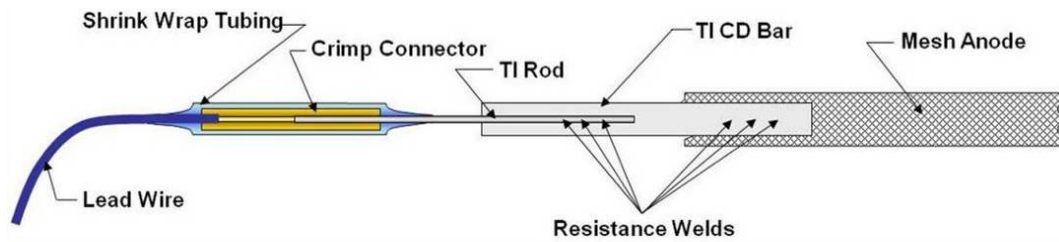


Figure 13. Schematic of the mixed metal oxide coated titanium mesh electrode, which can be used for both an anode and cathode [1].

For the Trinity installation, strip anodes were approximately 7 feet long and ½ inch wide. A red insulated cable was used for the anodes. Figure 14 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 15 shows cathode materials installed on this project.

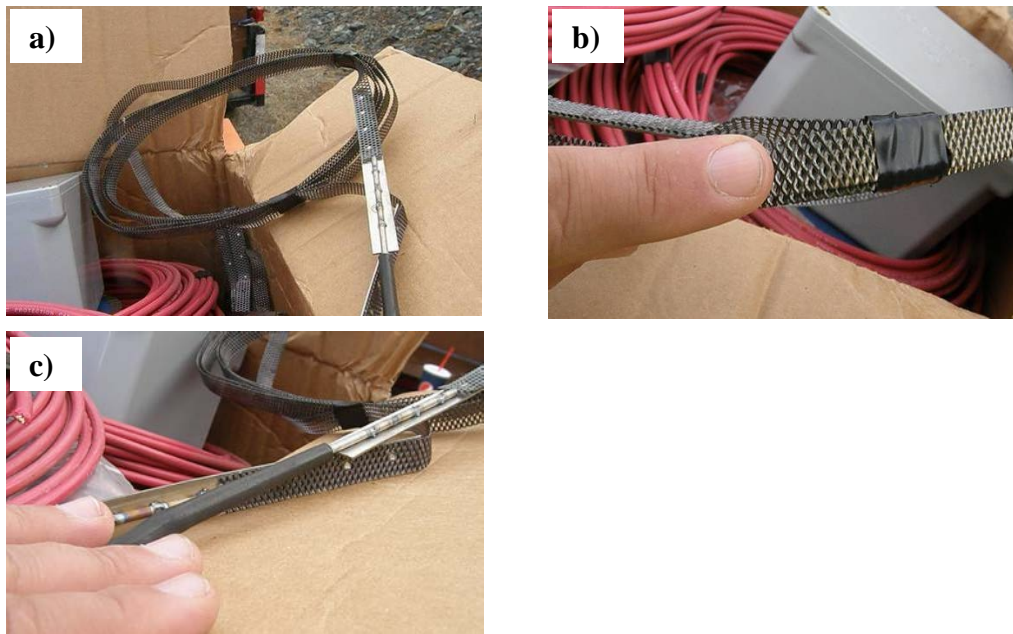


Figure 14. Mixed metal oxide coated titanium mesh strip type anodes installed in the concrete wall.

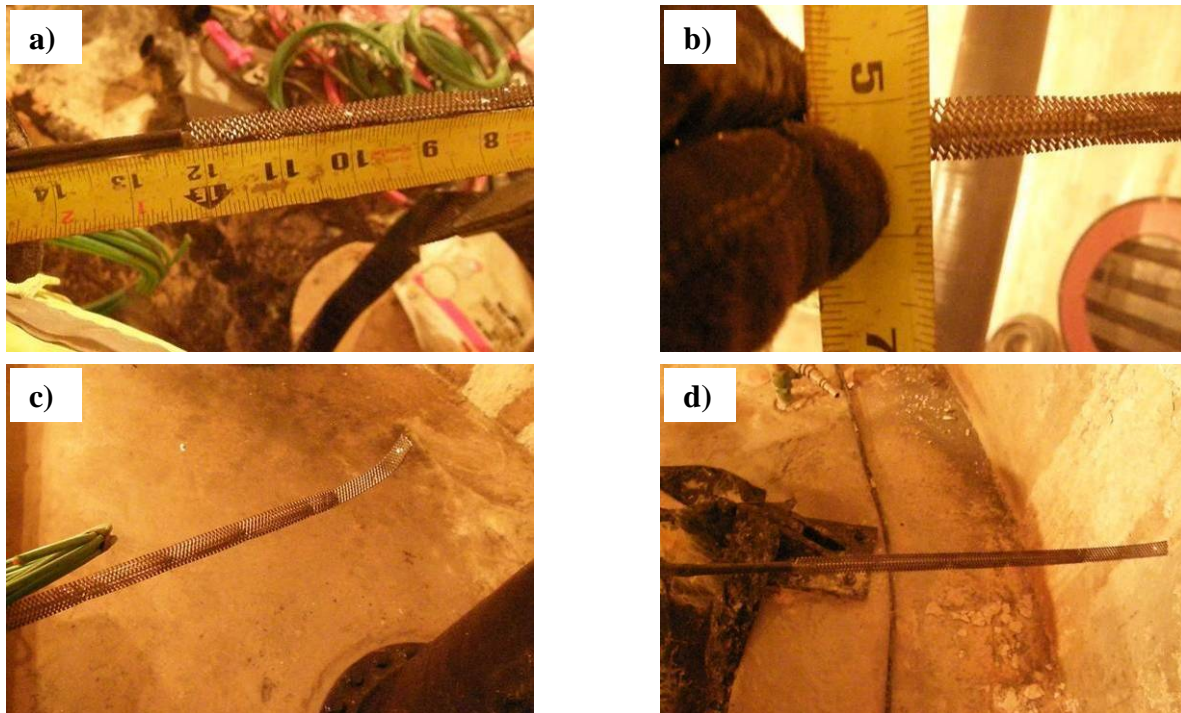


Figure 15. Mixed metal oxide coated titanium mesh strip type cathodes installed in the concrete wall.

Probe Type Anodes

Probe anodes were approximately 6 to 7 inches long and a little under ½ inch in diameter. The material was a mixed metal oxide coated titanium mesh formed into a tube shape. The probe electrodes had a screw type connection on one end to attach the lead cable. Figure 16 shows a probe anode installed on this project.

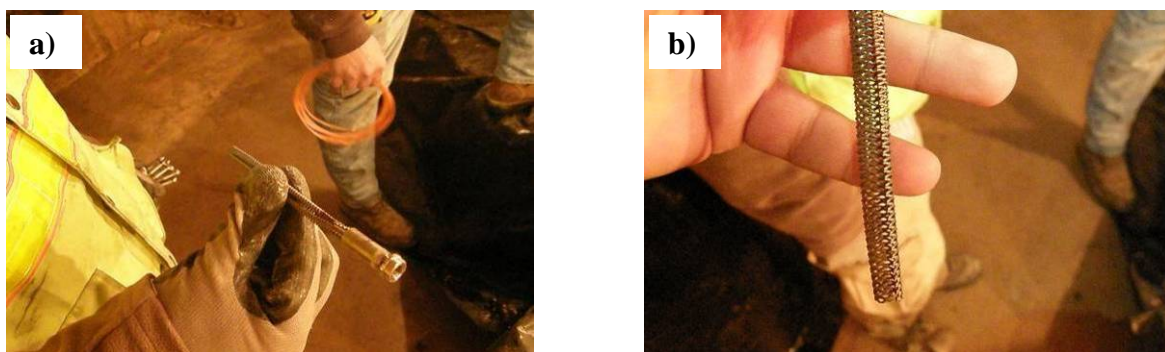


Figure 16. Mixed metal oxide coated titanium mesh probe type anodes installed in the concrete wall.

System Controller

The system controller is powered by a 120 V_{AC} circuit. Data is collected continuously by the controller and is stored on a secure digital memory (SD) card, which can be removed to easily download data for analysis. The controller contains a rectifying unit for changing the AC to DC, a surge protector, and the necessary electronics to set the output potential and pulse cycles. Figure 17 shows the unit used for the Trinity Dam system.



Figure 17. DC voltage controlled pulse unit installed at Trinity Dam for the EOP system.

Installation

Calcite Removal

The calcite deposits on the bonnet chamber wall opposite the hatched doorway were removed using a chipping hammer and a grinder (figure 18a and 18b). The area cleared off was approximately 14 feet wide and 6 ½ feet high starting from the floor. Removal of calcite required roughly 1 day, due to the sheer volume, as shown in figure 18c. The calcite came off the wall in chunks. The calcite deposits on the wall were an average of 0.5 to 1 inch in thickness as shown in figure 18d.

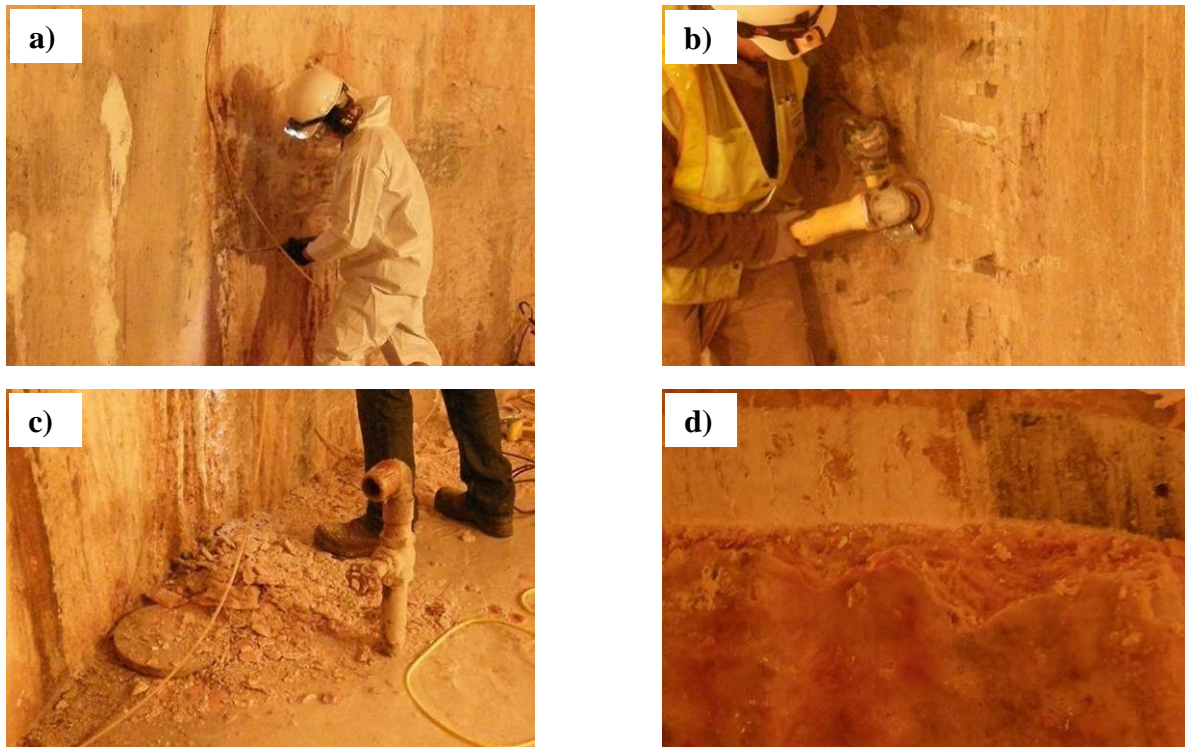


Figure 18. Removal of calcite from the concrete wall in the bonnet chamber using a chipping hammer (a) and grinder (b). The volume of calcite removed is shown in (c). Deposits on the wall were an average of 0.5 to 1 inch thick (d).

Anodes

Two types of anodes were used during this phase to see which would be most effective but we were not able to determine any difference.

Strip Anodes

Four strip anodes were installed in the test section. The anode material was installed in the wall at the floor joint and 6 feet above the floor. Two strips were installed at each location to cover the entire 14 feet.

A groove approximately 1 inch wide by 1 inch deep was cut in the concrete 6 feet above and parallel to the floor using a circular saw as shown in figure 19a-19d. A vacuum system was hooked up to the saw to minimize the concrete dust created during the saw cut. A second groove was cut approximately 6 inches above the anode groove for a water drip strip. The weather strip shown in figure 20a and 20b was installed to prevent water from the wall above from flowing over the test area, which might lead to erroneous readings. The anodes with lead wires attached (see figure 14) were inserted in the groove, and the groove was filled with a Portland cement grout (BASF Masterflow 928). Figure 21a-21c shows the installation of the upper strip anodes. The grout was smoothed flush with the wall with an anode cable at each end of the groove (figure 21d).

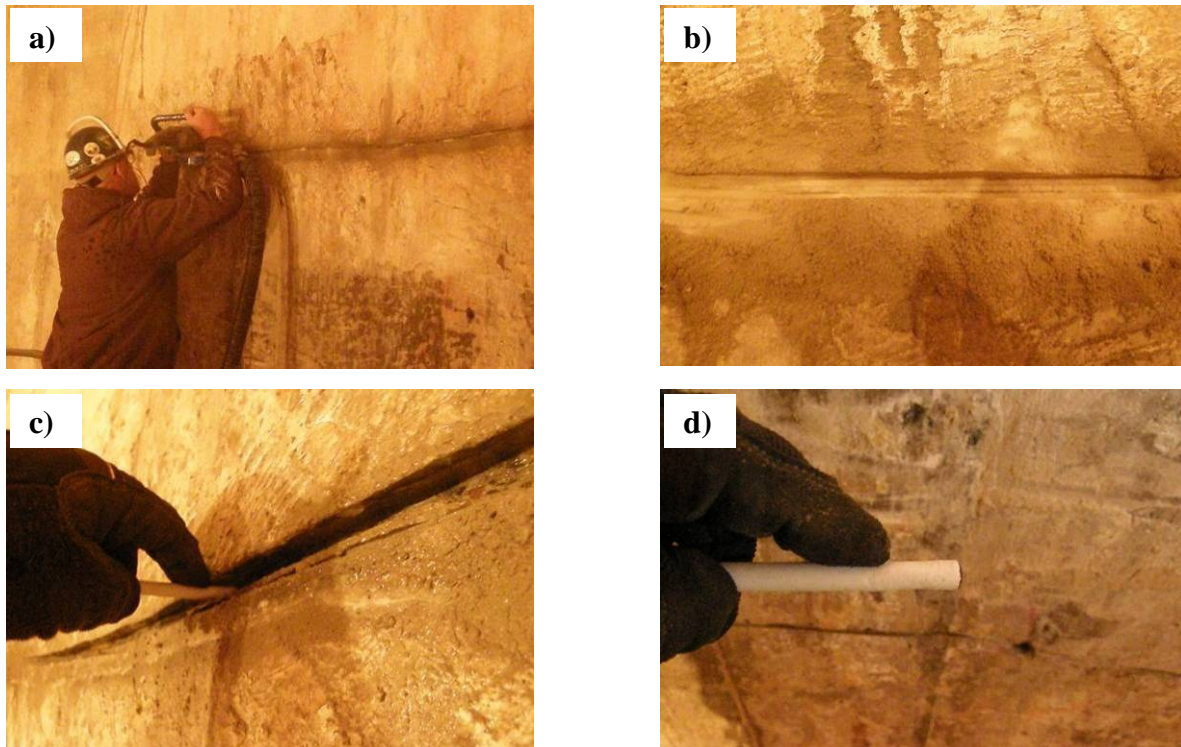


Figure 19. a) and b) show saw cutting of groove for strip anode installation. The finished groove, approximately 1 inch in depth, is shown in c), d), and e).

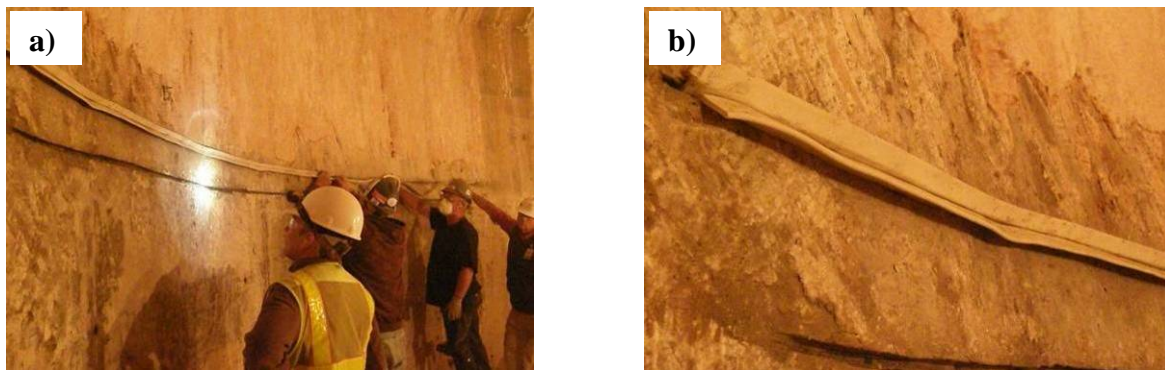


Figure 20. Installation of weather strip to act as a drip tray for water dripping down from above.

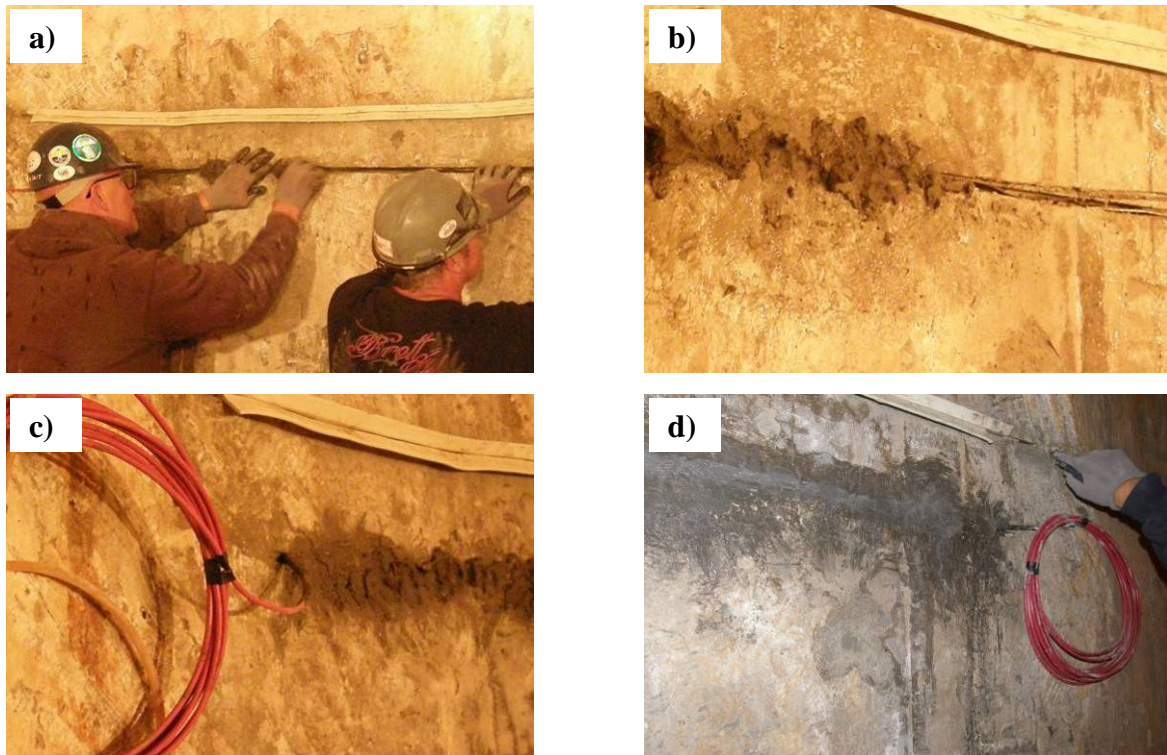


Figure 21. Installation of upper strip anode and hand packing of Portland cement grout into the groove shown in photos a), b) and c). Photo d) shows finished installation of upper anode strips and cable.

A groove about 1 inch deep was chipped out along the floor using a chipping hammer to accommodate a strip anode (figure 22a and 22b). The anodes with lead wires attached (figure 14) were inserted in the groove along the floor. Then, the groove was filled with a Portland cement grout (BASF Masterflow 928). Figure 23a-23c show the installation of the lower strip anodes. The grout was smoothed flush with the wall with an anode cable at each end of the groove (figure 23d).

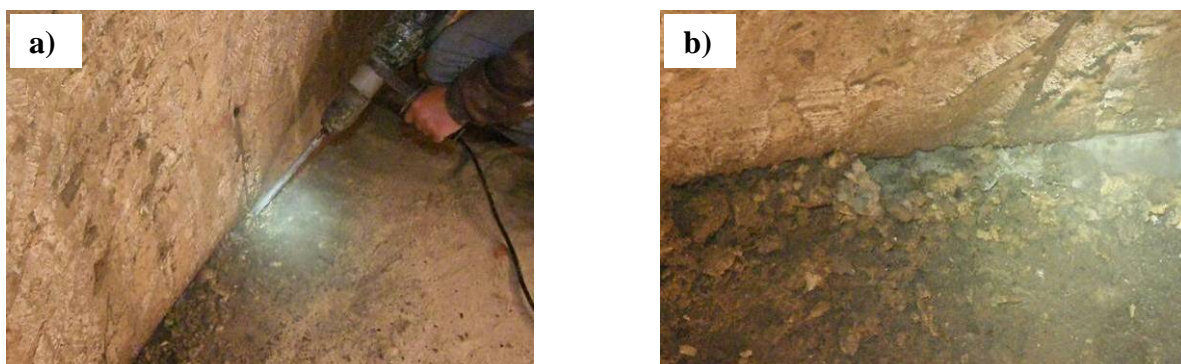


Figure 22. Groove for floor joint chipped out using chipping hammer to create a groove approximately 1 inch in depth.

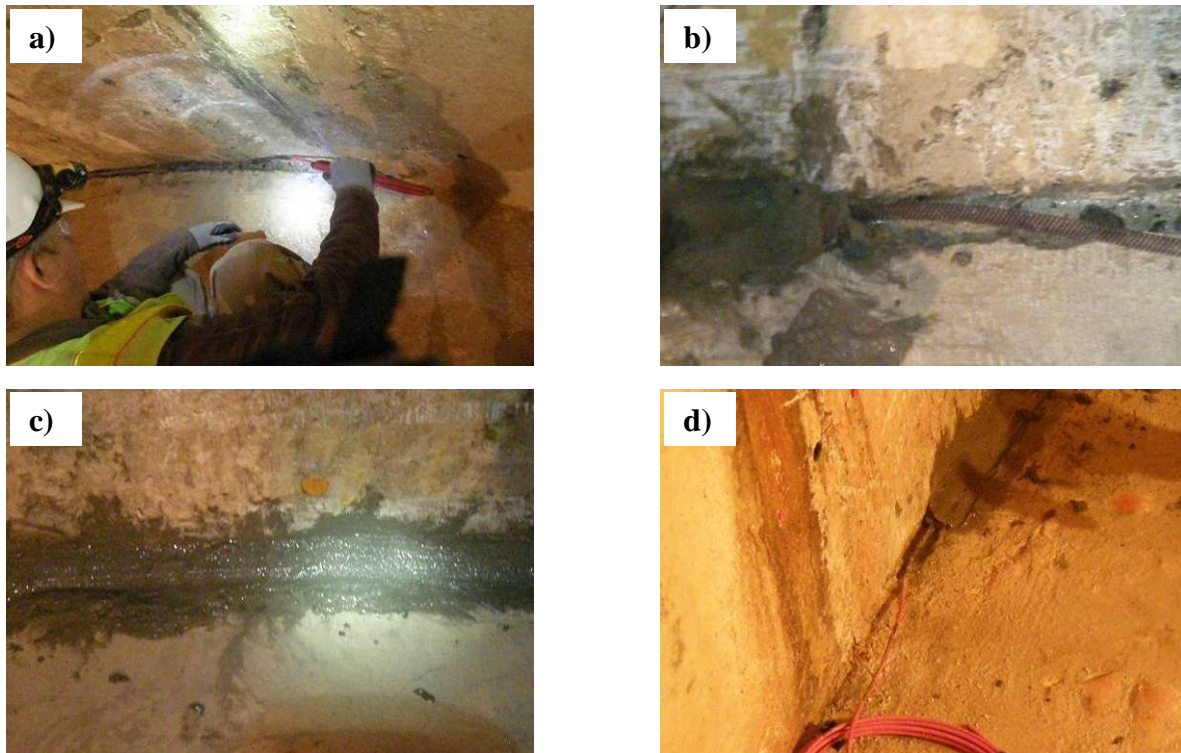


Figure 23. Strip anodes were installed in groove and then packed with a Portland cement grout.

Probe Type Anodes

Seven holes ($\frac{7}{8}$ inch in diameter) were drilled approximately 3 feet above the floor and approximately 2 feet apart (figure 4 and figure 24a). The holes were drilled to a depth of approximately 6 to 7 inches to accommodate the probe anodes. A groove was cut into the wall joining all the holes to embed the anode header cable as shown in figure 24b. The probes were inserted into the holes and connected to a single header cable shown in figure 25a-25c. The probe holes were then filled with grout, and the header cable was placed in the groove and filled with grout as shown in figure 25d-25f. The probe anode header cable was terminated in a junction box, connected to the other anode cables, and then connected to the main anode header cable, which connects to the system controller.

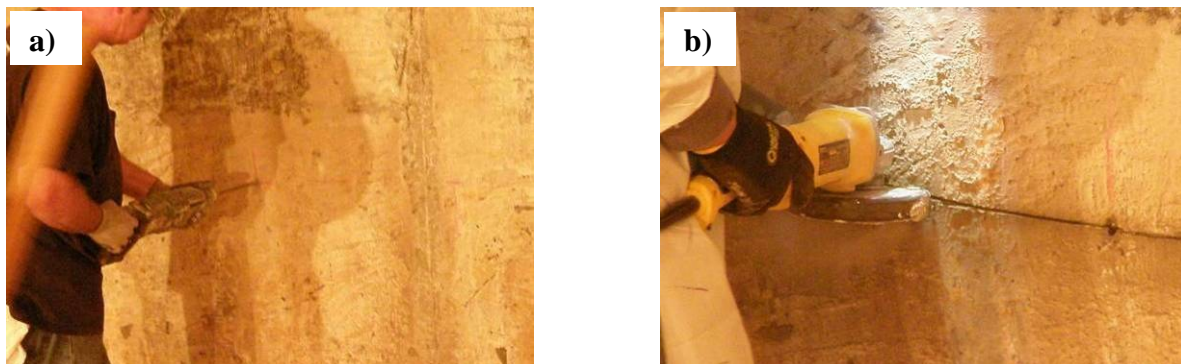


Figure 24. Holes were drilled for probe anodes as shown in a) and a groove was cut for embedding the cable as shown in b).

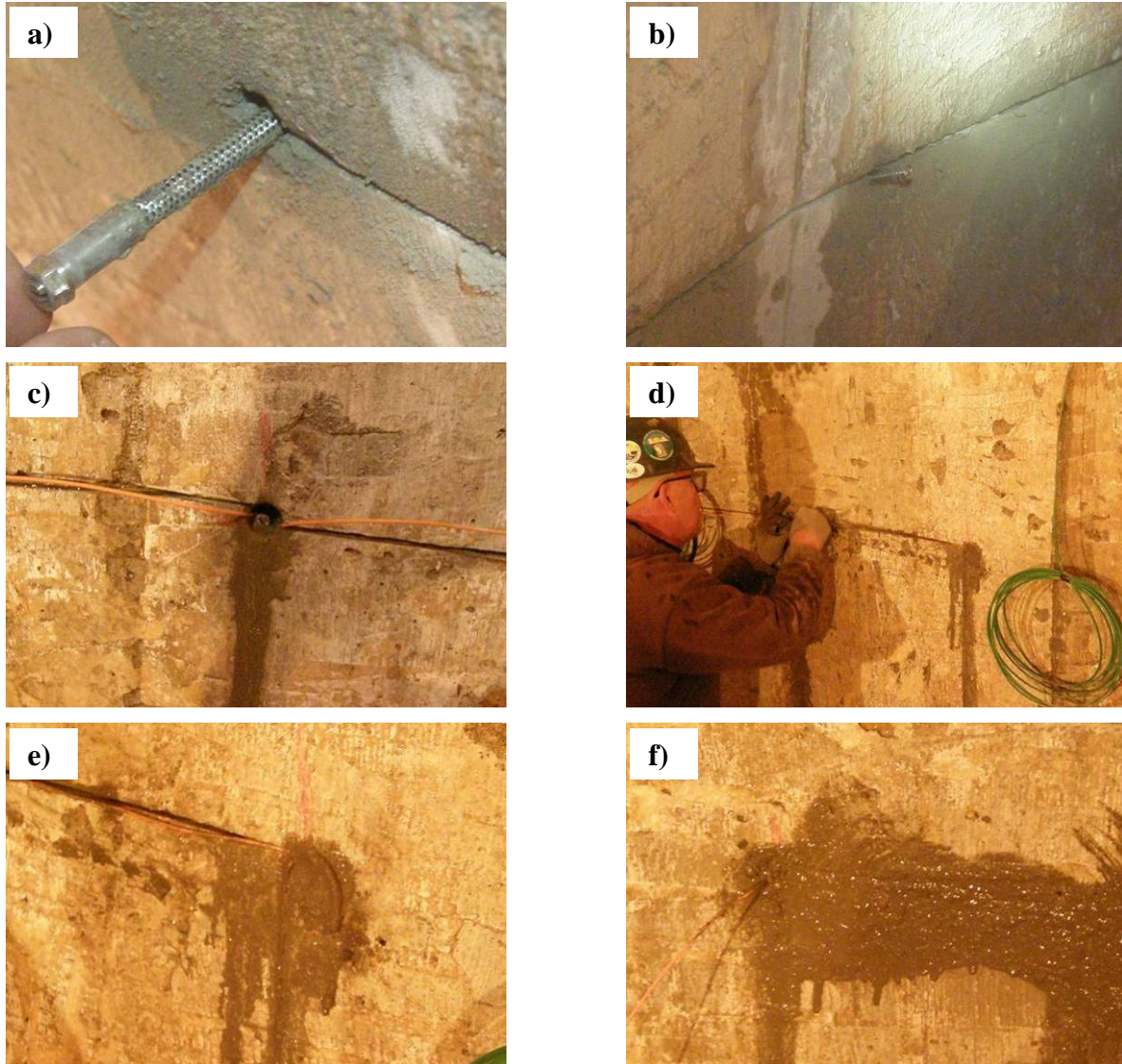


Figure 25. Probe anodes were inserted into the hole as shown in a) and b). The anodes were connected to a single header cable, which was placed in the saw cut groove as shown in c), d), and e). Portland cement grout was poured in the holes around the anodes, and the anodes and cable were grouted in as shown in e) and f).

Cathodes

Eight holes ($\frac{7}{8}$ inch in diameter) were drilled to a depth of approximately 12 inches and at a slight downward angle for the cathode strips. Four holes were drilled approximately 1 foot above the floor, and four holes were drilled approximately 4 feet above the floor as shown in figure 4 and figure 26a and 26b. The cathode strips were cut to fit based on the actual depth of the hole. Then, the holes were filled with a Portland cement grout. Figure 27a - 27c show the installation of the cathodes and grouting.

The cathode holes were placed at an equal spacing along the test section, approximately 3 feet 10 inches apart as shown in figure 4, and the top row was slightly offset from the bottom row. Figure 4 and figure 28 show the locations of the cathodes.

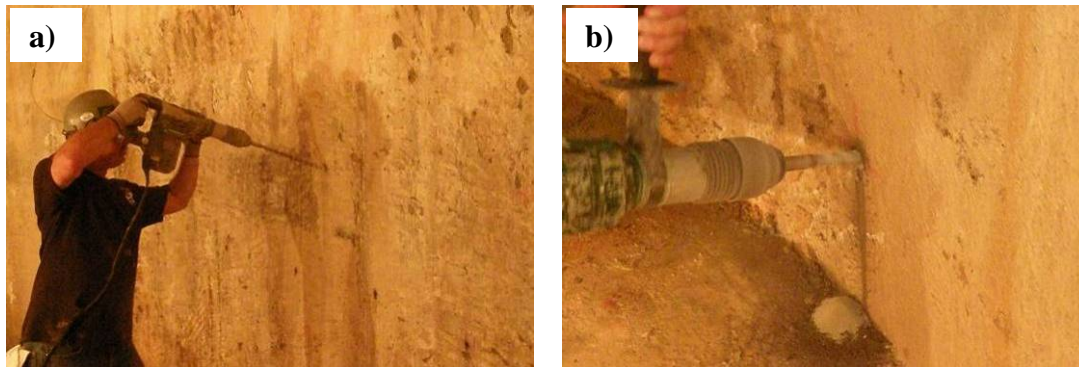


Figure 26. Drilling holes for cathode installation. Note the slight downward angle.

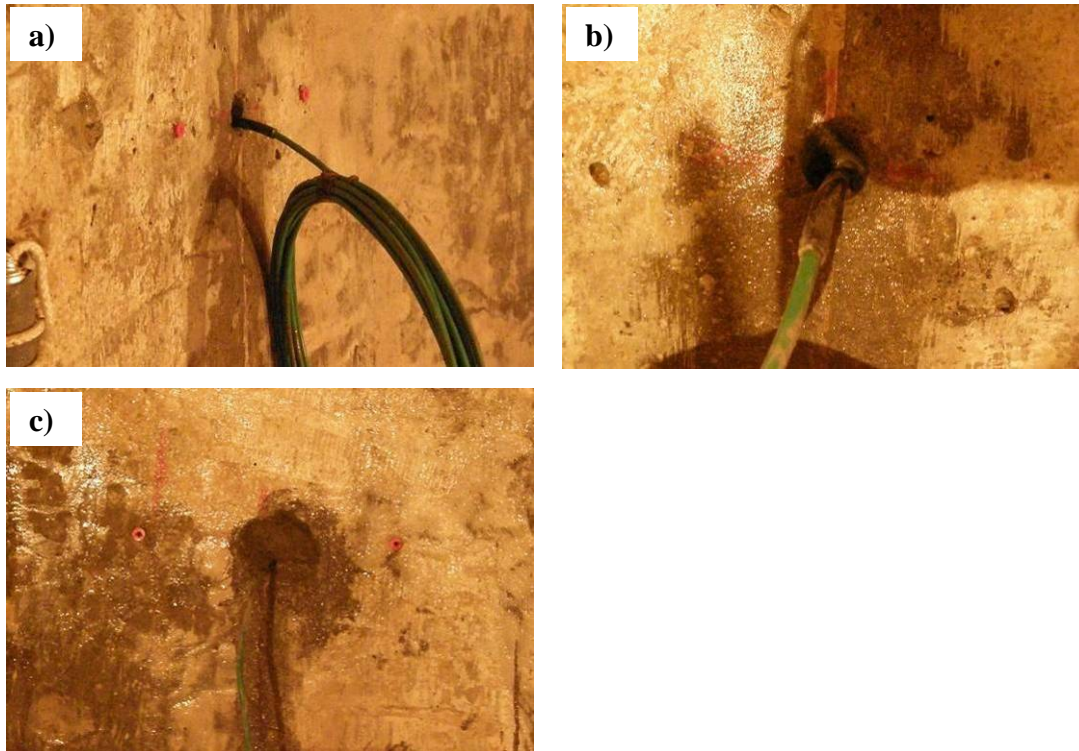


Figure 27. Installation and grouting of cathodes.



Figure 28. Locations of cathodes (green cables) in relation to each other and to anodes (red cables).

Junction Boxes

Junction boxes were installed at each cathode location (figures 29a and 29b). The cathode cables were then run through the junction boxes (figures 30a and 30b). The anode cables were placed and grouted into grooves cut into the wall and into the cathodes' junction boxes, and then they were run in the same conduit as the cathode cables shown in figure 31a and 31b.

The rebar was located, and a hole was drilled in order to expose one of the bars. A tapped connection was then made to the rebar as shown on the left side of figure 30b. This connection allows the system to supply the rebar with a small amount of protective current and prevents any damage to the rebar due to operation of the system.

All the cables were terminated in a main junction box. Figure 32 shows cables being connected to header cables in the 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 33 shows the complete installation of all electrodes and junction boxes.

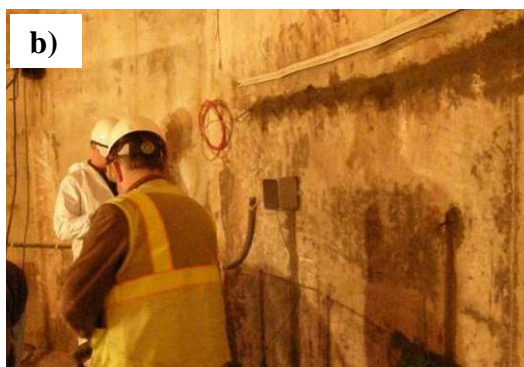


Figure 29. Installation of junction boxes and wiring of system.



Figure 30. Cables were run through conduit to main junction box.



Figure 31. Anode cables were embedded into the wall to the cathode junction box, and cable was run through the same conduit as the cathode cables.



Figure 32. All 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 33. Completed installation with junction boxes and conduit.

Permanent systems only include one junction box and conduit to a control unit, depending on the size of the structure. The anode cables are embedded in the concrete wall, and the cathode cables would either be embedded in the concrete wall or buried, depending on the location of the cathodes and control unit.

System Control Unit and Power

The control unit was mounted on the wall just outside of the hatch for the bonnet chamber to prevent collection of water and calcite on the unit as shown in figure 34a. Figure 34b shows the internal components of the unit to include the location of the SD card used for storage of the collected data. The card is located on the side behind the front panel. The conduit containing the anode header cable, cathode header cable, and the cable for the rebar connection was installed

between the EOP test section along the wall and through the open hatch to the control unit. The control unit was wired into a 120 V_{AC} power source, using a series of extension cords, to an outlet at the top of the shaft approximately 420 feet away. Figure 35 shows the conduit containing the cables and the yellow electrical cord for the power.

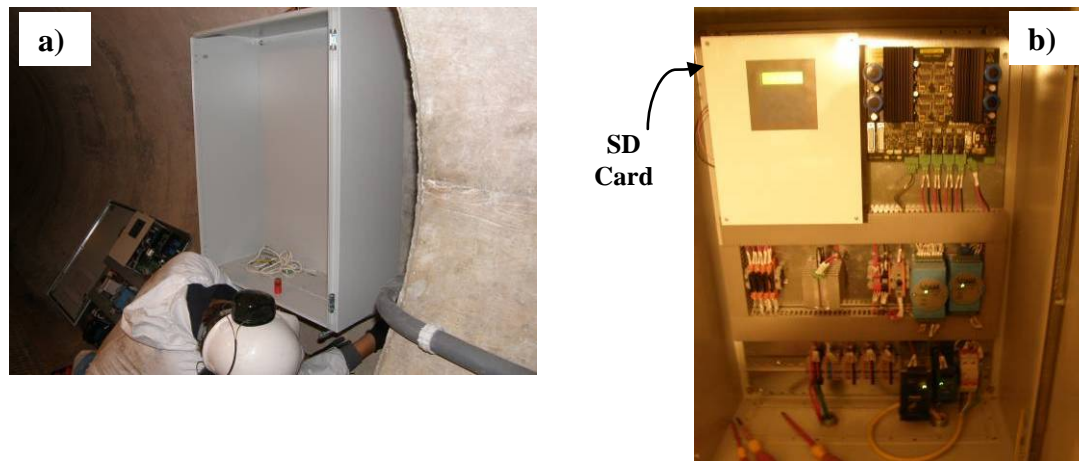


Figure 34. The cabinet was installed on the wall outside the chamber as shown in a). Photo b) shows the internal components of the unit. The arrow points to the location of the SD card used for data storage.



Figure 35. The conduit containing the anode header cable, cathode header cable, and rebar cable. The unit is powered by the yellow extension cord wrapped around the conduit.

The system was activated and programmed for operation on September 29, 2011, at 11:37 a.m. as shown in figure 36a and 44b. The unit was programmed to hold a potential of 24 V_{DC} with a current applied to the rebar of approximately 1-2 milliamperes (mA).

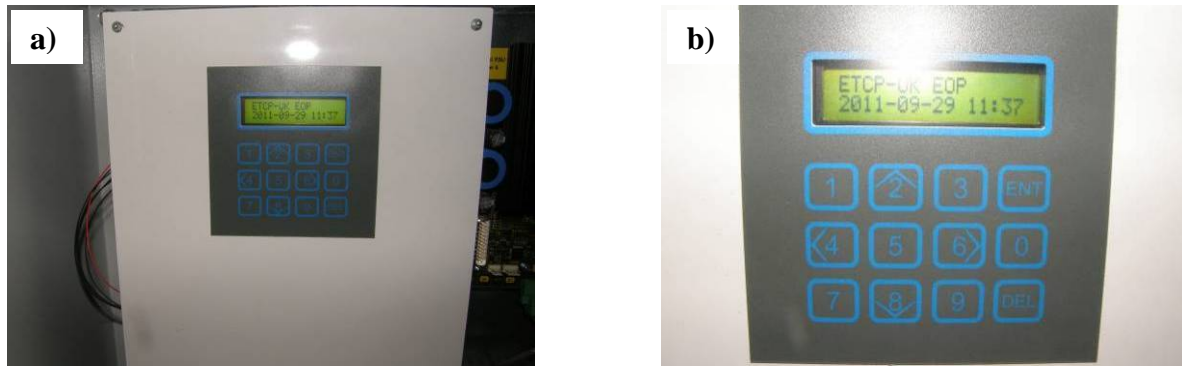


Figure 36. The photos show the operational unit, noting the date (2011-09-29) the unit was energized.

Test Data

As-Left Condition

The wall of the chamber where the test section was located showed a saturated or wet concrete, both to sight and touch, as shown in figure 37a and 37b. These photos were taken to document wall moisture conditions to help determine if the system was operating using visible wall moisture conditions.

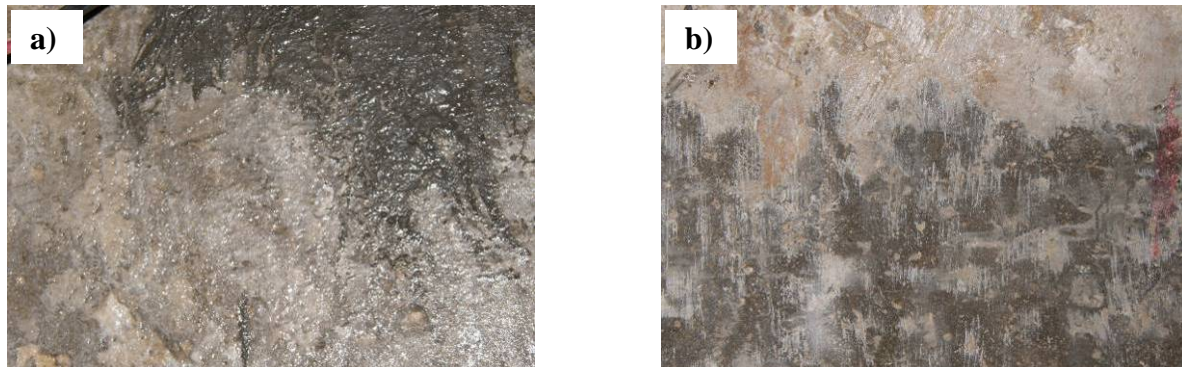


Figure 37. Condition of wall at installation location after installation prior to energizing of the system. Note the wall was damp to sight and touch.

Initial Two Weeks of Operation

On October 12, 2011, after about 2 weeks of operation, the system was evaluated and data collected from the SD card. Figure 38a- 38d all show dry areas of concrete after 2 weeks of operation. Figure 38b still shows an area where the concrete appears damp. The humidity in the chamber is nearly 100 percent due to high levels of water and moisture in the chamber. The weatherstrip installed to act as a drip tray was full of water and had calcite in it, as shown in Figure 38c. The tray was not draining as designed, causing water to drip down onto the wall below in some areas as shown in Figure 38d. The water primarily was dripping down onto one of the center junction boxes.

The unit collects and saves data to the SD card in an Excel spreadsheet format every 4 hours. Each file contains all the data for a single month. Table 1 shows an example of the data collected in the month of October. The collected data is then 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. Figure 39 shows that over the initial first 2 weeks of operation, the measured total current decreased and the calculated resistance increased. The data trend shown in Figure 39 indicates that the system is operating as designed. Observations of wall moisture also indicated that the wall was drying as shown in Figure 38a-38d.

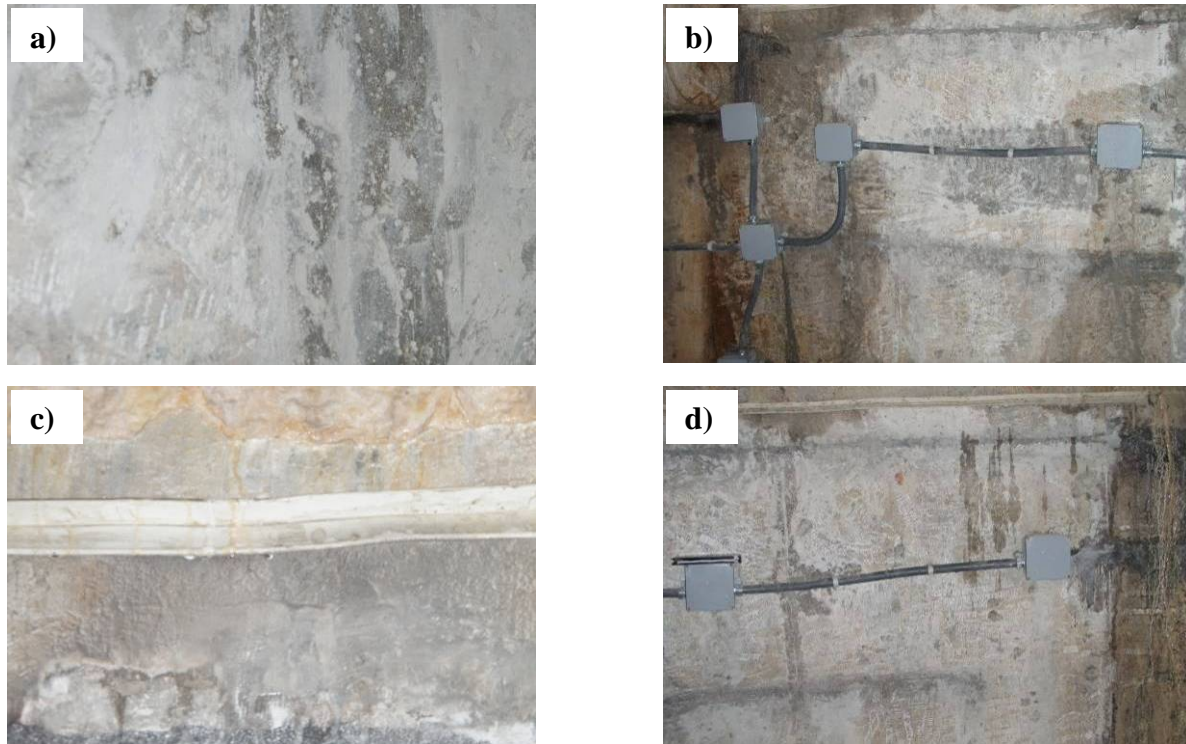


Figure 38. Concrete wall at location of installation after 2 weeks of operation. The wall was dry to sight and touch over most of the test section as shown in a) and b). Damp areas and drips, as shown in b) and c), resulted because the drip tray was filled up with calcium carbonate saturated water and unable to drain properly as shown in d).

Table 1. Example data collected for the beginning of October

Date	Time	Voltage (V)	Total Current (mA)
10/1/2011	0:00	23.8	3,798
10/1/2011	4:00	23.8	3,756
10/1/2011	8:00	23.8	3,714
10/1/2011	12:00	23.8	3,687
10/1/2011	16:00	23.8	3,665
10/1/2011	20:00	23.9	3,634
10/2/2011	0:00	23.8	3,596
10/2/2011	4:00	23.8	3,559
10/2/2011	8:00	23.8	3,546
10/2/2011	12:00	23.8	3,554
10/2/2011	16:00	23.8	3,555
10/2/2011	20:00	23.9	3,536
10/3/2011	0:00	23.8	3,529

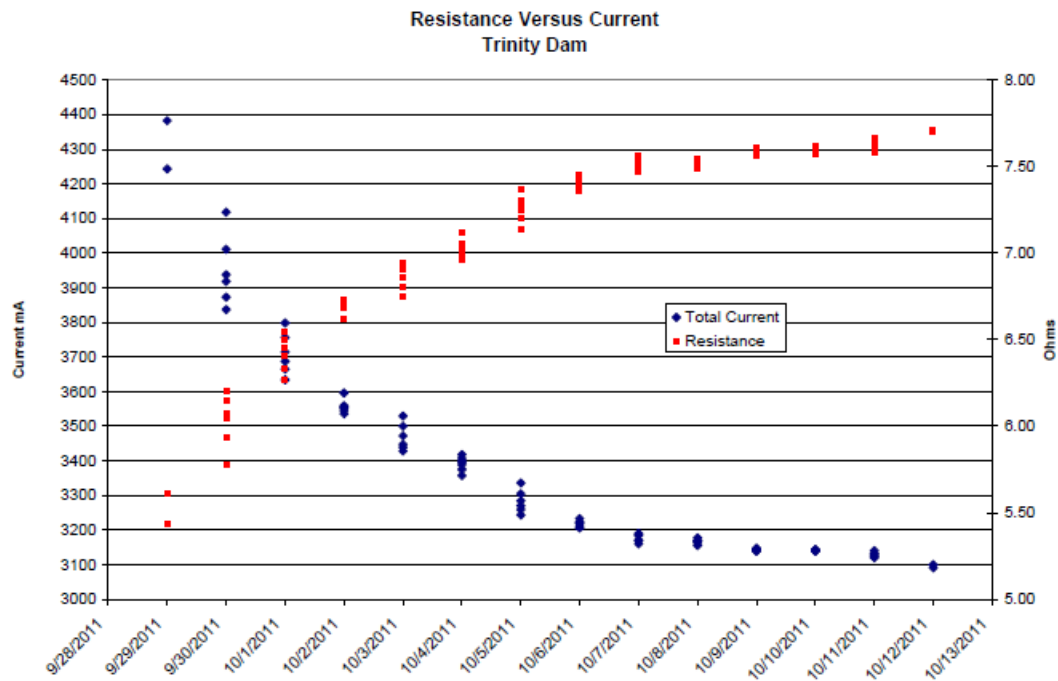


Figure 39. Data from the first 2 weeks of system operation showing the current and resistance over time. The data shows that the moisture content in the concrete is decreasing over time.

Five Weeks of Operation

Data was collected after 5 weeks of operation to determine operation and the current and resistance trend for the system. Figure 40 shows the analyzed data for total current output and resistance. The total current continues to decrease, and the resistance continues to increase. This indicates that the system is still operating as planned and the moisture content of the concrete

continues to decrease. The resistance calculated after 5 weeks of operation is nearly double its original value.

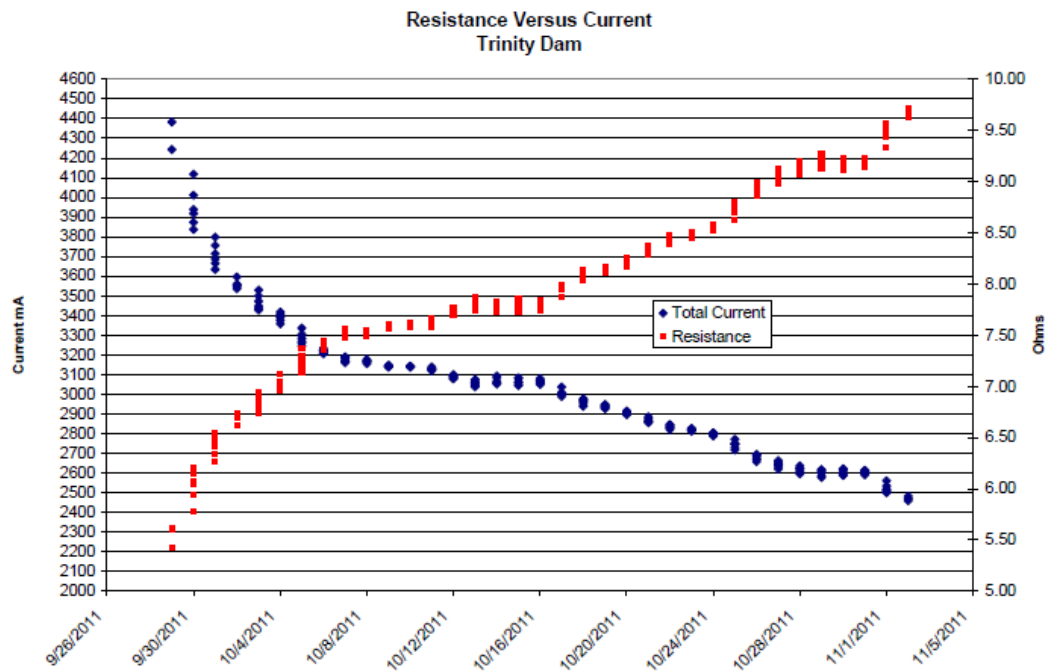


Figure 40. Data from the first 5 weeks of system operation showing the current and resistance over time. The data shows that the moisture content in the concrete is decreasing.

Eleven Weeks of Operation

Data was collected after 11 weeks of operation to determine operation and the current and resistance trend for the system. Figure 41 shows the analyzed data for total current output and resistance. The total current continues to decrease, and the resistance continues to increase. This indicates that the system is still operating as planned and the moisture content of the concrete continues to decrease. The resistance calculated after 11 weeks of operation is almost 2.5 times larger than its original value.

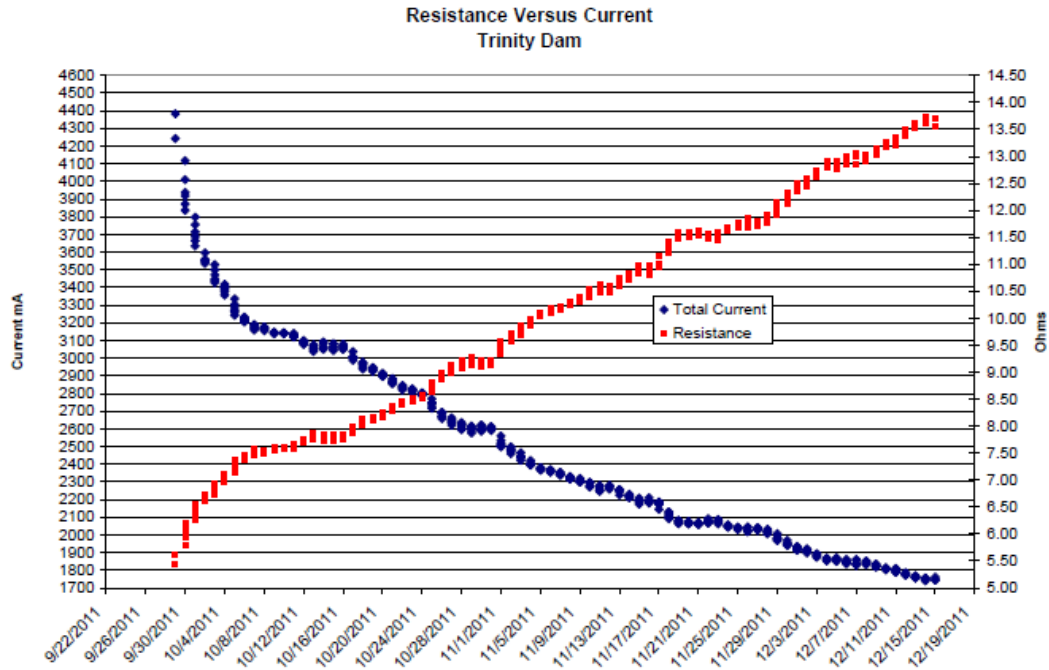


Figure 41. Data from the first 11 weeks of system operation showing the current and resistance over time. The data shows that the moisture content in the concrete is decreasing.

Fifteen Weeks of Operation

Data was collected after 15 weeks of operation to determine operation and the current and resistance trend for the system. Figure 42 shows the analyzed data for total current output and resistance. The total current continues to decrease, and the resistance continues to increase. This indicates that the system is still operating as planned and the moisture content of the concrete continues to decrease. The resistance calculated after 11 weeks of operation is almost 3 times larger than it was originally. Visual observations shown in figures 43a-43c indicate that the test section wall is dry, except where water is dripping down from the overflowing drip tray. The drying of the surface of the wall can be observed when comparing a location after 2 weeks (figure 38b) to the same location after 15 weeks (figure 43a). Note the buildup of calcite where water is dripping down at the end of the drip tray shown in figure 43c compared to the photo taken of the same area after 2 weeks (figure 38d). The drip tray is overflowing, and water is dripping down onto the wall and junction boxes in some locations. The streaks from the overflowing water on the drip tray, shown in figure 44, indicate that the water is rich in calcium.

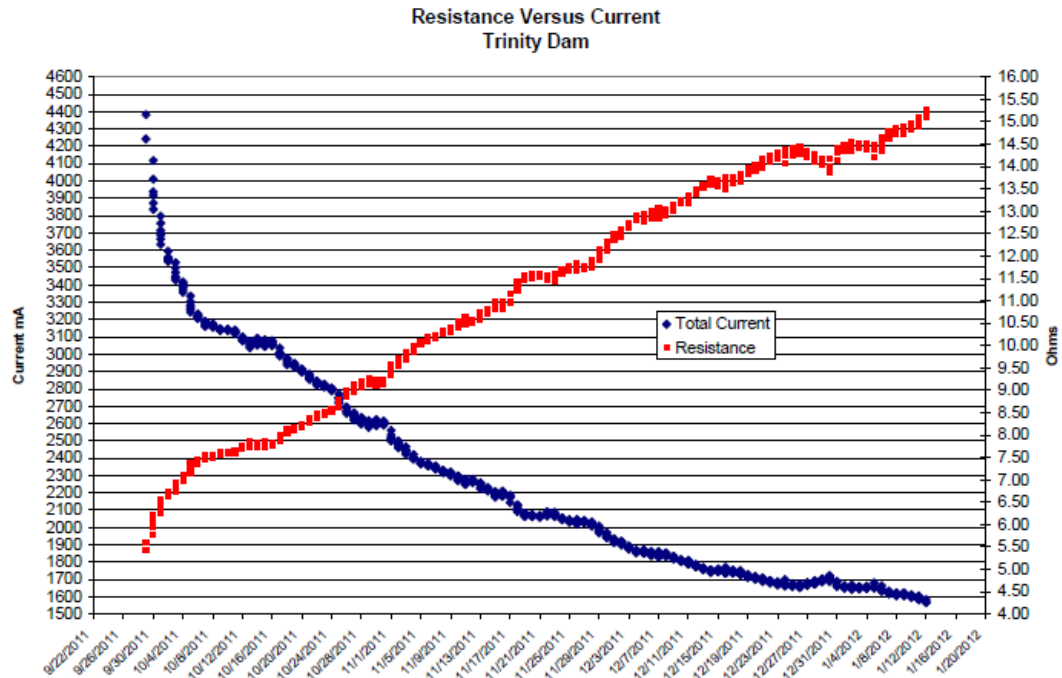


Figure 42. Data from the first 15 weeks of system operation showing the current and resistance over time. The data shows that the moisture content in the concrete is decreasing.

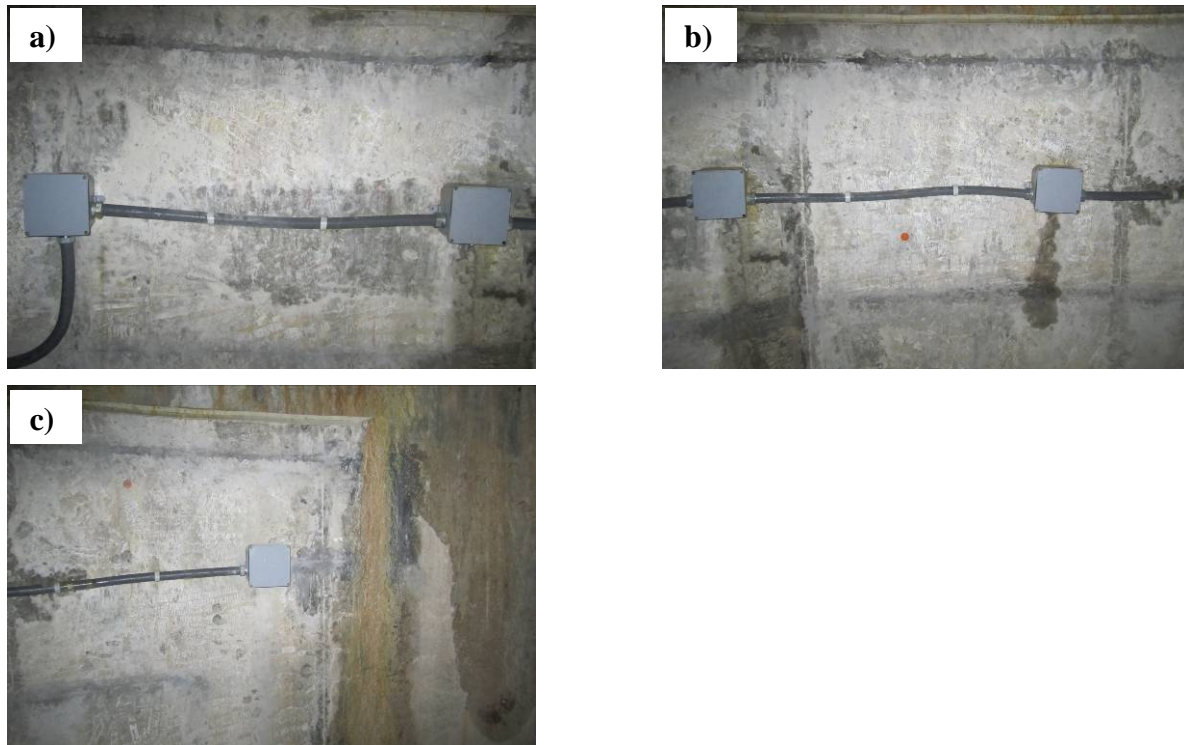


Figure 43. Concrete wall at location of installation after 15 weeks of operation. The wall was dry to sight and touch over most of the test section as shown in a), b), and c). The observed damp areas and drips resulted because the drip tray was filled up with water and unable to drain properly. Note the new buildup of calcite on the wall at the end of the drip tray in c).



Figure 44. Visible water overflowing the drip tray, allowing water to fall onto the wall and junction boxes below. Note the color of the streaks of water, indicating that the water is rich in calcium carbonate.

Determination of Decreasing Concrete Corrosivity

The resistance calculated from the power supply output using Ohm's law (resistance equals voltage divided by current), shown in Figure 40, was compared to the resistance calculated using equation 5 at various resistivities. The comparison is shown in figure 45 and indicates that the

resistance calculated from the power supply follows a similar trend to the linear calculation for resistance (R_{ra}). The trend indicates that the resistivity is increasing over the operation period, as shown in figure 46, after 11 weeks of operation. Resistivity is often used to help determine the possible corrosivity of the environment. Results indicate that the concrete has become a less corrosive environment for the rebar.

$$R_{ra} = \left(\frac{0.00521\rho}{NL} \right) \left(\ln \left(\frac{4L^2 + 4L\sqrt{S^2 + L^2}}{dS} \right) + \frac{S}{L} - \frac{\sqrt{S^2 + L^2}}{L} - 1 \right) \quad (5)$$

Where:

- N = number of anodes
- L = length of anode, feet
- D = diameter of anode, feet
- S = twice the depth of the anode, feet
- P = material resistivity

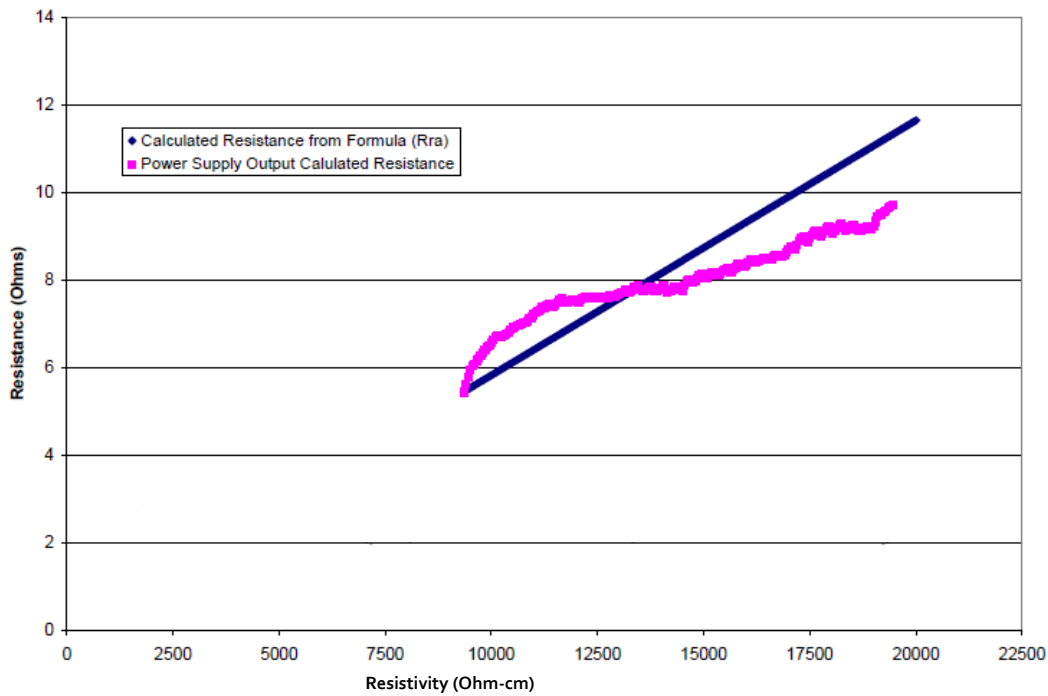


Figure 45. Calculated resistance using equation 5 versus the resistance calculated using the actual power supply outputs.

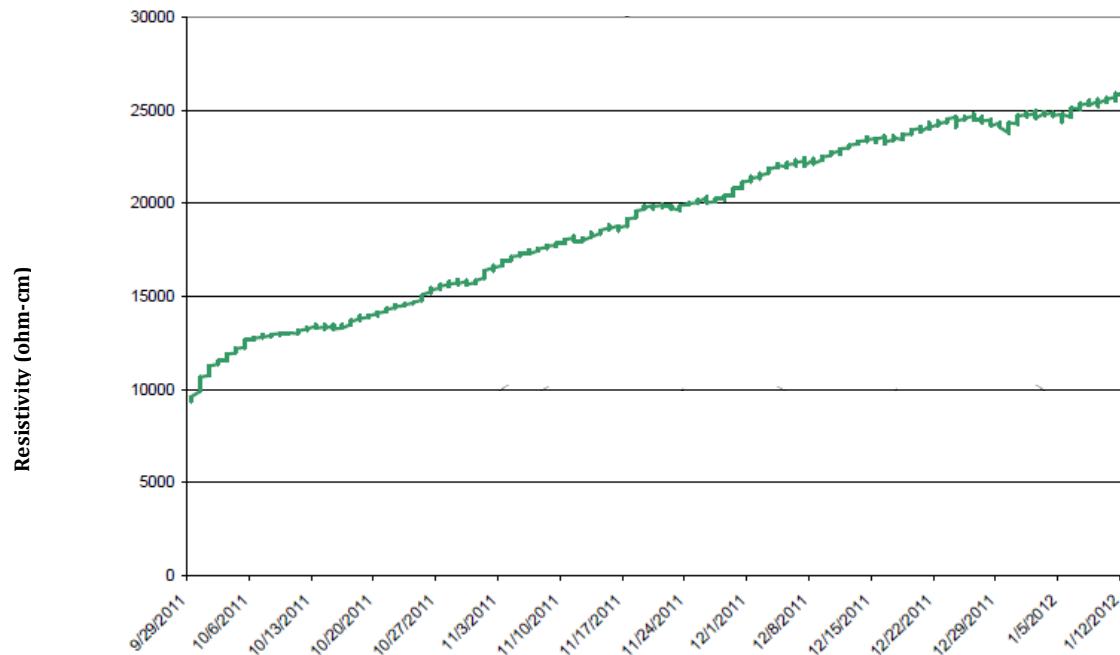


Figure 46. Calculated resistivity over the period of 15 weeks of operation.

Future Work

We recommend a phase three trial test location containing cracks and deeper calcite deposits. The proposed location for the next test section is the entire circumference of the bottom 10 feet of the shaft as shown figure 47. Cracks are desired in the next test section to show that after crack repair has been performed, the EOP system will work and improve long-term water tightness in the locations where cracks were grouted.

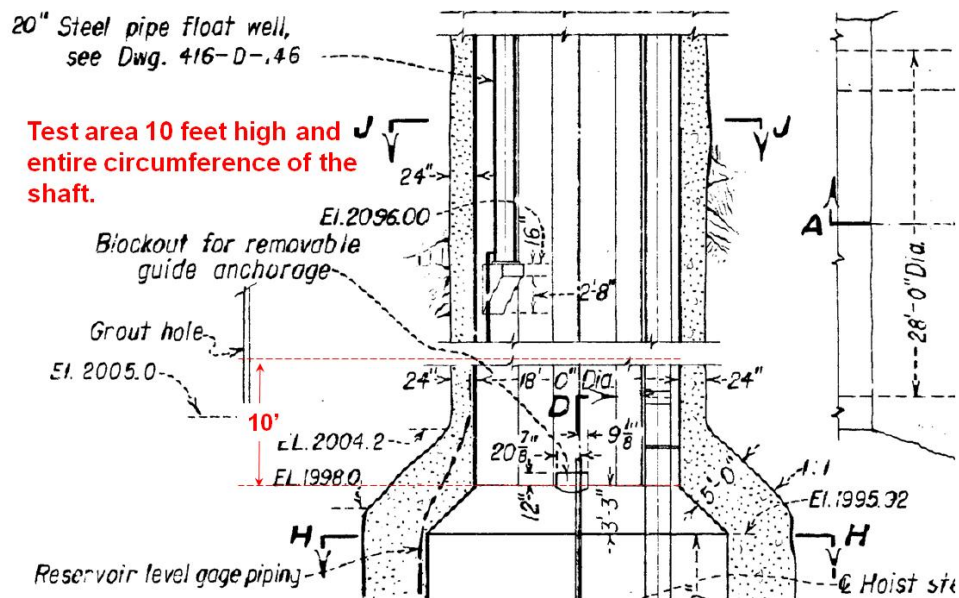


Figure 47. Proposed test section area for phase three of the EOP study.

Petrographic Analysis and Core Testing

Core samples should be taken from the lower chamber wall to analyze the concrete. Three 6-inch-diameter concrete samples should be collected and tested for composition and traditional core testing. The results will be used to mathematically evaluate the resistance against expected water content and, subsequently, estimate the humidity in the concrete. Figure 48 is an example graph showing the relationship for a different concrete composition and properties. The concrete testing will be performed by Materials Engineering Research Laboratory personnel.

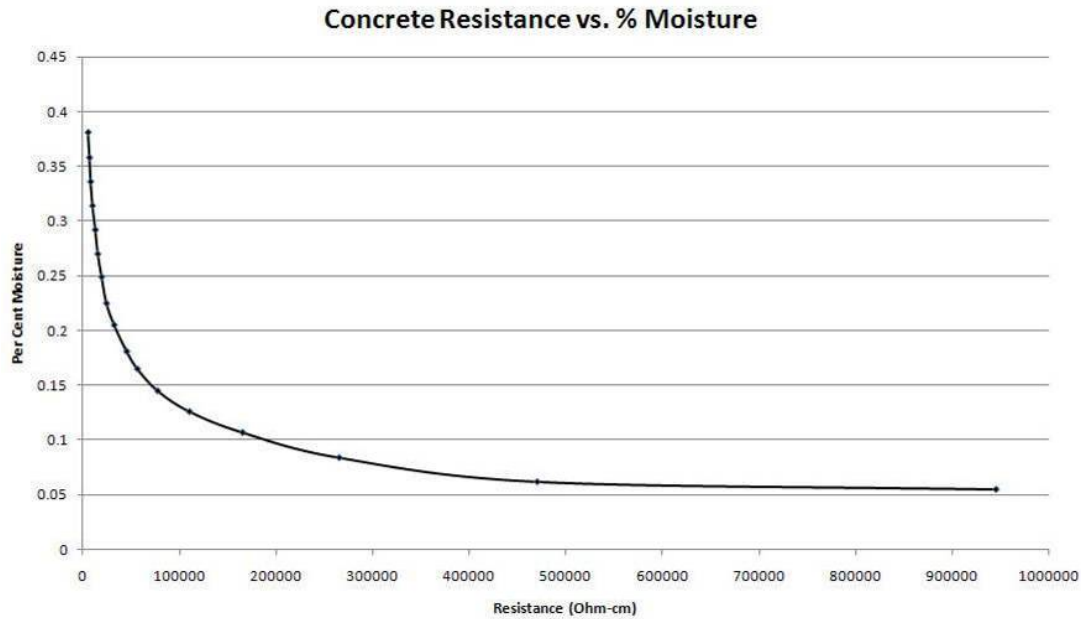


Figure 48. Example of relationship between concrete resistance and percent moisture in concrete [24].

Core testing to be performed should include the following:

- Water soluble chlorides – American Society for Testing of Materials (ASTM) C1218
- Acid soluble sulphate - ASTM C114
- Compressive strength - ASTM C42
- Air void analysis - ASTM C457
- Petrographic analysis - ASTM C856
- Specific Gravity

The petrographic analysis will include an identification of constituents, assessment of overall concrete quality, and investigation of potential causes of distress. In addition, features related to the original placement, such as approximate water/cement ratio, finish, consolidation, bleed, etc., are addressed where possible. Characterization of the occurrence and distribution of any secondary effects of water leaching, such as carbonation, aggregate reaction, sulfate attack, and their relationship to any visible distress, will be evaluated.

References

- [1] Noyce, P., Personal communication, General EOP system figures, Electro Tech CP, LLC, Accord, New York, 2011.
- [2] 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.
- [3] U.S. Army Corps of Engineers, "Electro-Osmotic Pulse (EOP) Technology - Product Sheet," Engineer Research and Development Center, Champaign, Illinois, 2005.
- [4] Kosmatka, S.H., and M.L. Wilson, *Design and Control of Concrete Mixes, EB001, The Guide to Applications, Methods, and Materials*, 15th edition, Portland Cement Association, Skokie, Illinois, 2011, pp. 48-52, 165-176.
- [5] Lea, F.M., *The Chemistry of Cement and Concrete*, 3rd edition, Chemical Publishing Company, Inc., New York, New York, 1971, pp. 177-249.
- [6] Taylor, W.H., *Concrete Technology and Practice*, 2nd edition, Angus & Robertson Ltd., Sydney, Australia, 1967, pp. 249-257.
- [7] Thomas, J., and H. Jennings, "The Science of Concrete," Northwestern University, Evanston, Illinois, 2008.
- [8] Powers, T.C., "The Nonevaporable Water Content of Hardened Portland Cement Paste - Its Significance for Concrete Research and Its Method of Determination," Research Department Bulletin RX029, Portland Cement Association, Skokie, Illinois, 1949.
- [9] Scherer, G.W., "Theory of Drying," *Journal of the American Ceramic Society*, Vol. 73, No. 1, 1990, pp. 3-14.
- [10] McMillan, F.R., and I. Lyse, "Some Permeability Studies of Concrete," *Journal of the American Concrete Institute, Proceedings*, Vol. 26, 1929, pp. 101-142.
- [11] Reuss, F.F., *Memoires de la Societe Imperiale des Naturalistes de Moscou*, Vol. 2, 1809, p. 327.
- [12] Glasstone, S., *Textbook of Physical Chemistry*, 2nd edition, Van Nostrand Company, Inc., Princeton, New Jersey, 1946.
- [13] Hamill, W.H., R.R. Williams, and C. MacKay, *Principles of Physical Chemistry*, 2nd edition, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1966.
- [14] Tikhomolova, K.P., *Electro-Osmosis*, Ellis Horwood Ltd., Chichester, West Sussex, England, 1993.

- [15] Smith, B.M., “Moisture Problems in Historic Masonry Walls,” National Park Service, U.S. Department of the Interior, 1984.
- [16] Hock, V.F., M. McInerney, and P. Malone, “Decision Paper - The Applicability of Electro-Osmotic Techniques for Preventing Water Seepage Through Porous Building Materials,” U.S. Army Corps of Engineers – Engineer Research and Development Center, 1999.
- [17] Hock, V.F., O.S. Marshall, M.K. McInerney, S. Morefield, P. Malone, C. Weiss, A.H. Kleinschmidt, K. Holtz, D. Goran, K. Richardson, and R. Condon, “Electro-Osmotic Pulse Technology for Control of Water Seepage in Various Civil Works Structures,” ERDC TR-06-9, U.S. Army Corps of Engineers, Engineer Research and Development Center, 2006.
- [18] McInerney, M.K., S. Morefield, S. Cooper, P. Malone, C. Weiss, M. Brady, J.P. Bushman, J. Taylor, and V. Hock, “Electro-Osmotic Pulse (EOP) Technology for Control of Water Seepage in Concrete Structures,” ERDC/CERL TR-02-21, U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, 2002.
- [19] Morefield, S., V. Hock, M. McInerney, O. Marshall, C. Marsh, and S. Cooper, “Control of Water Migration Through Concrete Using Electro-Osmosis,” Tri-Service Corrosion Conference, 2005.
- [20] 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.
- [21] 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.
- [22] 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.
- [23] Hock, V.F., M.K. McInerney, and E. Kirstein, “Demonstration of Electro-Osmotic Pulse Technology for Groundwater Intrusion Control in Concrete Structures,” Tri-Service Corrosion Conference, 1997.
- [24] Marshall, O.S., Personal communication, General EOP system figures and graphs, U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, Illinois, 2010-2011.

Biography



Daryl A. Little is a Materials Engineer on a team of corrosion experts at the Bureau of Reclamation's Materials Engineering and Research Laboratory. He has been with the bureau for over 7 years and studied and worked in corrosion for 16 years. He received his PhD in materials science and engineering from the University of Virginia and has NACE International Cathodic Protection Technologist certification and is a member of a number of NACE International committees.



Kurt F. von Fay is a Civil Engineer with the Bureau of Reclamation's Materials Engineering and Research Laboratory with over 20 years' experience in concrete materials, mixture proportioning investigations, maintenance and repair, and chemical grouting. He graduated from the University of Colorado, and holds an MBA from the University of Denver. He is Reclamations Concrete Repair Expert and has worked in research, development, and field evaluation of repair technology, and developed repair plans and provided technical evaluations of numerous projects.