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NATURAL RESOURCES
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INNOVATIVE TECHNOLOGY DEMONSTRATION

PILOT STUDY

Enhanced Stabilization of Dikes and Levees Using Advanced ElectroKinetic Technology

December 2006

Reported By

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EXECUTIVE SUMMARY

From late July through mid-October, 2006, a study was conducted on the use of Direct Current (DC) for the dewatering and consolidation of a dike constructed at the Erie Pier Confined Disposal Facility (CDF) in Duluth MN. The study was performed by Electro-Petroleum, Inc (EPI) of Wayne, PA; electrochemical processes, llc (ecp) of Stuttgart, Germany; and the University of Minnesota Duluth's Natural Resources Research Institute (NRRI); with major assistance from Harrison Marine Electronics, Duluth; and with oversight by the U.S. Army Corps of Engineer's (USACE) Detroit District, and Waterways Experiment Station (WES), Engineer Research and Development Center (ERDC), Vicksburg, MS. EPI, ecp, NRRI, and Harrison Marine Electronics had previously demonstrated that fine silt could be stabilized and water could be removed from fine silt using Direct Current[1]. EPI had also used Direct Current to remove water from mud pits generated by oil well drilling operations in the oil patch, aiding in the solidification of the mud for final disposal. Based on these and other previous experiences, Dr. Falk Doering of ecp proposed that a leaking dike could be stabilized and made less permeable by way of electrokinetic dewatering and electrochemically plugging soil pores with clays stabilized with aluminum. The aluminum could be introduced through the corrosion of anodes inserted into the dike.

In total, four electrode (anode and cathode) configurations/combinations were tested on the dike. The tests demonstrated that direct current technology can be an effective method for: 1) reducing the flow of water through a dike; and 2) physically stabilizing a dike structure by dewatering and in-situ electrolytic introduction of aluminum to the soil. The most significant demonstration effects took place within the first 14 days of operation. During those first two weeks, measured dike leakage dropped by more than 70 percent, and dike settlement/consolidation reached 50 percent of the final project total of 0.156 feet (47.5mm).

Despite the limited availability of time and resources, the test program provided some important information about the technology's viability. Therefore, it is recommended that the technology be further applied and evaluated at one or more "real world" sites where dewatering and consolidation of soils or sediments is needed. It is also recommended

that future application and evaluation of the technology have built into it even more rigorous and quantitative monitoring and measurement of project variables.

BACKGROUND

Dikes and levees at CDFs and river banks can be structurally stabilized, and the permeability to water reduced, by the use of electrokinetics and the electrochemical process. Electrokinetics is used to reduce water content of the soil, and electrochemistry is used to cement the soil structure through ion exchange. This technology has been successfully used in Europe.

Summary of Proposed Project

The technologies offered for the reinforcement of dikes belong to the group of electrokinetic and electrochemical mechanisms where compaction of soils takes place by water removal and ion exchange of mono-/bivalent clay constituents against bi-/trivalent metal ions in the lattice of clay-containing soil particles. The ion exchange mechanisms further impact the electro-osmotic drainage of the clays (process of water removal) by producing an irreversible loss of the capacity of clay particles to store uptake water via the compaction of clay in the soil as the lattice structure of the clays collapses.

The proposed technology to be used in this demonstration has been applied frequently in Germany. Prof. Casagrande, Harvard University, used the technology in Poland, Switzerland, and Japan to compact the soil during the construction of artificial islands.

ecp llc has had experience in Germany with the referenced electrokinetic technology and has used it as follows. When performing a test remediation in Deuben (Greater Leipzig) in late 1992, the loamish soil (loess) turned to a slurry-like consistency with almost no load bearing capacity after heavy rains. Dr. Doering was caught in this slurry, sank into it up to his chest, and had to be rescued by the onsite work force. After 60 days of remediation by the electrochemical/electrokinetic process, heavy trucks were rolling over the same part of the site where Dr. Doering was stuck. Despite heavy subsequent rains, the water content of the soil was less than 10% after 60 days of treatment.

ecp treated another site for a tank regiment of the French Army near Orlean, France. This site was being treated using the ECGO technology for removal of undefined organic pollutants. A byproduct of this treatment was the stabilization and compaction of the soil in the area being treated.

The literature mentions other examples:

- Stabilization of sliding slopes of the lignite mine in Gondiswil (Switzerland), performed by ETH Zurich
- Port for German submarines during WWII in Drontheim/Norway by Casagrande

- Compaction/stabilization of the railway dam in Salzgitter, Germany (Technical University of Clausthal)
- Stabilization of the sliding slopes of the construction site for a sewage plant in Bordeaux (France)
- Weadock Power Plant (UK)

Electro-Petroleum, Inc. (EPI) has also used the same technology for the dewatering and stabilization of drilling mud in pits in the oil field.

A review of the construction design for dikes from the USACE related to the Black Lagoon CDF in Michigan shows that the CDFs are constructed primarily of existing soils with geotextile liners. In order for the electrokinetic technology to be successful, it is necessary that water be present on at least one side of the dike or levee. Under these conditions, remedial action can be seen within a few days dependent on the type of metal ions used in the treatment. For iron, the process takes about 5-6 days while for aluminum, the process may be accomplished in about 2 days. In addition to the stabilization, a compaction in volume of about 10% will be noted and the height of the dike may have to be increased after treatment.

Proposal For A Test: Original Concept

EPI and ecp proposed to demonstrate the ElectroKinetics Stabilization Technology to the USACE at one of the Confined Disposal Facilities (CDFs) they operate. Two sites were suggested: the Black Lagoon CDF near Detroit, Michigan, or the Erie Pier Site in Duluth, Minnesota, although other sites could also have been used. For example, a location near New Orleans may have been of interest to the Corps.

As originally conceived, the process would be implemented by the insertion of electrodes into the dike area. Working on the cross section of the dike, a series of horizontal electrodes would be placed, one above the other. A series of aluminum electrodes about 30 feet in length would be placed in the top third of the dike and a length of aluminum about 40 feet in length in the lower third of the dike. A second set of counter-electrodes would be placed about 10 to 12 feet distant from the aluminum electrodes. This series of cathodes, i.e., 2 inch perforated steel pipes, must be capable of collecting and draining the water from inside the dike. A second set of electrodes would then be installed 10 feet from the first set of steel pipes and another set of aluminum electrodes would be installed. The first set of aluminum electrodes and the steel pipes would form the first pair of electrodes, the aluminum being the anode. The steel pipes and the second set of aluminum bars would form the second pair of electrodes, aluminum again being the anode. It was assumed (under the condition that sufficient current could be driven) that the aluminum would be transported into the soil within 2 to 3 days. The flow of displaced water would be the highest within the first 2 hours, and completely dried out after a day. Following the test, the steel pipes would have to be pulled from the dike/ levee.

Electro-Petroleum, Inc., with the assistance of James Harrison of Harrison Marine Electronics, previously demonstrated that the settling rate for silt from the CDF could be enhanced under a DC Field. EPI had also previously used Direct Current to remove water from mud pits generated in the oil patch, aiding in the solidification of the mud for final disposal. This work is covered under a US Patent No. **4,382,341.** The use of electrokinetics as a dewatering method is reported many times in the literature and a review will not be covered in this report.

The Demonstration Site

The Erie Pier Confined Disposal Facility (CDF) is located in the Port of Duluth- Superior and is the repository for sediments dredged from the harbor. An aerial view of the CDF is shown in Figure 1. Two items are identified in the picture. The first is the location at the top (north) corner of the CDF where the demonstration took place. The second is the perimeter berm that surrounds the CDF and contains the dredged material placed in the CDF. The road girdling the CDF is at the outside base of the containment berm. The berm to the southwest of the demonstration location was leaking, and the electrokinetic process was suggested as a possible method of plugging the leak.

Figure 1. Erie Pier CDF

The photograph in Figure 2 was taken at the location along the berm of the CDF where leakage was observed. A onsite visit the previous winter also showed considerable ice build-up at the base of the berm; during the summer, seepage water was observed along the road at the same location.

Figure 2. Area along the CDF where leakage was occurring

TEST AND TEST METHODOLOGY

Test Dike Construction

Prior to startup, a series of discussions were held between NRRI, the Duluth Seaway Port Authority (owner of the Erie Pier CDF), the Detroit and Duluth Offices of the U.S. Army Corps of Engineers, and EPI for choosing an appropriate location to conduct the dike demonstration. A decision was reached to build a dike and conduct the demonstration within the confines of an Erie Pier CDF test site that has been in use since 2002. The site was first used in 2002 and 2003 for an emerging technology demonstration project for in-situ remediation testing of ECGO on material dredged from Minnesota Slip[2]. Since 2004, the site has been used for follow-up evaluation of the ECGO technology. Consequently, much of the infrastructure and equipment needed for conducting the electrokinetic test was already in place on-site.

Dredged material that filled a control cell used during the 2002-2003 demonstration project was excavated and relocated to the eastern end of the cell, and a dike was constructed across the cell about 25 feet from the cell's western end. The Corps arranged for the use of a backhoe and material to construct a dike. The same material used in the construction and maintenance of the berms around the CDF was used in the test. It was also agreed to that the dike would be constructed in such a way that a pool of water would be placed behind the dike, insuring that a constant water head would provide liquid to the dike and sufficient head pressure to drive water leakage.

James Harrison of Harrison Marine Electronics performed all aspects of the construction process. The initial steps in the process were to remove the dredged materials used during the 2002-2003 ECGO demonstration project from the control cell and stockpile them on the south side of the cell. On July 21 and July 22, 2006, the cell was cleaned out with a John Deere backhoe, down to the underlying clay liner (Fig. 3). Figure 4 shows the conceptual outline for the dike construction and plastic-lined "pool" area behind the dike.

On July 24, 2006, a dike was constructed across the width of the excavated cell. The dike material, delivered the same morning, had a silty-sandy-clayey (loamish) composition and was built up by successively dumping bucket loads across the width of the cell with a Case Uni-Loader (similar to a Bobcat). The material was compacted by the loader's weight and its repeated back-and-forth movements during the day-long construction process. The original plan was to place and compact the material in 12-inch lifts across the cell, but the steepness and depth of the excavation made that impossible to achieve safely given the Uni-Loader's relatively small size and short wheelbase.

Figure 3. Preparation of the control cell prior to dike construction

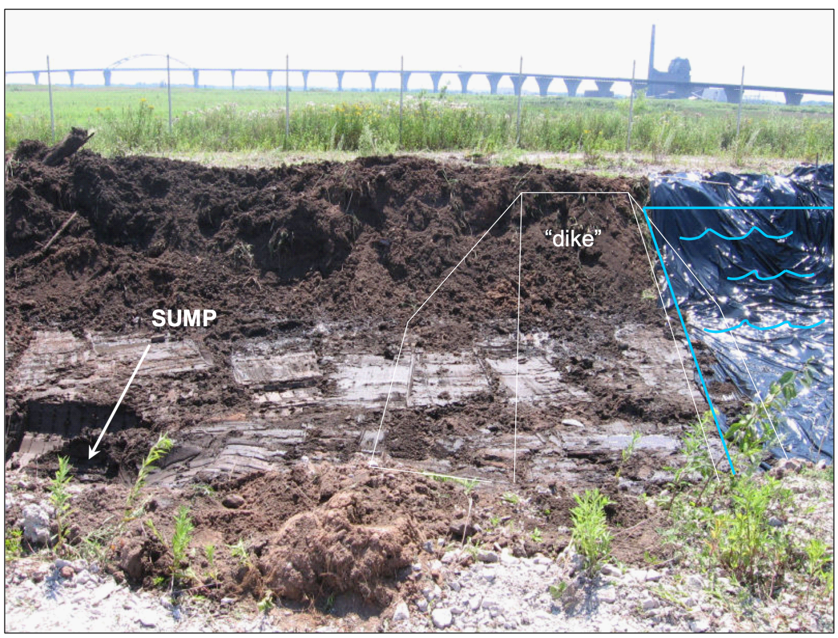

Figure 4. Schematic of dike prior to construction and plastic pool liner.

Following construction, the pool behind the dike was filled with water and allowed to sit for several days until the dike began to “leak”. The completed dike measured approximately 40 feet long, 6 feet wide at the top, 18 to 20 feet wide at the base, and 6 feet high. The dike material’s angle of repose was approximately 40°. Figure 5 shows the completed dike and pool, with the Uni-Loader in the background. Actual moisture content and compaction densities were not measured during dike construction.

Figure 5. Completed dike and pool, with loader in the background (to the right of the propane tank).

The pool volume was determined to be about 800 cubic feet (22.6 cubic meters), or 6,000 gallons, based on an average constant pool elevation of 610 feet above sea level. A contour map and rendered 3-D view of the test site is presented in Figures 6 and 7, showing the dike and pool position within the control cell excavation. The contour map, rendered 3-D image, and volume calculations are based on modeling the surveyed dimensions and geometry of the dike, pool, and control cell with Golden Software's *Surfer 8*. The control cell is depicted in a completely excavated state, and does not show the excavated material that was stockpiled at its east end.

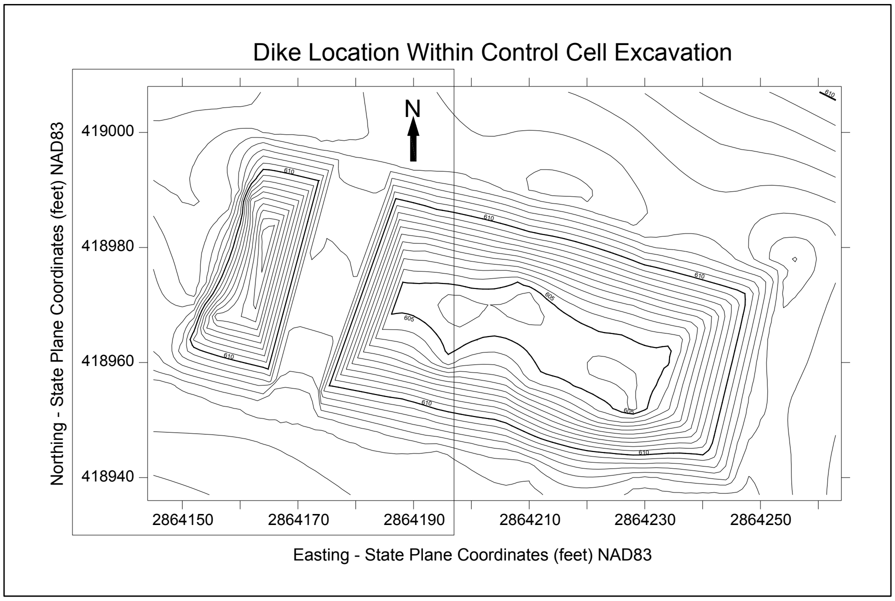

Figure 6. Contour map of dike and pool within control cell area.

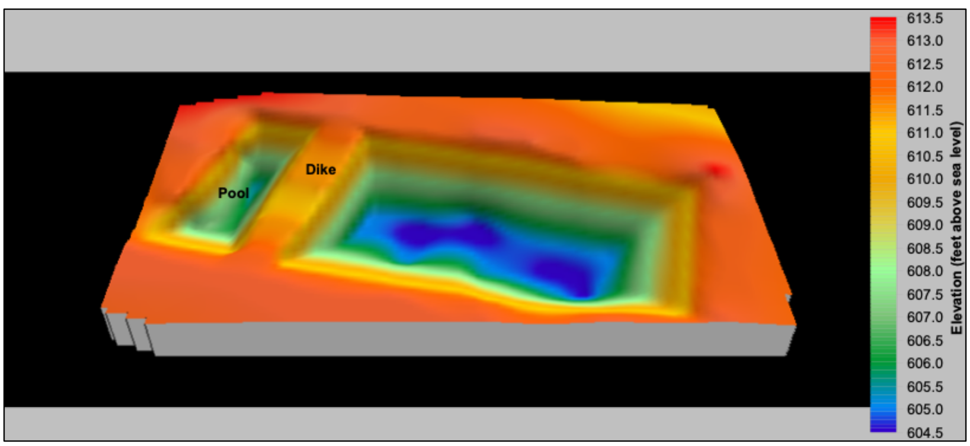

Figure 7. 3-D rendering of dike and pool within control cell area.

As constructed, the dike was anticipated to have sufficient water seepage for the test, and it did, as Figure 8 shows. The pool was equipped with a float valve (Fig. 9) that controlled a water supply pump to maintain a nearly constant water level on the pool side of the dike.

Figure 8. Wet areas along dike showing initial seepage/leakage.

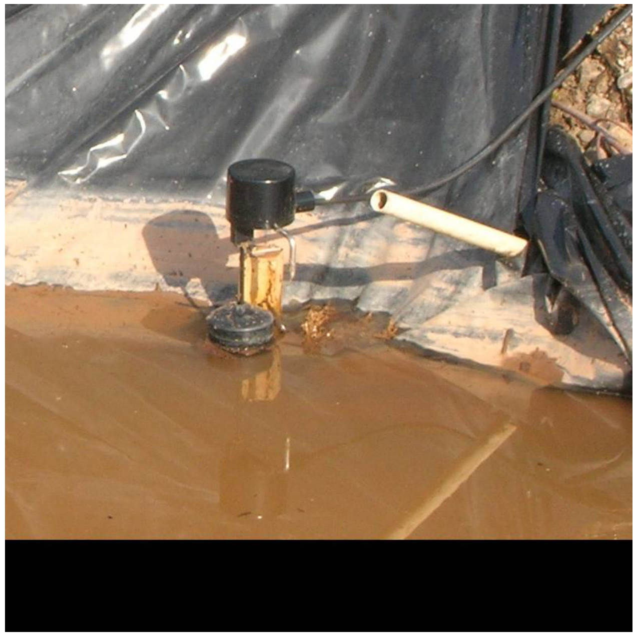

Figure 9. Float device for maintaining pool level.

Testing

Electrode installation began on July 27, following the arrival of Drs. Doering and Wittle, and representatives of the U.S. Army Corps of Engineers. Figure 10 shows Dr. Doering, ecp, and Larry Zanko, NRRI, marking the location for the installation of the anodes on the dike.

Figure 10. Dr. Doering and Larry Zanko on the completed dike.

Test Configurations

Three primary test configurations (four electrode combinations, total) were proposed and tested. Each configuration served a specific purpose and had its own advantages. The three test configurations were:

- **Test 1:** Three aluminum anodes installed vertically at each end of the dike, and a single steel cathode driven horizontally approximately one-half of the way into the base of the dike at its midpoint. In this configuration, water was to be drawn to (and drained through) the cathode.
- **Test 2:** Vertical aluminum anodes placed along the center line of the dike with a set of vertical steel cathodes placed on the pool side of the dike. In this configuration the water would be retarded from flowing through the dike.
- **Test 3:** The same vertical anode configuration as in Test 2 (placed along the centerline of the dike), but with:
    - **a)** two rows of cathodes placed along both edges of the dike. This configuration would dewater the dike from the center outward to the two sides; and
    - **b)**_the same configuration as Test 3a, but with only the sump side row of cathodes connected. This configuration would dewater the dike from the center outward to the sump side.

By using aluminum anodes throughout the demonstration project, additional dike stabilization clay could be achieved by aluminum exchange with cations in the soil.

Measured test parameters

In all tests the following parameters were measured: leakage rate; power input; current distribution to the electrodes; and total settling (subsidence) of the dike. Piezometer measurements were added after Test 1 was complete.

- Leakage rate was measured several times a day by diverting the leakage through the face of the dike with a small dam networked to a common exit point (Fig. 11). The leakage rate was measured by timing the flow of liquid into a graduated beaker.

Figure 11. Exit point for collecting leakage rate from the face of the dike.

- Power Input was measured by recording amps and volts as provided from the two rectifiers supplying power to the test area. Each power supply is capable of supplying 50 amps current at 300 volts DC.

- Current distribution to the electrodes was measured using a Fluke clamp-on DC ammeter which was clamped on to each cable feeding each electrode. The total current was checked against the sum of the individual currents feeding each electrode.

- Dike settling (subsidence) was measured with a theodolite (transit) throughout the testing period by referencing two rows of points set across the top of the dike on either side of the dike's centerline. An off-site benchmark located 444 feet (135 meters) away was also referenced as a check against potential subsidence at the surveying instrument's location.

- Piezometer readings were taken at five piezometer well locations following their installation on August 2 along the sump side of the dike. The piezometers allowed for monitoring the hydraulic head in the dike and the influence of the respective electrode arrays on the height of that head.

The location of the settling measurement points and piezometers is shown schematically in Figure 12.

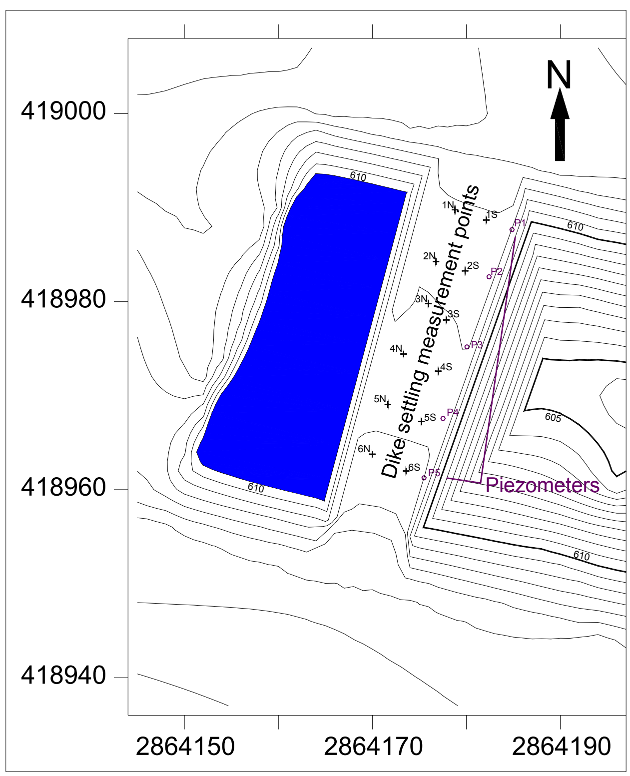

Figure 12. Settling (subsidence) reference points and piezometer locations.

TEST RESULTS
<u>TEST 1: July 28 to August 1</u>

Test 1 consisted of:

- two sets of vertical anodes (three per set) spaced about three feet (one meter) apart in a line on each end of the dike; and
- a single steel cathode inserted horizontally halfway through the dike at its base from the sump side, midway between the two sets of vertical anodes.

This electrode configuration is shown schematically in Figure 13. In this concept the moisture in the dike is driven toward the central horizontal cathode, while aluminum ions donated by the anodes further stabilize the dike material.

The anodes, made of 10-foot long heavy walled aluminum pipes, were installed with a Case Uni-Loader. The loader was used to direct-push the anodes into the dike, as shown in Figure 14. The cathode, a 15-foot long steel tube, was fitted with a wooden point and driven into the dike with a come-along winch and blows from a sledge hammer. The cathode was perforated with three rows of holes along its length to facilitate drainage of water from the dike.

During the tests the leakage rate through the dike, the power input to the system, the current flow to each of the electrodes, and the change in dike reference height (settling) were measured.

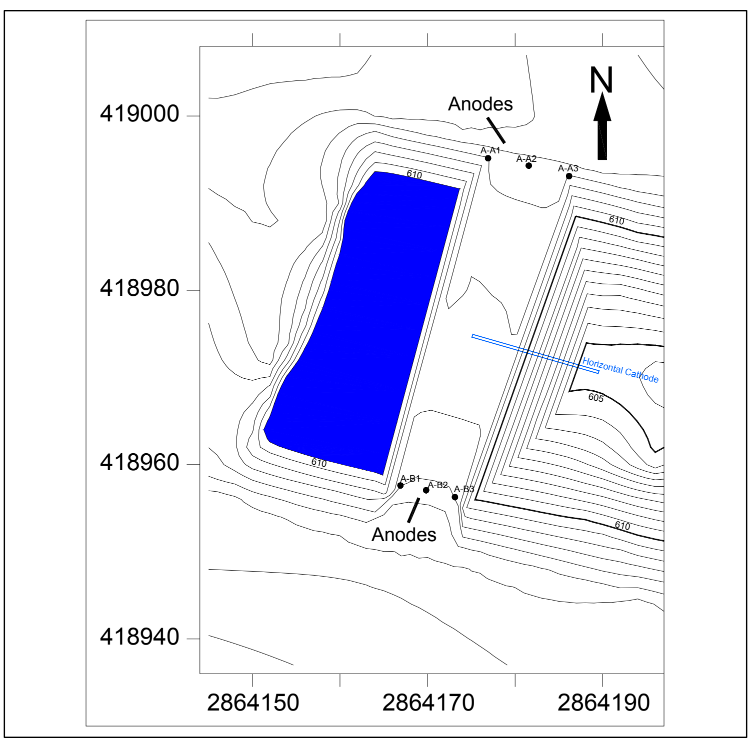

Figure 13. Test 1 configuration with anodes at opposite ends of the dike, and central horizontal cathode.

Figure 14. Direct-push installation of aluminum anodes

Results of Test 1

Leakage rate

Average daily dike leakage measured during the five-day test period dropped from 720 gallons per day prior to startup on July 28, to 250 gallons per day by August 1 - a 65%

reduction. The most significant reduction occurred within two days of power-up, i.e., by July 30. Between July 29 and July 30, the dike leakage rate dropped from 596 gal/day to 321 gal/day, a single-day reduction of 46%.

At the same time, average daily drainage from the horizontally installed cathode doubled (increased by 100%) from a 27 gal/day rate just prior to the 9:50AM startup on July 28 to 54 gal/day by mid-afternoon the same day. Cathode drainage stayed at a maximum through July 30, and dropped steadily through August 1, back to 27 gal/min.

Dike leakage and cathode drainage rates are plotted in Figure 15. At a minimum, the rates confirm electro-osmotic movement of water to the cathode. Furthermore, the increased rate of flow through the cathode was visually obvious almost immediately after power was applied to the system on July 28. Second, the decreased rate of dike leakage and cathode drainage suggests consolidation (tightening) of the dike material via the combined effects of electro-osmotic water movement toward the cathode and electrochemical addition of aluminum ions to the soil matrix from the anodes, especially by the 2nd and 3rd days of operation.

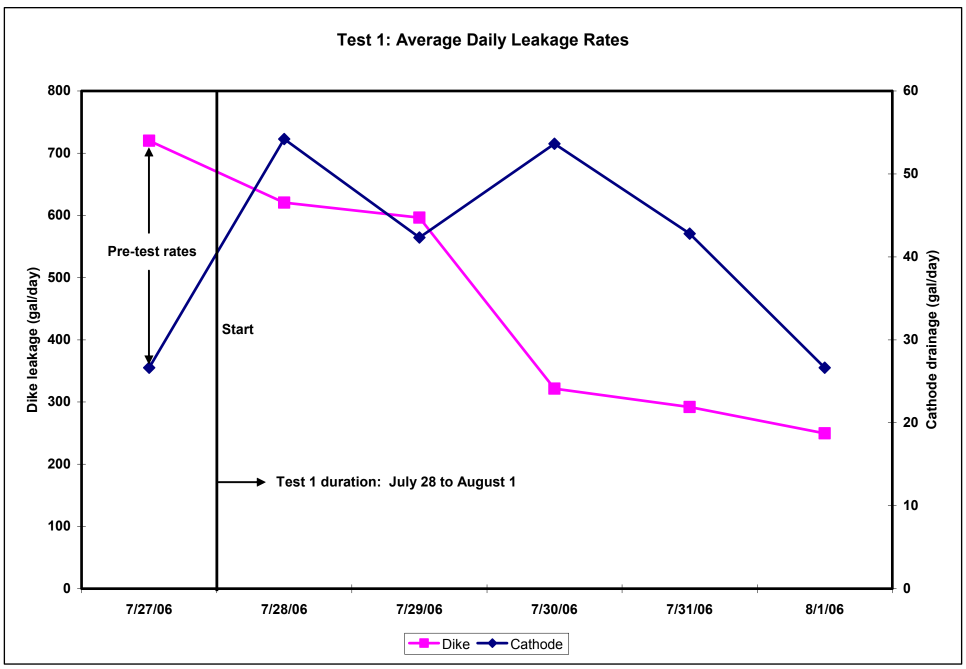

Figure 15. Test 1 dike leakage and cathode drainage rates.

Power input

Power input was calculated by multiplying the amps and volts to give DC watts being fed to the electrode system. Little variation in the power input over the test period was noted. The results of the power input during Test I is shown in Figure 16.

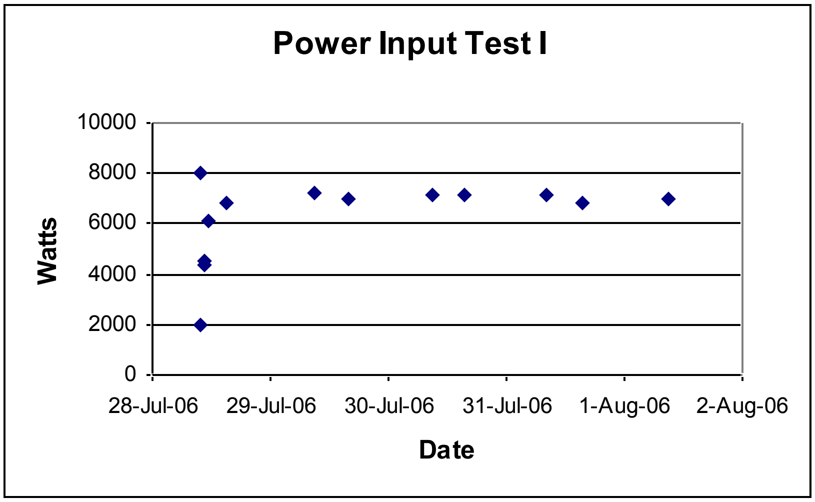

Figure 16. Power Input to the System During Test 1.

Change in Water Flow vs. Current

In a short term test lasting about 15 minutes the current flow to the system was varied in ten amp steps from 20 to 50 amps. The water flow was measure coming from the cathode after it has appeared to "stabilize" in approximately 5 minutes after setting the current level. As can be seen in Figure 17. The water flow with current is linear at these current settings.

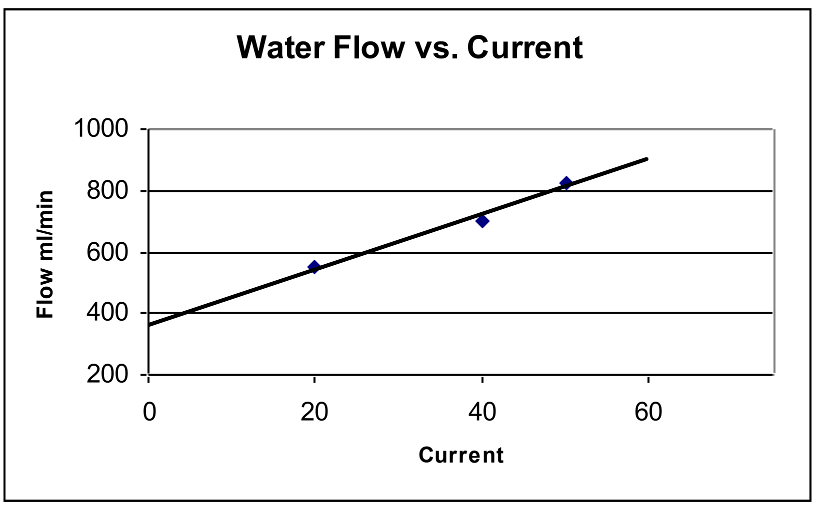

Figure 17. Water flow to the cathode vs. Current

<u>Current distribution</u>

The current distribution to each of the six anodes was measured during Test 1. This measurement was made with a clamp-on ammeter during the test. Anodes A and B designates the side of the dike where the electrodes were located. A anodes were located on the north side of the dike, closest to the power supply and B anodes wee located on the South side of the dike. The first anode A1 was located closes to the pool while A2 was in the center of the dike and A3 was closest to the sump. The B anodes followed the same configuration. This can be seen in Figure 13. The current flow as measured is shown in the following figure, Figure 18. This indicates that the center anodes, A2 and B2 were carrying the major current to the cathode while the anodes A1, A3, B1 and B3 carried only about 20% of the current.

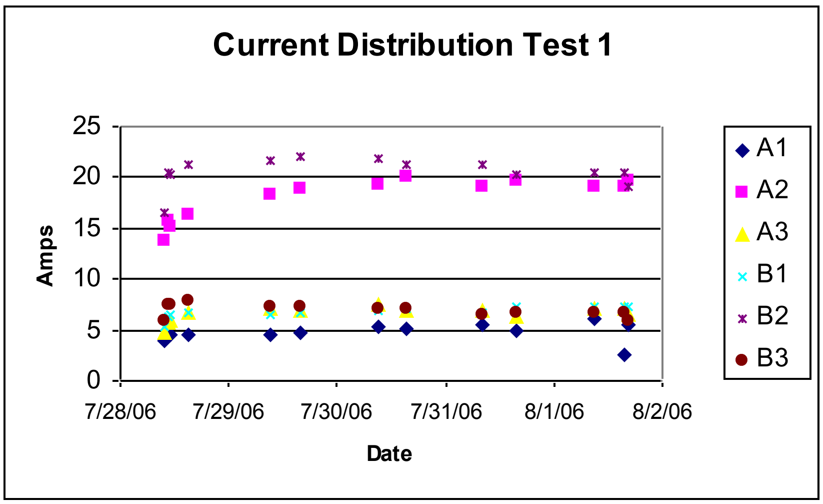

Figure 18. Current Distribution Test 1

Dike settling

By August 1, the six north dike reference points settled an average of 0.022 feet (6.7mm). Four of the six south reference points settled an average of 0.048 feet (14.6mm); the other two points were rendered unusable due to surface erosion caused by heavy rains (described below). All points combined for a dike settling average of 0.032 feet (9.8mm).

Observations and Comments on Test 1

This test was run for a five-day period. Significantly, it must be recorded that from July 29 to July 31, a series of rain storms hit the area, with an estimated 5 inches of rain falling on the test site. This created erosion problems along the sides of the excavated control cell and on the sides of the dike, and the resulting influx of eroded mud into the sump pit negatively impacted sump pump operation during this first test period. However, the dike held even with this extreme rainfall and, as Figure 15 shows, the dike leakage rate still decreased, further suggesting that internal dike stabilization had occurred.

The intense rain also provided an opportunity to illustrate the stabilizing effects of electrokinetics at a smaller scale. Previously saturated and unstable silty material that had been electrokinetically dewatered during a concurrent ex-situ silt dewatering demonstration[1] and left exposed to the weather maintained its form despite being subjected to the heavy on-site rainfall, as shown in Figure 19.

Figure 19. Material after initial removal   Material after 5 inches of rain

<u>TEST 2: August 2-August 27</u>

For Test 2, a row of aluminum anodes was inserted along the centerline of the simulated dike, and a parallel row of cathodes made from thin-walled steel conduit was installed on the wet (pool) side of the dike. The anodes and cathodes were installed vertically with a fencepost driver. In this configuration the use of electrokinetics to retard the flow of water from the pond and through the dike was being demonstrated. A schematic of the test layout is shown in Figure 20. One vertical cathode (C1-4, not shown) was left uninstalled.

Prior to the start of this test, five PVC piezometer wells were installed along the sump side of the dike to monitor the change in water level (hydraulic head) in the dike itself.

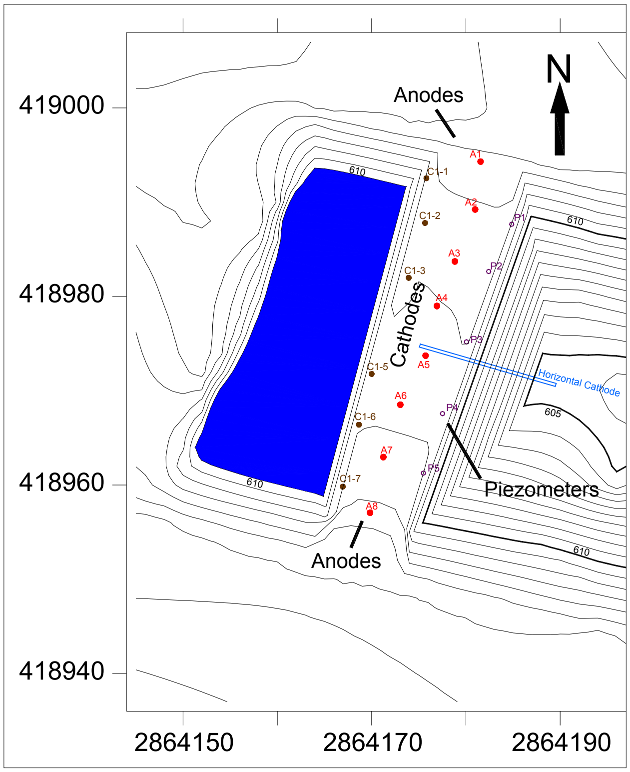

Figure 20. Test 2 configuration showing electrodes in test dike with cathodes in back (pool side) and anodes down the center. Piezometers are also indicated on the sump side of dike.

Results of Test 2

Leakage rate

Average daily dike leakage measured during the 25-day test period fell from 250 gallons per day on August 2 to 181 gallons per day by August 27 - a 28% reduction. During this period, leakage decreased at a relatively steady rate, as shown in Figure 21. Drainage through the horizontal cathode was not measured during this or subsequent tests, as its flow slowed to a single drip every 2 to 4 seconds..

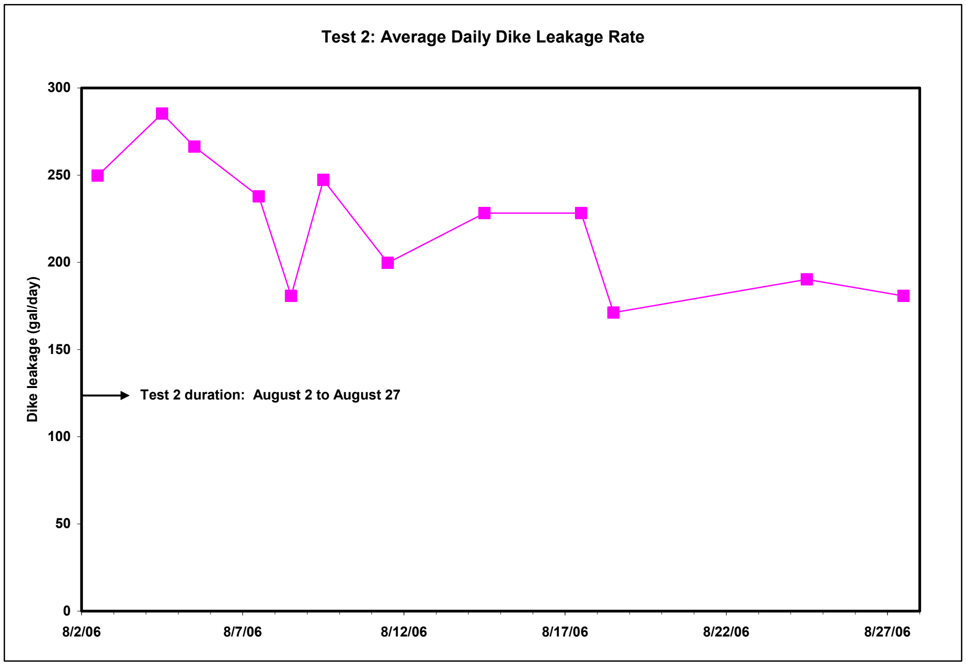

Figure 21. Plot of average daily dike leakage rate during Test 2.

Power input

Power input during test 2 and 3 was provided by two power supplies during this period. One power supply provided power to the electrodes on the north side of the dike and a second to the south side of the dike. The total power to the system from the two power supplies is shown in Figure 22..

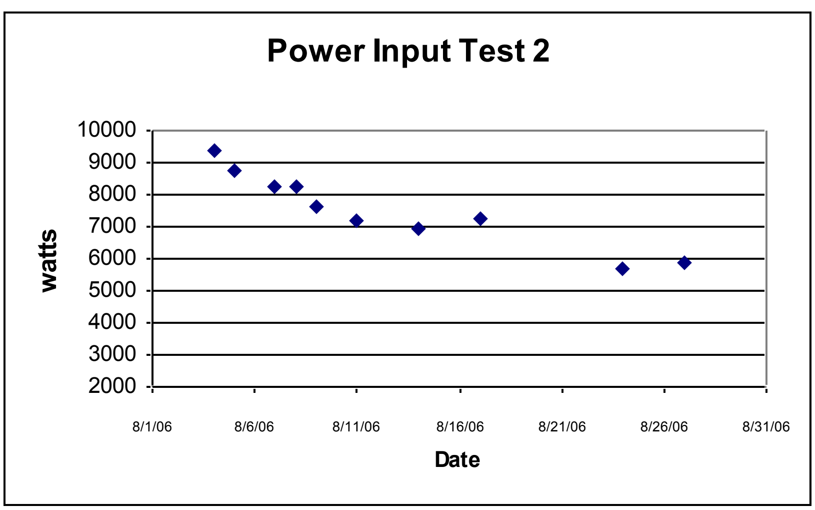

Figure 22. Power Input Test 2

Current distribution

Current Distribution to the two sets of electrodes is shown in Figure 23.

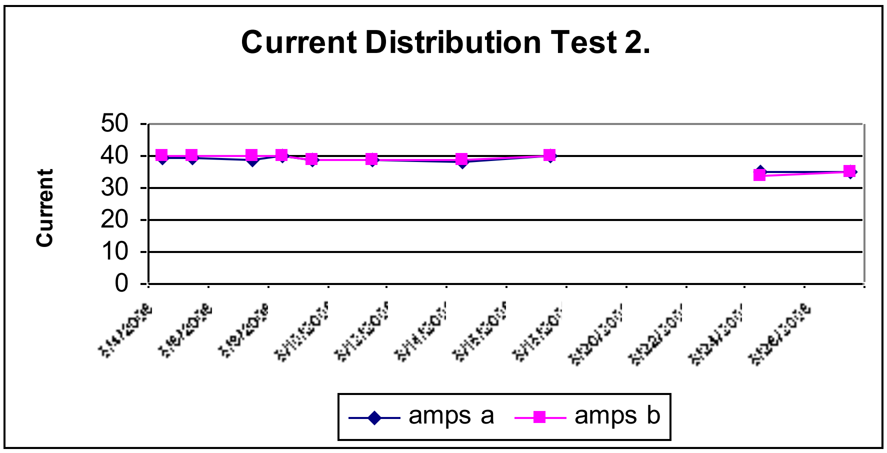

Figure 23. Current Distribution Test 2.

Dike settling

Between August 1 and August 22, the six north dike reference points settled an average of 0.077 feet (23.5mm), and the remaining four south reference points settled an average of 0.079 feet (24.1mm), for a combined dike settling average of 0.078 feet (23.8mm). Interestingly, the most significant settling occurred within a day of Test 2's start on August 2. Between August 1 (the last day of Test 1) and August 3, surveying showed that the six north dike reference points settled an average of 0.032 feet (9.8mm), and the four south reference points settled an average of 0.049 feet (14.9mm), for a total dike settling average of 0.039 feet (11.9mm). In other words, almost 50 percent of dike settling that occurred during Test 2 took place in the first two days.

Piezometer readings

Following their installation on August 2, the water level in each of the five 5-foot long piezometer wells was recorded. These measurements provided a way to monitor the possible influence of the tested electrode configurations on the hydraulic surface within the dike. Figure 23 plots the difference between piezometer levels and a mean constant pool elevation of 610.0' (above sea level) during Test 2. Water levels in piezometers P2 to P5 rose quickly following installation, while the water level in P1 rose at a slow and relatively constant rate. It is believed that the slowly rising water level in P1 reflected its dike position, i.e., at the end of the dike which was constructed first and therefore compacted the most; conversely, P5 was located at the far end of the dike which was constructed last and therefore the least compacted. Because piezometers P2 to P5 (especially P5) penetrated the less-compacted and more permeable portions of the dike, it is not surprising that they filled more rapidly than P1 as water followed the path of least resistance through the dike.

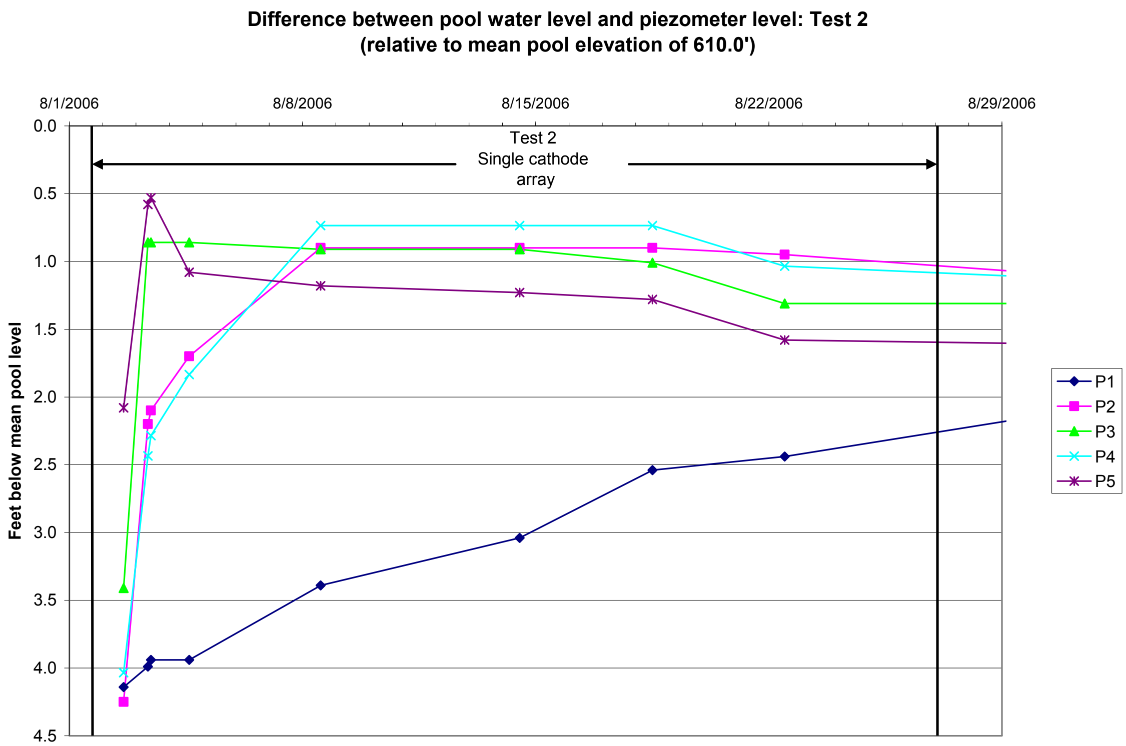

Figure 24. Test 2 piezometer levels relative to pool elevation.

Observations and comments on Test 2

The piezometer measurements illustrated in Figure 19 provide a possible explanation for how the Test 2 electrode array was working. Piezometer P3 and P5 water levels rose the quickest and by the greatest amount after installation (to 0.5 to 0.9 feet below pool level within a day). Meanwhile, the water levels in P2 and P4 rose quickly initially (to 2.1 and 2.3 feet below pool level, respectively), but their fill rates then slowed, taking another five to six days to "catch up" with P3 and P5.

What accounts for the fill rate and water level differences in the first week of Test 2's operation? One possible explanation might be found in the influence of the "missing" uninstalled cathode (C1-4), which would have been located at the center of the dike on the pool side, opposite piezometer P3, and between cathodes C1-3 and C1-5. Test 2 was configured to drive water from dike's interior toward the pool side, i.e., retard flow to the sump side. However, cathodes C1-3 and C1-5, spaced 11 feet (3.35m) apart, would be responsible for pulling water toward them from the centerline anodes, particularly anodes A4 and A5. This relative geometrical arrangement, when combined with the presence of the horizontal cathode at the center and base of the dike and the absence of cathode C1-4, may have meant that the center of the dike (piezometer P3's location) was more likely to be reflective of a hydraulic "funneling" effect.

By August 8, water levels in piezometers P2 to P5 stabilized, and remained fairly constant for the next ten days. Then, from August 14 to August 22, water levels dropped by 0.3 to 0.4 feet in P3, P4, and P5. This closely coincides with a reduction in average daily dike leakage (see Fig. 18) during the same interval. Perhaps the system needed time to equilibrate before showing evidence of overcoming the hydraulic head that had developed within the dike, and eventually retarding flow.

It is also worth noting that by August 3 (just six days after project startup), the dike had already reached 45 percent of the *total* settlement that would be measured as of the final (October 2) project survey (66 days after startup). By the end of Test 2 (August 27), the dike had reached over 70 percent of its total. This significant settling rate differential is illustrated in Figure 24. Blue bars represent the July 28 to August 2 rate; maroon bars represent the August 2 to October 2 rate. The rate is given in feet per day.

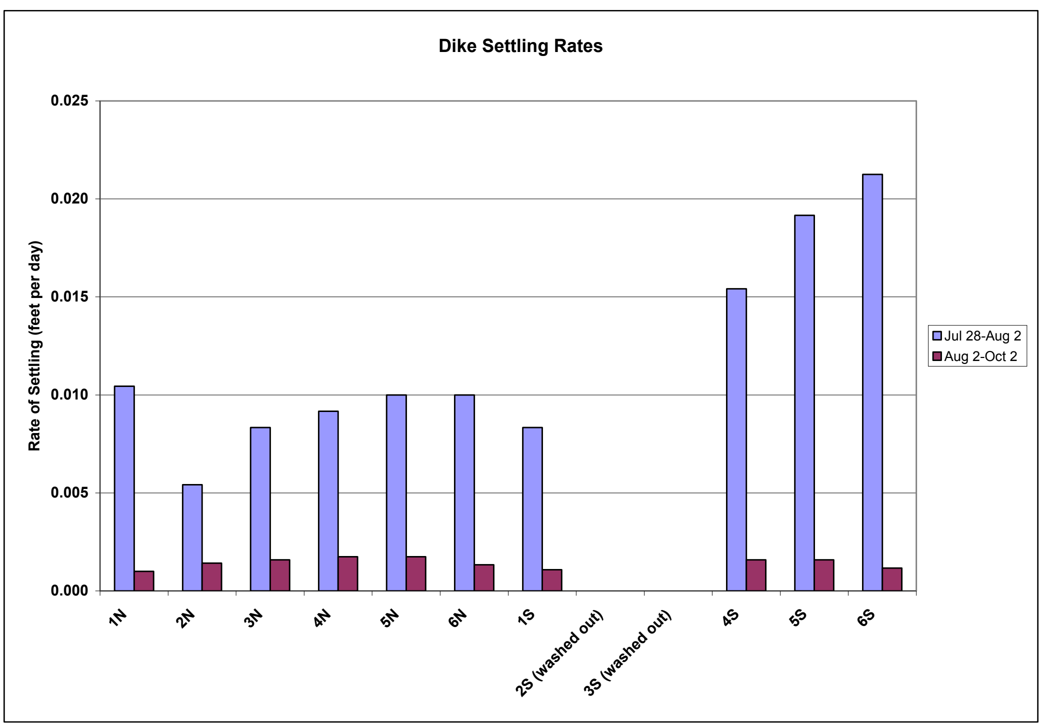

Figure 25. Dike settling rate (feet per day) comparison.

A plot of average dike leakage rate (gal/day) against cumulative dike settlement (Fig. 25) indicates a potential relationship between the two variables The plot suggests that the most significant electrokinetic and electrochemical effects (dewatering and consolidation via aluminum ion addition) had occurred by the early days of Test 2 (**NOTE**: in order to plot both variables at the appropriate relative chart scale, cumulative dike settlement, in mm, was increased by a factor of 10).

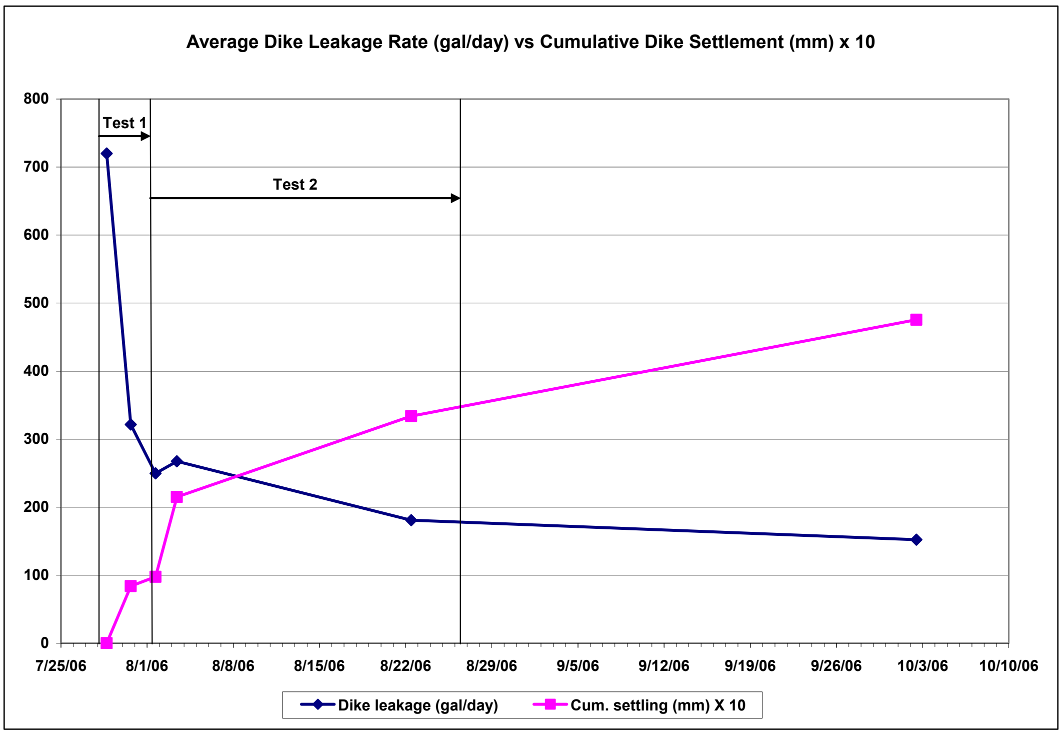

Figure 26. Plot of dike leakage and dike settlement over time.

TEST 3 (a & b): September 13-October 9

Following 17 days of downtime for generator repair, the demonstration project was resumed on September 13.

<u>Test 3a</u>

Test 3a (September 13 to October 1) was designed to move water in the dike away from the center to the two sides. This was accomplished using the aluminum anodes previously installed along the centerline of the dike in Test 2 and adding a second row of cathodes (C2-1 to C2-7) on the sump side of the dike, as shown schematically in Figure 26. For the test, previously "missing" cathode C1-4 was added to the pool side row of

cathodes (C1-1 to C1-7). The system was operated in the same manner previously described with leakage rate, power, current distribution, piezometer readings, and subsidence being recorded throughout the test.

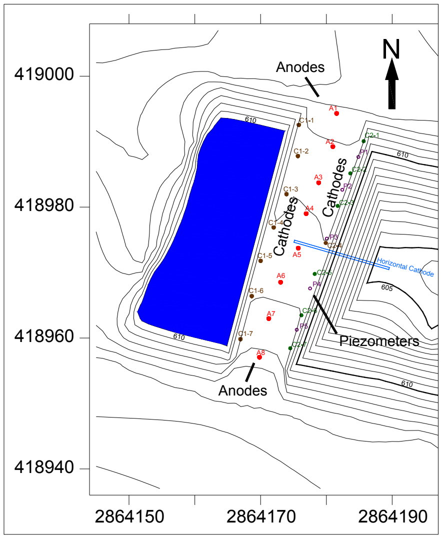

Figure 27. Test 3a setup with anodes in center of dike and cathodes on both sides.

<u>Test 3b</u>

Test 3b, begun on October 1, 2006, and run until shutdown on October 9, had the same configuration as Test 3a, but with only the anodes and sump side row of cathodes connected (Fig. 28). This configuration (the opposite of Test 2) would dewater the dike from the center outward to the sump side. A photograph of the dike during Tests 3a and 3b is shown in Figure 29.

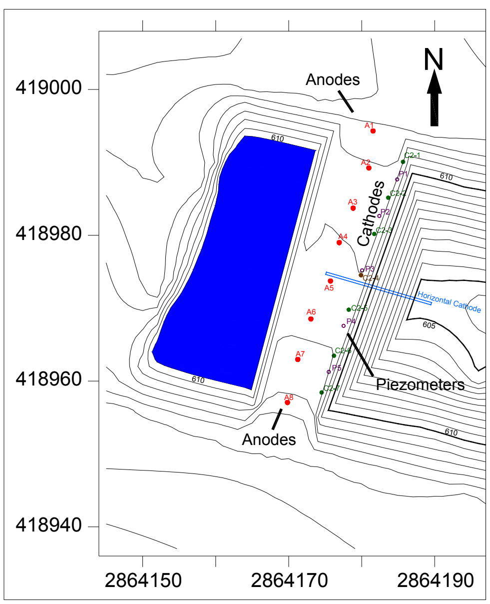

Figure 28. Test 3b setup with anodes in center of dike and cathodes on sump sides.

Figure 29. Dike during Tests 3a and 3b.

Results of Test 3

<u>Leakage rate</u>

The average daily dike leakage rate was nearly the same at the beginning and end of the Test 3 test period – 86 gal/day on September 13, and 76 gal/day on October 9 (Fig. 29). It is difficult to interpret the leakage rate data and conclude that a definite technology effect occurred, especially when an increase in measured leakage coincided with a wet period, as was the case between September 16 and 23.

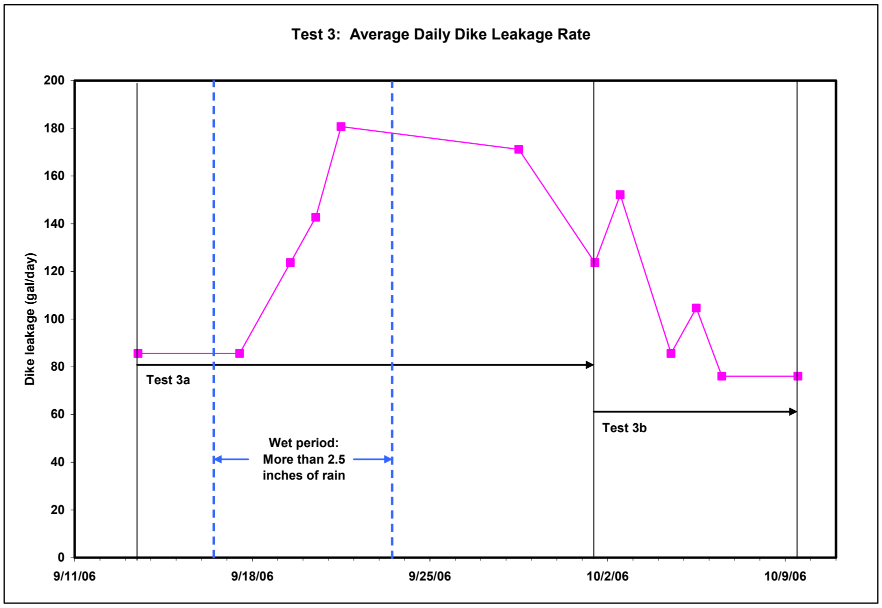

Figure 30. Test 3 average daily dike leakage rate.

Dike leakage during the Test 3 period can be put into the context of leakage recorded during the entire demonstration project, as summarized in Figure 30.

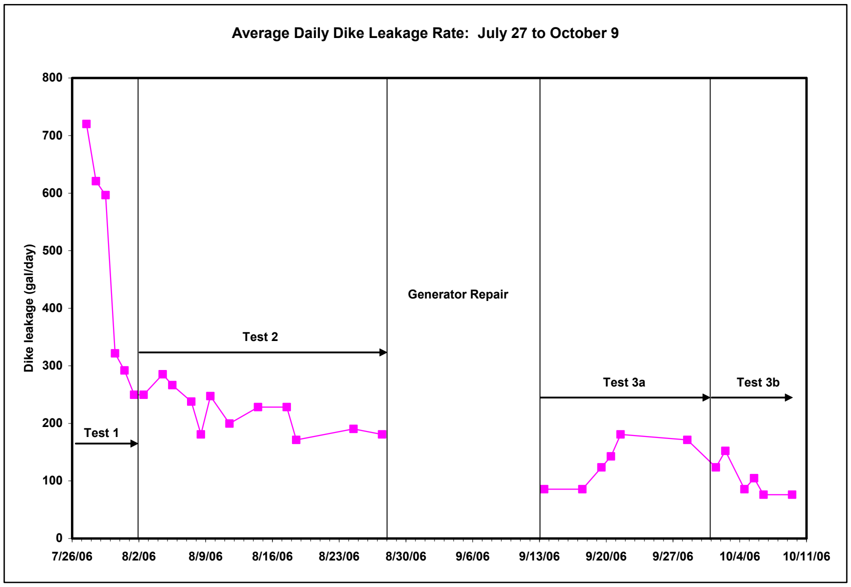

Figure 31. Average daily dike leakage rate for entire demonstration (July 27 to October 9, 2006).

Power input Test 3

Power input during Test 3 was calculated as the sum of the two power supply inputs and is shown in Figure 32.

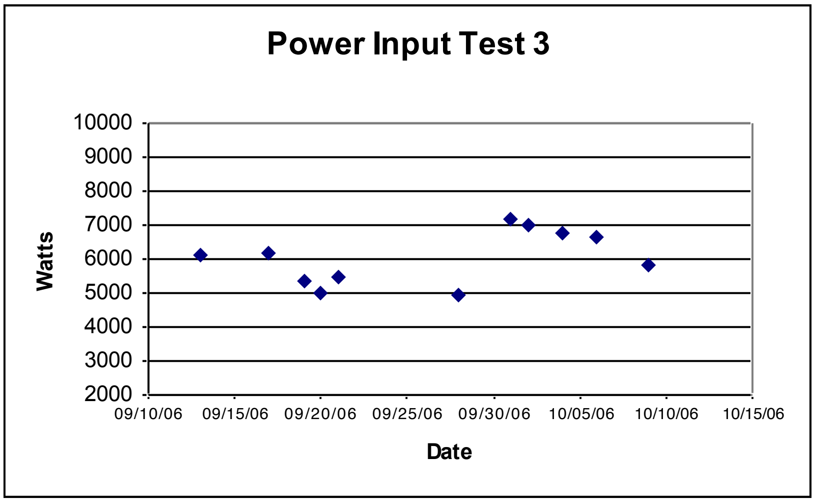

Figure 32. Power input Test 3

Current distribution

During test three the current distribution was equivalent between the electrodes on the two sides of the dike. This is indicative of the fact that the excess moisture on the north side of the dike at the start of test 1 had been reduced to that observed on the southern side of the dike.

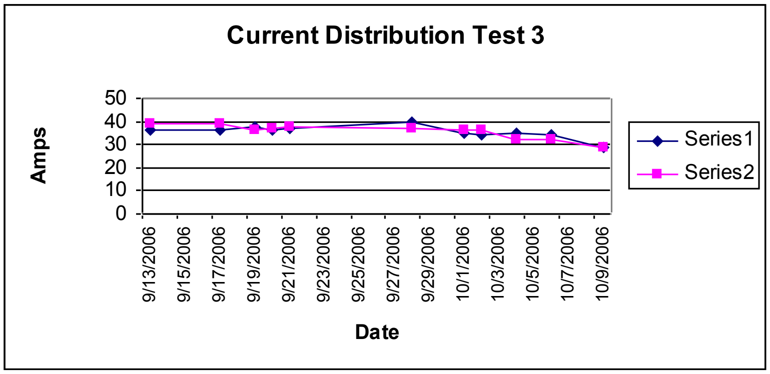

Figure 33. Current Distribution Test 3

Dike settling

Between August 22 and October 2, the six north dike reference points settled an average of 0.043 feet (13.1mm), and the remaining four south reference points settled an average of 0.079 feet (15.5mm), for a combined dike settling average of 0.046 feet (14.0mm). This amount represents the final 30 percent of dike settling measured during the entire demonstration period (refer to Fig. 21).

Total dike settlement is illustrated in Figure 34 at each reference point location, These data suggest a greater degree of settlement/consolidation occurred in the central to southern portion of the dike, as well as on the dike's sump-side.

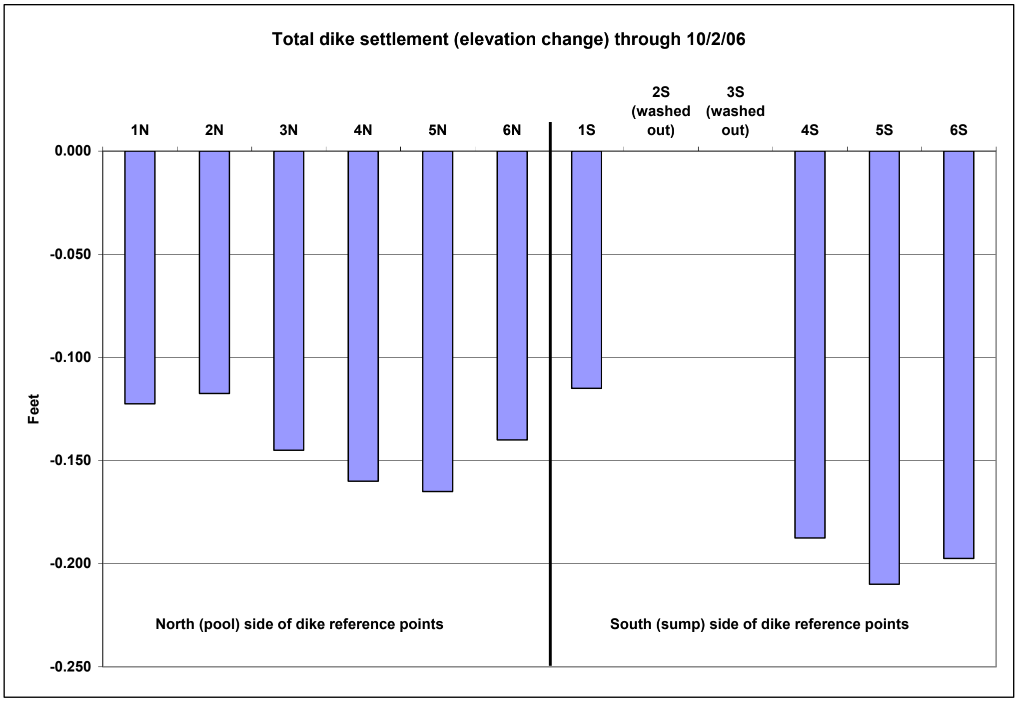

Figure 34. Total dike settlement through October 2, 2006

The fact that 70 percent of total measured dike settling took place between July 28 and August 22 (in 25 days), and that the remaining 30 percent occurred between August 22 and October 2 (in 41 days), as Figs. 24 and 25 previously illustrated, shows that most of the consolidation took place relatively quickly.

<u>Piezometer readings</u>
Test 3 piezometer levels are summarized in Figure 28, and are shown in relation to the demonstration project's complete piezometer data set.

The 17-day generator repair hiatus from August 27 to September 13 provided an opportunity to make piezometer measurements (on September 5) when no power had been applied to the dike electrodes for nine days. Water levels in piezometers P2 to P5 bottomed out during that downtime, and rose again once the system was powered back up for Test 3a. This suggests water was being driven outward and upward from the dike's interior to the newly-installed sump-side (C2-n) cathodes during Test 3a, and reached a steady state by September 21.

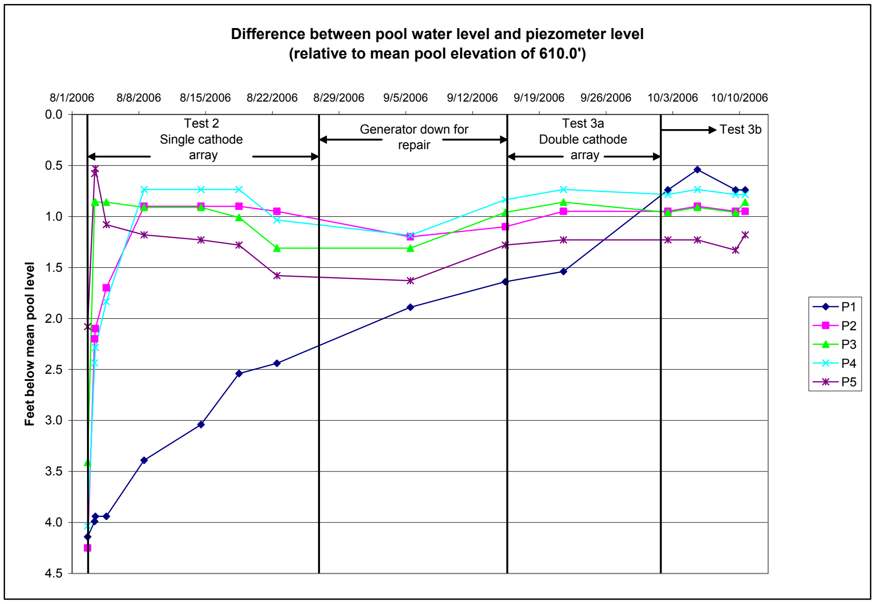

Figure 35. Plot of piezometer data for Tests 2 and 3, August 2 to October 10.

Test 3b, which began on October 1, may have influenced the water level in piezometer P1. From the start of Test 2 through Test 3a, piezometer P1 was an anomaly by exhibiting a slow but steady increase in its water level in comparison to the other four piezometers, as shown in Fig. 28. However, its water level (uncharacteristically) increased more rapidly following the start of Test 3b. It is suspected that Test 3b's configuration, i.e., with only the cathodes on the sump-side of the dike connected, resulted in more water being driven to the cathodes located to either side of P1 (cathodes C2-1 and C2-2). This effect is discussed and shown in the following section.

Piezometer readings

Figure 36 show the elevation difference between the pool and piezometer levels (piezometric surface). The first slide assumes a constant pool elevation throughout; the second slide shows the elevation difference relative to what the level of the pool was at the same time the piezometer readings were made. Given the intermittent pumping to refill the pool, this level can fluctuate during the day, so there would be a lag between filling/seepage and infiltration to (or drainage from) the piezometers.

At any rate, Piezometer 1 shows a slow, steady rise in its water level, while the water level in the other four rose pretty quickly and then stabilized. However, if one assumes a constant pool level (first slide), Piezometers 2-5 may be showing a slight drop in the piezometric surface starting on August 8.

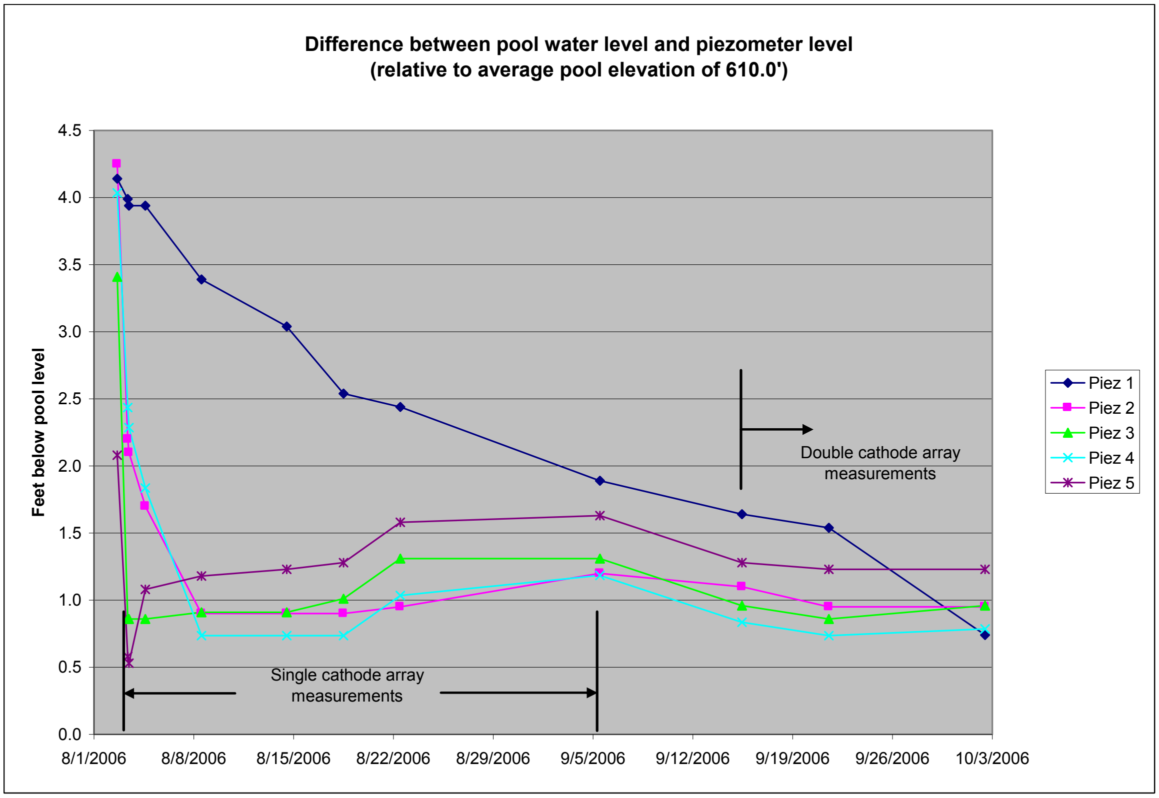

Figure 36. Elevation difference between the pool and piezometer levels

Observations and comments on Tests 3a and 3b

This configuration demonstrated how water was actively moving to the cathodes. Figures 37 and 38 illustrate this clearly, and show how water was emerging around the cathodes where they entered the dike surface.

Figure 37. Water drawn to new cathode (C2-4) on sump side of dike, September 21, 2006, Test 3a. Note PVC piezometer (P3) to the left.

Figure 38. Water drawn to new cathode (C2-5) on sump side of dike, September 21, 2006, Test 3a.

FINAL COMMENTS

It could be argued that the reduced dike leakage rates and dike settling were due simply to natural consolidation and/or slumping of the dike after it was built. To eliminate that as a possible explanation, perhaps a period of time, e.g., 2 weeks, should have been devoted to establishing baseline leakage rates, piezometer levels, and dike settling after the dike was constructed but before electricity was applied. Likewise, additional parameters should have been monitored and recorded, such as the amount of water needed to maintain the pool level behind the dike; this would have been a useful additional measure of dike leakage. A rain gage would also have been useful to have on-site throughout the project as a direct measure of water input due to precipitation.

Lastly, chemical and/or mineralogical analysis of the dike soil would have shown to what degree aluminum was delivered to the dike by the anodes, because significant electrochemical depletion of the aluminum anodes occurred, as shown in Fig. 39.

Figure 39. Depleted aluminum anode compared to an intact anode.

Nevertheless, a sufficient amount of the project's reported quantitative and observational information supports the occurrence of a positive technology effect.

Two additional Figures are appropriate: Figure 40 shows the overall power into the system over the three test periods and Figure 41 shows the leakage rate during the threee tests. Both indicate that the highest effectiveness for stopping a leak is in the initial phases of the treatment.

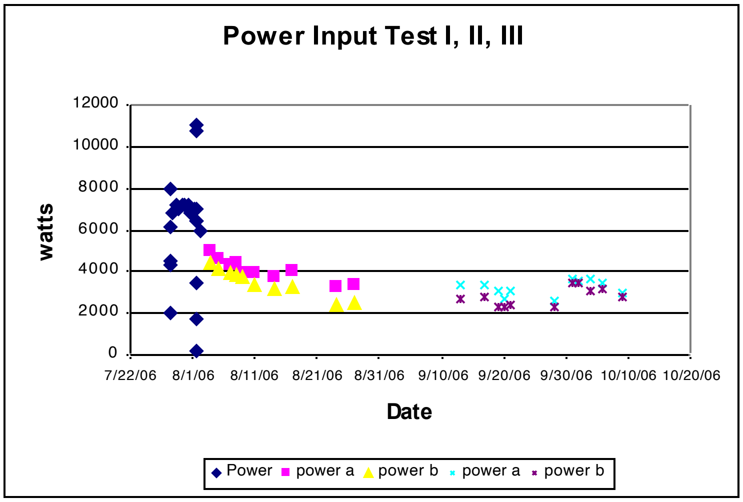

Figure 40. Power input Test 1,2 3

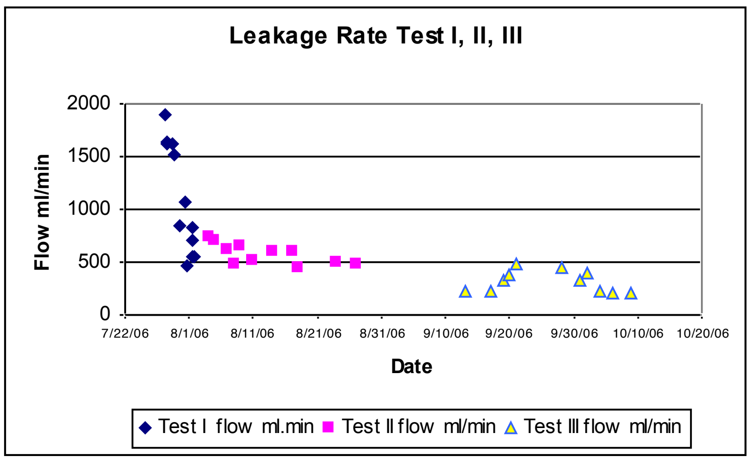

Figure 41. Leakage Rate in ml/min during the Test Series.

Leakage vs. Rainfall

During the period of test the site was plagued with rain. It was therefore difficult to make quantified meaningful measurements of the amount of water pumped from the sump during the test but by grab sampling the quantity leaking through the dike. We did attempt however to measure and plot the rainfall vs the apparent leakage rate as shown in Figure 42 .

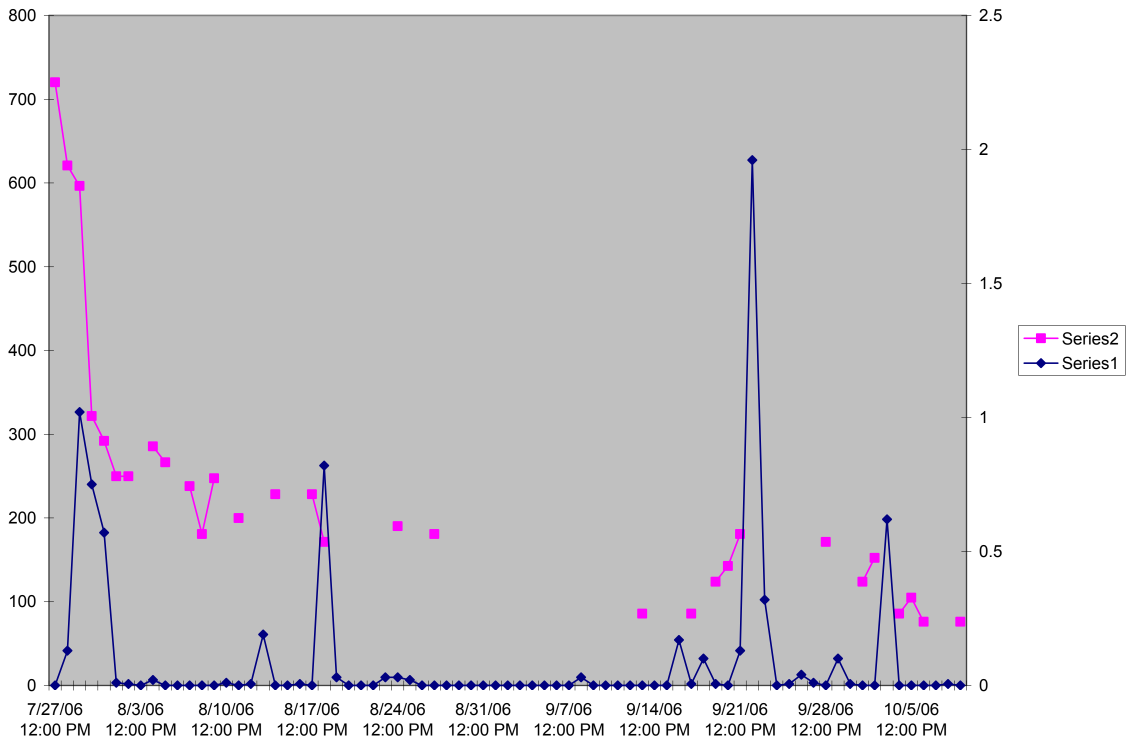

Figure 42. Rainfall and Leakage Rate during the Test Period.

Final comments

Despite the limited availability of time and resources, the test program provided some important information.

Ideally, a period of time (perhaps 2 weeks) should have been devoted to establishing baseline leakage rates, piezometer levels, and dike settling after the dike was constructed but before electricity was applied.

CONCLUSION

The demonstration showed how electrokinetics can simultaneously dewater (and retard water movement through) a leaking dike. The most significant demonstration effects took place within the first 14 days of operation. During those first two weeks, measured dike leakage dropped by more than 70 percent, and dike settlement/consolidation reached 50 percent of the final project total of 0.156 feet (47.5mm), or 2.6 percent of the original dike height of 6 feet.

Other indicators and evidence of the technology's impact include: changing piezometer levels over time; clearly visible movement of water to both the horizontal and vertical cathodes; and significant electrochemical deterioration of the aluminum anodes.

Despite the limited availability of time and resources, the test program provided some important information about the technology's viability. Therefore, it is recommended that the technology be further applied and evaluated at one or more "real world" sites where dewatering and consolidation of soils or sediments is needed. It is also recommended that future application and evaluation of the technology have built into it even more rigorous and quantitative monitoring and measurement of project variables.

[1] Wittle, J.K., et al., 2006, Innovative technology demonstration pilot study: electro-kinetics dewatering and consolidation of Erie Pier fine silts: draft report

[2] Zanko, L.M., and Oreskovich, J.A., August 2004, Emerging technology demonstration at the Erie Pier Confined Disposal Facility, draft NRRI Report of Investigation (unpublished)