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Control of Water Migration Through Concrete Using Electro-osmosis

Sean Morefield, Vincent Hock, Michael McInerney,
Orange Marshall, Charlie Marsh, Sondra Cooper

U.S Army Engineer Research and Development Center
Construction Engineering Research Laboratory
P.O. Box 9005
Champaign, IL, 61826-9005

ABSTRACT

Electro-osmosis, in the form of Electro-osmotic Pulses (EOP) can be used as a means to prevent water intrusion in below grade spaces. This technique has been evaluated in a test basement, and at implemented at several field locations. The testing within the scope of this work looked at the effectiveness of EOP with two different backfills, and in conjunction with conventional repair techniques. EOP was found to control moisture in a concrete wall effectively with both a clay and a gravel backfill, with the clay performing slightly better than the gravel. When the EOP configuration was changed from four cathodes surrounding the test basement to two cathodes, no significant change in EOP effectiveness was observed.

Keywords: Electro-osmosis, Moisture Control, waterproofing, concrete

INTRODUCTION

Moisture intrusion in below grade structures that causes “damp basements” is a common and costly maintenance problem. In older buildings severe damp basement problems can cause serious damage. Moisture can ruin expensive equipment commonly located in basement space, increase maintenance requirements (frequent repainting or cleaning to combat mold growth), and make affected areas uninhabitable or even unusable (e.g., by poor air quality).

Traditional methods to control moisture in below grade structures involve negative side and/or positive side waterproofing methods. Positive side methods refer to waterproofing applied to the outside (wet) face of a buildings substructure. Negative side methods are those applied to the inside (dry) face of a buildings substructure. Both positive and negative side traditional methods involve the application of coatings and film barriers. Some common materials used in positive side waterproofing include bentonite clay, modified bitumen sheets, liquid applied membranes (LAMs), built up bituminous membranes, prefabricated elastomeric sheets, prefabricated thermoplastic sheets, and cementitious or crystalline coatings. Some common materials used in negative side waterproofing include crystalline coatings, cementitious coatings with metallic oxides, and cementitious coatings with various densifying additives.

Whether used as part of initial construction or as a retrofit solution, traditional waterproofing methods generally have high installation costs and a short lifespan. Conventional remedial action for a military building requires the use of concrete sealants or tiling at a typical total installation cost of about $315/linear foot. Failure is generally due to designer error, negligent construction practices, and defective materials (Henshell 2000[1]). Even successful negative side repairs can fail prematurely because the presence of water near joints and seals tends to shorten their lifespan. Additionally, many urban areas have restrictions that limit or prevent the application of certain types of coatings that present an environmental hazard due to their constituent volatile chemicals. Sometimes, where buildings experience very high seepage rates, sealants may not work at all. In such cases, excavation and backfill, drainage, retiling, woodshoring, and dampproofing may be required, at significant additional cost.

Present methods to protect porous structures from moisture intrusion involve creating a barrier, typically with coatings and membranes and drain tiles to remove water from the vicinity. These conventional repair methods are labor intensive, require substantial modification to existing structures, and can have a relatively short lifetime.

A commercial system that uses electro-osmotic pulse (EOP) technology within concrete structures offers an alternative to the trench and drain approach that can mitigate water related problems from the interior (negative side) of affected areas and eliminate costs of excavation. Application of EOP technology can also eliminate corrosion damage to mechanical equipment and improve indoor air quality by con trolling the relative humidity (RH) on the interior wall and floor surface at a level below 55 percent, preventing mold, bacteria growth, and mineral deposits (efflorescence), eliminating rising damp in walls, and improving indoor air quality.

For applications in concrete, EOP technology has significantly outperformed conventional technology. Previous work (Hock et al. 1998[2]) has shown that EOP technology can eliminate groundwater intrusion in concrete structures and circumvent the need for conventional negative side waterproofing methods (excavation, tiling, and coatings or membranes) applied to below grade concrete structures.

This study was undertaken to determine the conditions in which EOP technology works best, specifically, by examining the factors that affect the use of EOP technology to control water seepage (on both new construction and renovation applications) through nonhomogeneous, porous materials. This work extended previous research by performing laboratory and field tests to document the characteristics of the materials commonly used in EOP installations, and to optimize the successful application of EOP technology.

Osmosis Overview

Electro Osmotic Pulse (EOP) technology is a new application based on the old concept of electro-osmosis. It uses the forced movement of an aqueous solution containing a net electric charge due to an applied external electric field. EOP technology dramatically and effectively extends the basic concept of electro-osmosis to below grade concrete structures and soil through the novel application of an asymmetric dual polarity pulse and innovative electrode materials.

In 1809, F.F. Reuss originally described electro-osmosis in an experiment that showed that water could be forced to flow through a clay-water system when an external electric field was applied to the soil (Reuss 1809[3]). Research has since shown that flow is initiated by the movement of cations (positively charged ions) present in the pore fluid of clay or similar porous medium such as concrete; the water surrounding the cations moves with them. Electro-osmosis can be used to arrest or cause flow of water as well as the ions in it. Electro-osmosis has been used in civil engineering to dewater dredgings and other high water content waste solids, consolidate clays, strengthen soft sensitive clays, and increase the capacity of pile foundations. It has also received significant attention in the past 5 years as a method to remove hazardous contaminants from groundwater or to arrest water flow.

The basic equation for movement of the pore solution in a capillary porous system, such as clay or concrete, contains several forces (Tikhomolova 1993[4]):

$$
\begin{aligned}
\rho \frac{d\bar{v}}{dt} = \bar{g}\rho & \qquad \text{1a} \\
- \operatorname{grad} p & \qquad \text{1b} \\
+ \eta \nabla^2 \bar{v}^0 & \qquad \text{1c} \qquad\qquad (1) \\
+ \left(\frac{\rho^+ z^+ e_0}{m^+} + \frac{\rho^- z^- e_0}{m^-} \right) \vec{E} & \qquad \text{1d} \\
- \frac{kT}{m^+} \operatorname{grad} \rho^+ - \frac{kT}{m^-} \operatorname{grad} \rho^- & \qquad \text{1e}
\end{aligned}
$$

$\rho =$ density of the solution

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

$\vec{v} =$ velocity of the solution (center of mass)

$\vec{v}^{\,0} =$ velocity of the solvent

$\bar{g} =$ acceleration of gravity

$p =$ pressure

where: $\eta =$ shear viscosity coefficient

$z^{\pm} =$ 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

$k =$ Boltzman constant

$T =$ temperature

The terms on the right side of the equation are associated with the following forces: 1a is the component of force due to gravity; 1b designates the force component due pressure, 1c is the component due to viscosity, 1d is the force component due to electro-osmosis, and 1e represents the component due to temperature.

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.
For electro-osmosis to be effective, capillary pores must be present in the medium, the medium must have fixed surface charges (clays, concrete, and related materials are common media), the medium should be saturated, and the fluid must be a dilute electrolyte. The velocity equation of the pore solution is:

$$V_e = \frac{\varepsilon \xi E}{4\pi \, v l} \qquad (2)$$

where:

Ve = flow velocity of solution (m/second)

ε = dielectric constant of water (Farads/meter)
ξ = zeta potential
E = potential applied across material (Volts)
ν = viscosity of liquid (centipoises)
l = distance between electrodes (meters).

Equation 2 can also be expressed in terms of the current density:

$$V_e = \frac{\varepsilon \xi j}{4\pi \nu \sigma} \qquad (3)$$

where:
Ve = flow velocity of solution (m/second)
ε = dielectric constant of water (Farads/m)
ξ = zeta potential (V)
ν = viscosity of liquid (centipoises)
j = current density (Amperes/m2)
σ = electrical conductivity of material (Siemens/m)

The water and ions form an electrolyte where the positive ions tend to be solvated and the negative ones unsolvated. Thus, as the positive ions move through the pores, the water molecules move as well. So the water movement in practice is heavily dependent on ion concentration, type of material, and magnitude of applied electric field. Of the independent variables, E can be controlled to redirect the movement of the solution.

EXPERIMENTAL PROCEDURE

In order to examine the effectiveness of EOP under typical construction conditions, a field test was conducted. A basement test cell was constructed of poured concrete, approximately 8 ft square and 6 ft below grade. Figures 1 and 2 show the plan and elevation views of the test basement. Moisture conditions were monitored as different water seepage control techniques were applied. The test was conducted using a basement constructed at U.S. Army Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL) in Champaign, IL. The testing was conducted over a 9-month period that encompassed seasonal variations in ambient air temperature, humidity, rainfall, groundwater table, and soil temperature.

Sensors monitored the local water table, ambient room temperature, and relative humidity. Probes installed in the walls and floors at various depths were used to measure concrete moisture via electrical conductance. Electrical power used by the EOP and dehumidification systems was also recorded. The EOP system's ability to remove moisture from the interior of the walls and floor was recorded and later compared with the performance of other moisture control technologies. A hand held electrical conductance[1] instrument was used to quantify moisture conditions in the concrete.

Throughout the test, water was added through a drain tile installed around the foundation of the structure. Five hundred gallons of water was added to the sump each day, Monday through Friday. The height of the water local water table around the basement was observed with a differential pressure cell in a monitoring well.

Moisture control methods were applied in the following sequence:

- As built, no waterproofing

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[1] Protimeter Surveymaster is a brand name, part of GE Industrial Systems

- Crack repair with hydraulic cement
- Dehumidification
- EOP system turned on with initial pulse
- EOP on, modified cathode configuration
- EOP with modified pulse

Test Basement Construction

The basement was initially constructed using common construction materials and practices, while creating conditions that would represent a failed membrane or unsealed cold joint. No waterproofing was applied to the interior or exterior of the structure, on either the walls or floor. Two of the walls were backfilled with gravel (South and West), while the remaining North and East walls were backfilled with clay. The local water level around the basement was raised by periodically dumping water around the footing through a pipe in the summer. This 18-in. pipe was installed during the initial construction to direct water to the footer of the basement. A 4-inch PVC tube was installed on the outside the test basement, by the southwest corner to serve as a monitoring well. The floor was constructed as a poured concrete slab, which rested on the footing.

Data Collection

The test basement internal air temperature, internal relative humidity, and EOP current (when operational) were monitored through an automated datalogger that recorded this data every half hour. A differential pressure sensor, also connected to the datalogger, monitored the local water table level in a monitoring well located 3 ft to the southwest of the basement.

The moisture content of the East and West walls and floor were measured manually at 4 locations at three depths on a daily basis. These walls were chosen because each had a different backfill. The West wall was backfilled with gravel, while the East wall was backfilled with clay(2). A hand held electrical conductance meter was used to obtain moisture content at the surface and at four locations in the floor and wall, with three depths observed at each point. The moisture content of the walls and floor were measured using permanently installed electrical conductance probes. In the East and West walls, two sets of probes were fixed at 1.5 ft above the floor, each located one-third of the wall width. Each probe was installed to measure the moisture content at a particular depth in the wall. Each set of three probes in the wall measured the moisture content at 2-, 4-, and 7-in. deep. Each set of probes in the floor measured the moisture content at 2-, 4-, and 5-in. deep. Figure 3 shows a map of these sensors. Locations A and B represent data from the clay backfill, while C and D represent gravel backfill performance.

The installed electrical conductance pins were constructed of brass rods, 1/8-in. in diameter, covered with heat shrink tubing for insulation. The ends of these probes were exposed for good electrical conductivity. A pair of these probes was installed 50 mm apart in holes drilled into the wall and floor. The probes were then connected to a hand held electrical conductance meter that displayed the electrical conductance. A researcher recorded the moisture content from each depth and location, in addition to the information taken by the datalogger. This was done on a daily basis throughout the course of the test.

Because the conductance meter is an instrument that determines the moisture condition of building materials by measuring current, any electrical fields operating in the vicinity and of the same order of magnitude as the meter uses (or greater) will significantly affect the readings. Because of this, care was taken to suspend the EOP pulse during daily readings, then restore it when finished.

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[2] fine-silty, mixed, mesic, Typic Argiudoll

The test was started with the basement in an as built state, with no waterproofing applied. At the beginning of the test active water intrusion was observed at the wall to floor junction of the basement in its as constructed state. Since the structure was initially built with no external coating and no external water drainage system, active intrusion was inevitable. In addition to the other data collected automatically and manually, the height of standing water was measured at the basement center and recorded before the water was removed.

The first priority was to stop the active water intrusion. Crack repair was the next logical technology to apply because neither EOP nor dehumidification alone is designed to address water actively leaking into a structure. The concrete basement wall-to-floor joint was repaired. First, a 45 degree angle cut was made around the entire floor perimeter. Then a quick setting hydraulic cement was applied directly to the cut area. The cement was then smoothed out and allowed to dry. This repair stopped the active water intrusion. Within 5 days, the basement was free of all standing water. (Figure 4)

Once the basement was free of standing water, a 625 W dehumidifier was installed in the concrete basement. The unit was designed to remove 40 pints of water every 24 hours from air with a temperature of 80 ^{o}F and 60 percent air relative humidity. The dehumidifier was operated continuously on the driest setting. The unit would operate for a period of about 12 hours before the water reservoir would completely fill (4.5 L), which would automatically shut the unit off. The following day, the technician would empty the unit before restarting it.

At the end of the dehumidification period, an EOP system was installed. First, a ceramic covered wire anode was installed at the wall-to-floor joint. The installation started by power chiseling out a small recess at the wall to floor joint. Next, small amounts of hydraulic cement were used to set the ceramic anode wire in place around the basement perimeter. More hydraulic cement was then applied and smoothed to ensure the entire anode was wetted and covered with cement. Figure 5 shows details of ceramic coated anode wire installation at wall to floor joint in the basement.

Four cathodes were installed. Ground rods (8-ft long steel rods, copper clad, with a diameter of ½-in.) were driven into the ground and connected to the EOP circuit through junction boxes that protected the wire connections. The cathodes were installed approximately 4-feet from each basement wall. Figure 6 shows the relative locations of the cathodes to the basement.

The default waveform (Figure 7) as programmed in the Drytronic EOP power supply was applied during the first EOP test period, for 22 days.

After the initial period of application of EOP, the cathode was switched from all four cathodes to only using the north and west cathodes. This was done to observe the effect of modifying the electric gradient on wall and floor moisture content. Figure 6 shows the modified cathode configuration used for this period.

The EOP power supply applied pulse was modified to the waveform shown in Figure 7. The period was changed to 35 seconds compared to 40 seconds. This pulse was applied for the final 68 days of the test.

RESULTS

The concrete basement as constructed was insufficient to create a moisture free environment. Significant water intrusion at the wall to floor joint was observed at such a magnitude that neither dehumidification nor EOP alone would be capable of creating a habitable space. The water intrusion was severe enough that electrical monitoring equipment was in danger of water damage.

Within 5 days of the joint repair using Waterstop, the active intrusion rate dropped to zero, although the moisture content of the concrete remained as high as before the repair. (Figure 4) While the crack repair did stop the gross intrusion, the concrete retained its capacity to wick moisture from the outside, although the moisture content of the walls and floor remained constant as measured by the conductance measurements. Slight weeping at the wall to floor juncture was also present despite this repair.

The relative humidity of the air below grade was rapidly lowered and maintained at approximately 50 percent during dehumidification. Given the small scale of the basement and the large capacity of the dehumidifier, this was expected. The dehumidifier did not significantly affect the moisture content of the walls at the 2, 4, and 7-in. depths. The moisture content at all levels in the floor also remained constant. The dehumidification also did not address the periodic weeping observed at the wall to floor joint.

After the EOP system was turned on, no further weeping was observed. The general hypothesis for the self regulating behavior of the EOP system is as follows: as the concrete moisture content increases, its conductivity increases as well. This rise in conductivity allows more current to flow, which is the mechanism that osmotically moves water out of the concrete. Lowering the concrete water content causes its resistance to go up, which in turn lowers the system current completing the feedback cycle.

There was some positive correlation observed to support this. The EOP current does track with the moisture content. This relationship is more pronounced at the 7-in. depth in the wall, although some effect is visible at the 4-in. depth as well. The graph of EOP current and wall moisture content plotted with time (Figure 9) shows the positive correlation between EOP current and moisture content.

The EOP system was able to maintain the moisture content at a lower level than dehumidification. The effect was small but measurable, most notably in the wall measurements at the 4-in. depths as measured by electrical conductance. The 2- and 4-in. wall depths in general lowered more than the 7-in. depth locations.

The EOP power supply applied pulse was modified to the waveform shown in Figure 7. The period was changed to 35 seconds compared to 40 seconds. This pulse was applied for the final 68 days of the test, without observable affect on the moisture content of the walls or floor at any depth.

Backfill Performance:

The North and East Walls were surrounded by clay. Figures 10, 11 and 12 show the relative moisture content at 2-, 4-, and 7- inch wall depths for the EOP application period. In general, the 7-in. locations for the clay backfilled wall remained saturated at about 37 percent. The moisture content at the 2-in. depth for the clay backfill wall A location was about 7 percent and the 4-in. depth was about 30 percent on average for all the EOP trials. The moisture content at the 2- and 4-in. depths for the B location was 10 and 7 percent, respectively, on average for the EOP trials.

The clay backfilled location A was immediately adjacent to the fill tube. The daily 500 gal local addition of water affected this location the greatest. In spite of this effect on moisture content at the 4-in. level at location A, the moisture content at the 2-in. level remained low and consistent with the other 2-in. depths during the period of EOP application. Also, the surface moisture content at this corner tracked very closely for this period of application as well. This is a surprisingly good result, considering the daily deluge that corner of the basement was subject to.

The West and South walls were surrounded by gravel. In general, the 7-in. locations for both locations C and D remained saturated at about 37 percent. The moisture content at the 2- and 4-in. depths for the location C was about 5 and 14 percent respectively for the EOP trials. The moisture content at the 2- and 4-in. depths for location D was about 7 and 12 percent, respectively, on average for the EOP trials.

The moisture content observed in all four wall locations was consistently lower than all four floor locations. This applied equally to all phases of testing. As this difference in moisture content was independent of the applied treatment, it was likely due to an existing configurational cause. The most obvious explanation for this is that the floor is at a lower elevation, and completely supported by saturated sand, whereas the wall moisture measurements were typically well above the water table measured locally.

The clay and gravel backfills performed differently during the EOP application. Since the laboratory water transport rate using EOP was very large in clay compared to sand, a corresponding difference in moisture content was expected at different locations with different backfill types.

Despite the variation within the moisture content data, a small quantitative difference in performance in the walls with backfill variation was discerned. The moisture content at the 4-inch depth was somewhat lower for the clay backfilled wall compared to the gravel by about 5%. The 7-inch depth wall moisture content was approximately the same for both backfills. This is likely another boundary effect, caused by constant, deliberate external wetting from the daily water additions.

The clay backfill functioned as a slightly more effective backfill compared to the gravel with EOP applied. Differences between each of the four wall locations were observed, which did correlate to the type of backfill closest to each. As expected, the clay backfilled wall did have a slightly lower average moisture content than either of the two gravel backfilled wall locations, C and D, during the period of EOP application. This is consistent with the lab findings of higher steady state transport rates found in clays compared to sand (which has similar osmotic characteristics to gravel.)

Two distinct cathode configurations were used in different periods of the EOP trial. The first used four cathode ground rods, each at a cardinal direction to the basement. This allowed each wall to receive approximately the same current density. The second cathode configuration used only the ground rods on the North and East walls.

A corresponding change was expected in moisture content of the walls when switching cathode configurations. The walls with active cathodes nearby should have been dryer than walls without an active cathode. However, no discernable change in moisture content (relative to the instrument variance) was observed. As soil tends to have a relatively high resistance, it is likely that far field effects, as seen in cathodic protection, created a nearly uniform distribution of current.

CONCLUSIONS

EOP is capable of lowering the moisture content of the walls and floor of a concrete test basement. Modifying the pulse period from 35 seconds to 40 seconds did not have a significant effect on the moisture content of the walls or floor. Modifying the cathode configuration did not significantly affect moisture content at any depth. Both the gravel and clay backfills performed well with EOP, while clay slightly outperformed the gravel backfill.

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FIGURES

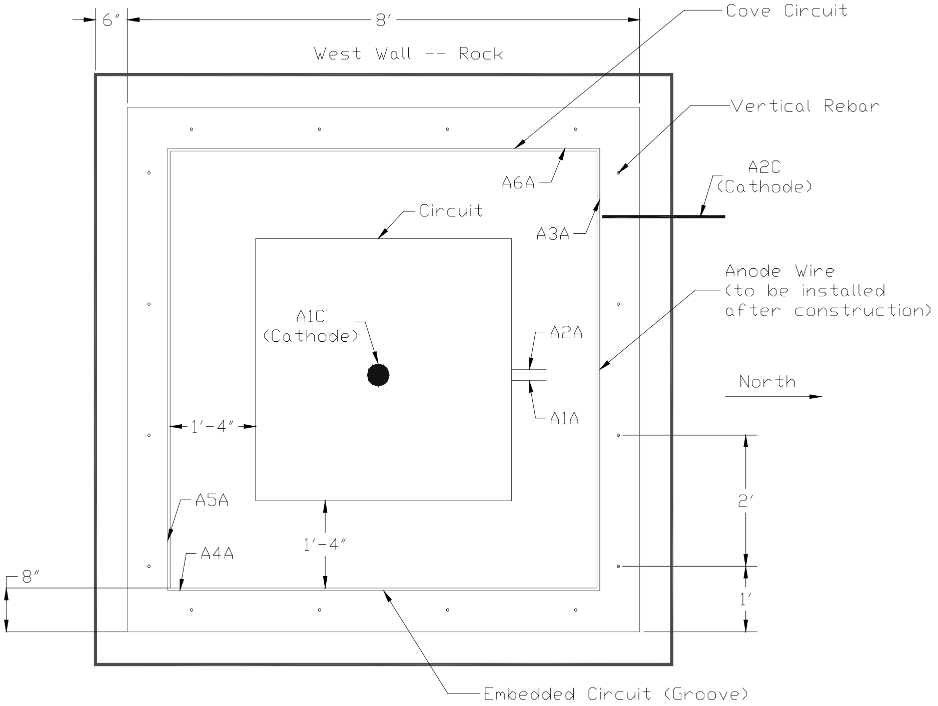

Figure 1. Floor Plan of Test Basement, showing anode circuit installed in the floor

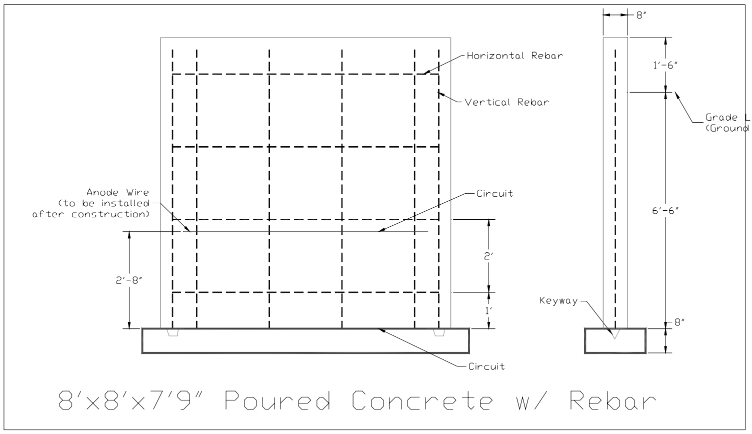

Figure 2. Elevation view of poured concrete test basement

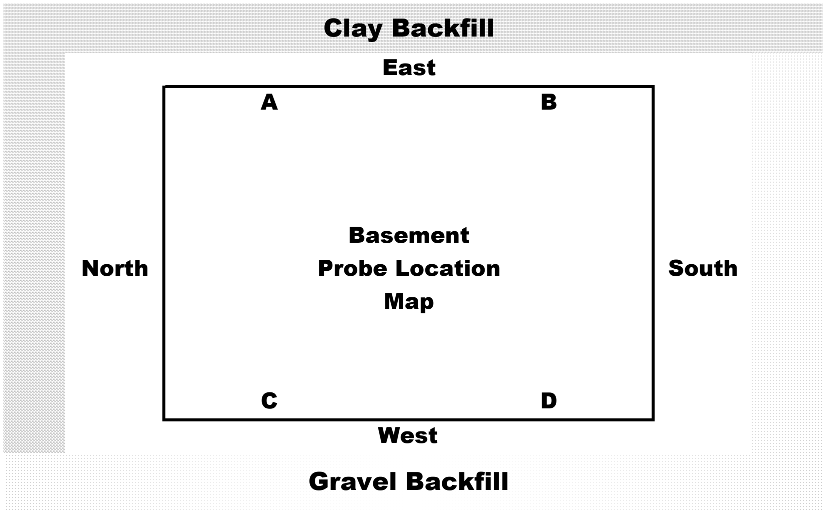

Figure 3. Moisture Sensor Map

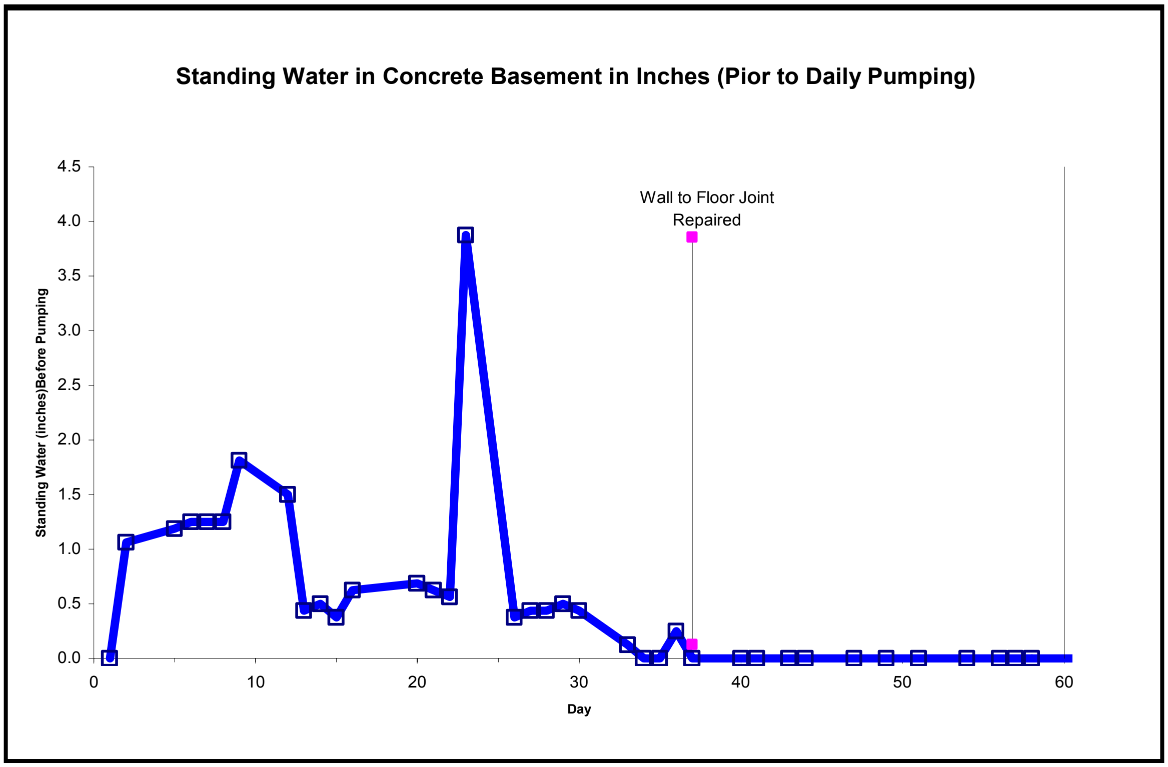

Figure 4. Plot of daily standing water on test basement floor. Basement was pumped down after reading.

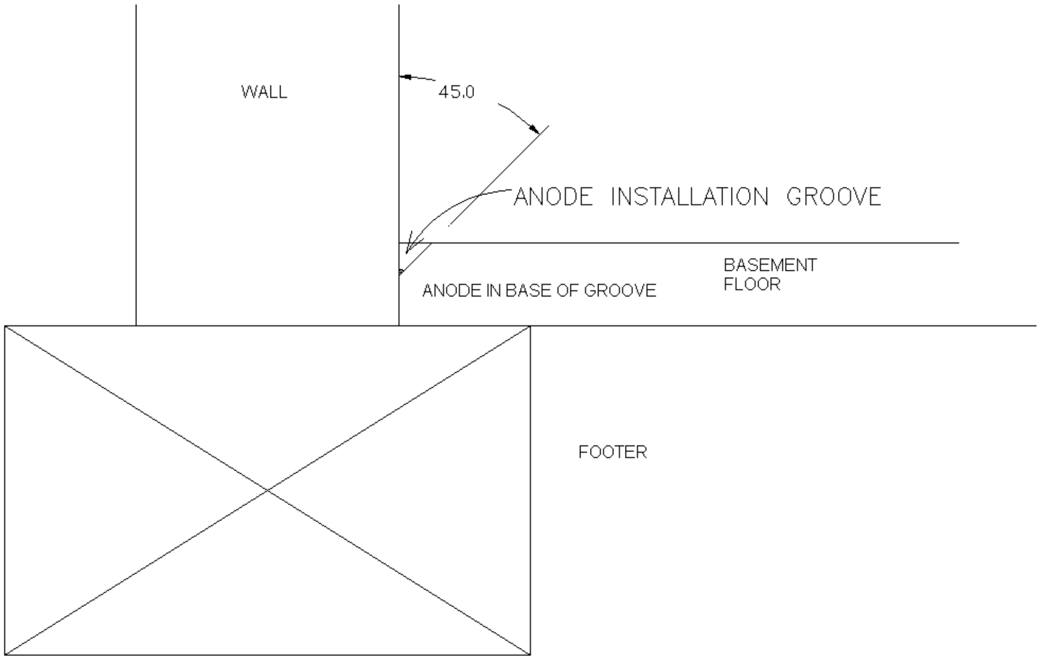

Figure 5. Anode installation detail at wall to floor joint

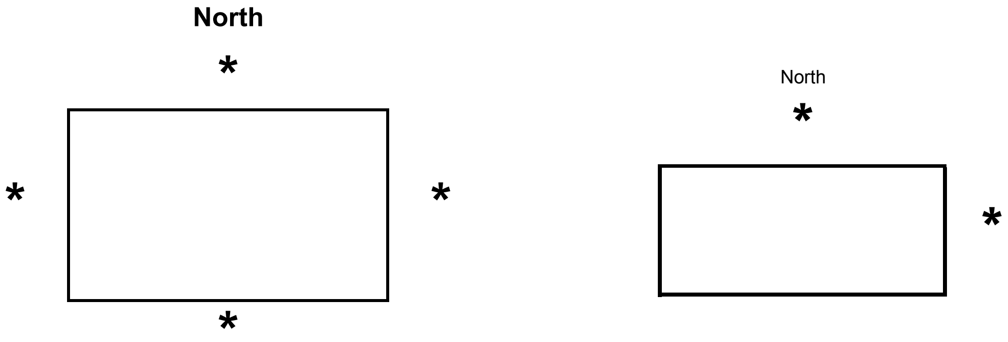

Figure 6. Location of the 4 cathodes around the basement used in the first trial

Location of the 2 cathodes used in the second period

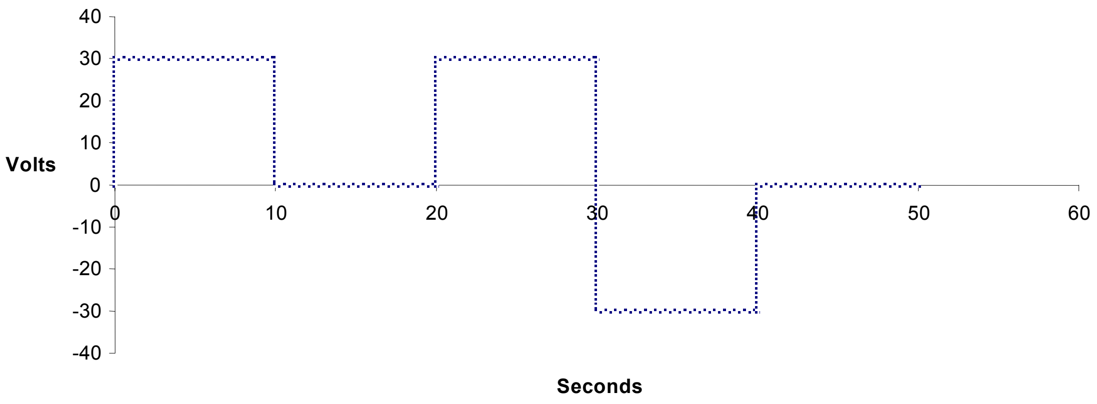

Figure 7. First EOP waveform (40 second periodicity)

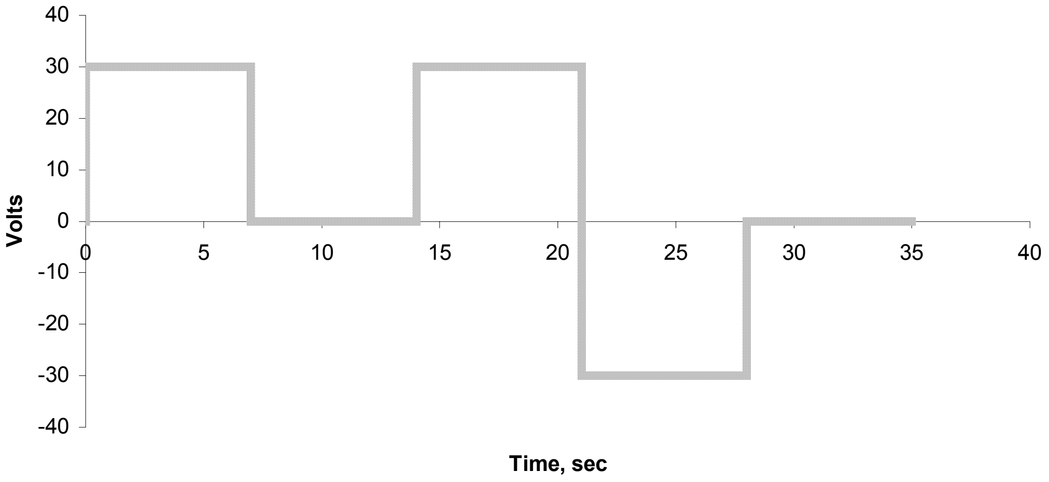

Figure 8. EOP reprogrammed signal with 35 second period

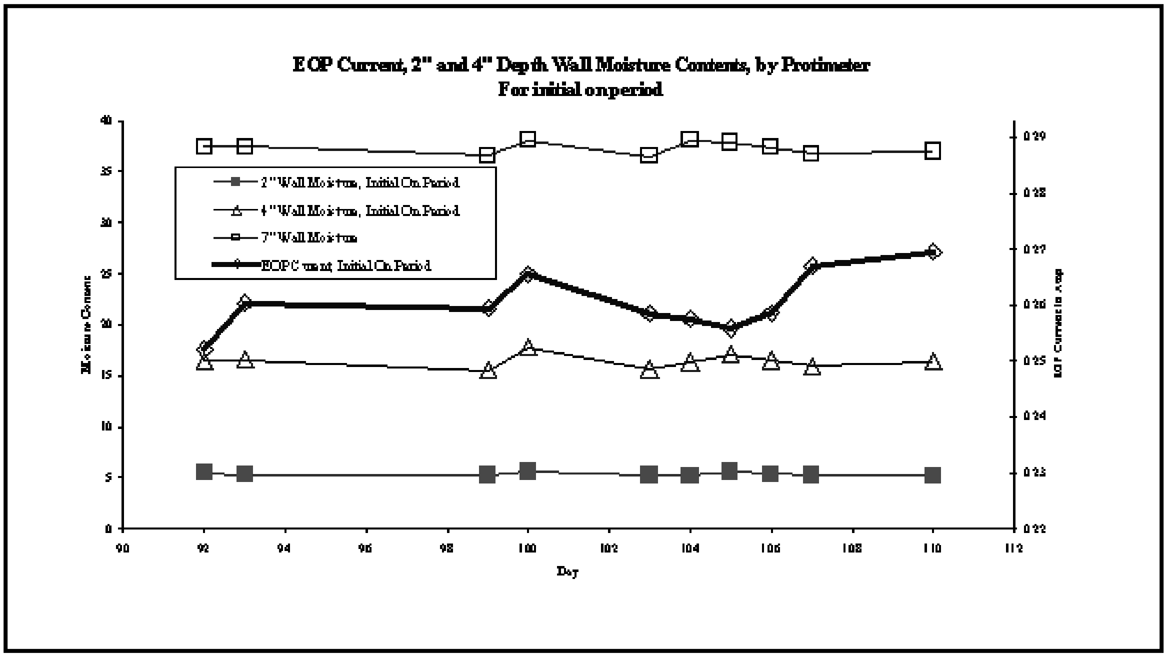

Figure 9. EOP current, 2-, 4-, and 7-in. depth wall moisture content for initial time period.

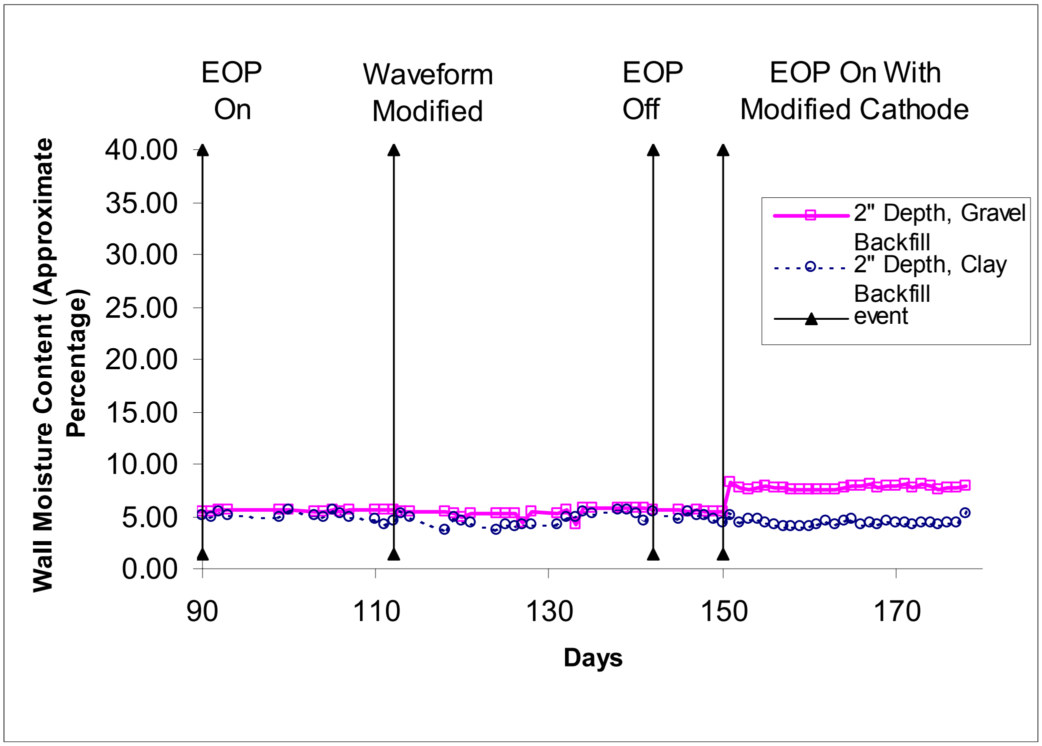

Figure 10. Moisture Content at 2-inch depth. Clay backfill v. Gravel Backfill

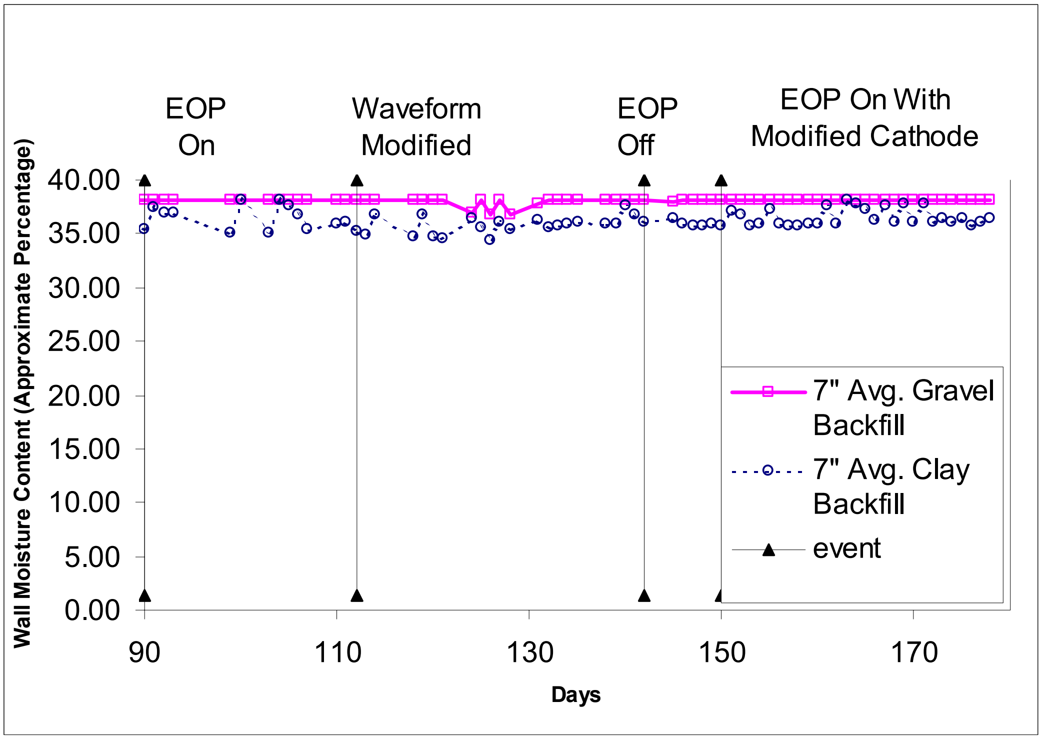

Figure 11. Moisture Content at 4-inch depth. Clay Backfill v. Gravel Backfill

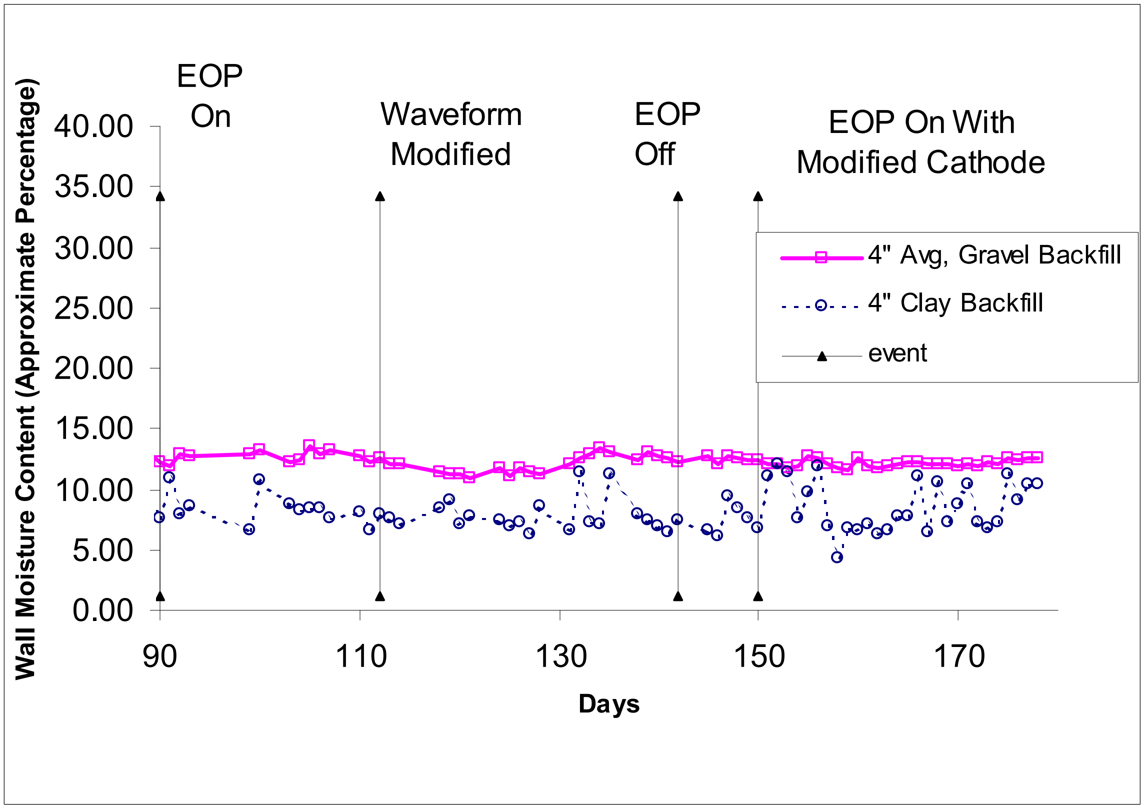

Figure 12. Moisture Content at 7-inch depth. Clay backfill v. Gravel Backfill