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DoD Corrosion Prevention and Control Program

Demonstration and Validation of Single-Well Electro-Osmotic Dewatering Systems for Corrosion Mitigation

Final Report on Project F10-AR07

Michael K. McInerney, Christopher Athmer,
and Lawrence Clark

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Michael K. McInerney

Construction Engineering Research Laboratory
U.S. Army Engineer Research and Development Center
2902 Newmark Drive
Champaign, IL 61822

Lawrence Clark

Mandaree Enterprise Corporation
812 Park Drive
Warner Robins, GA 31088

Christopher Athmer

Terran Corporation
4080 Executive Drive
Beavercreek, OH 45430

Final report

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Under Project F10-AR07, “Moisture Control Using Intelligent Single-Well Electro-Osmotic Dewatering Systems ”

Abstract

When precipitation, runoff, and snowmelt percolate into soil and overload existing drainage infrastructure, the water table around building foundations can rise and infiltrate through cracks and joints. When infiltration exceeds sump pump capabilities, standing water and residual dampness can corrode or ruin fixtures, equipment, and stored supplies, also promoting mold growth that can make workers ill. The conventional solution—trenching and installing drainage tiles—is expensive, disruptive, and often ineffective. This report documents the development and demonstration of a patented electro-osmotic dewatering technology that works with outdoor wells and pumps to lower the water table around subgrade structures, thereby reducing or eliminating damage to building contents and the subgrade structure.

After a pilot test at an installation in Japan and a site-selection procedure, an optimized prototype system was installed for an administrative building at Blue Grass Army Depot, KY. The system was able to nominally lower the water table, and electro-osmotic flow was confirmed to positively impact pumping rates. However, site-specific drainage issues allowed rainwater to bypass the system and infiltrate the basement. Given less problematic site conditions, the projected return on investment for the technology was 9.97. Recommendations are offered for further development that could significantly increase technology effectiveness.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Prevention and Control (CPC) Project F10-AR07, “Moisture Control Using Intelligent Single-Well Electro-Osmotic Dewatering Systems.” The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM) and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Ismael Melendez (IMPW-E), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). Significant portions of this work were performed by Mandaree Enterprise Corporation, LLC, Warner Robins, GA. At the time of publication, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Michael K. McInerney, CEERD-CFM, was the ERDC CPC Program Coordinator. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Lance D. Hansen.

James Sivley, Chief of Facilities for the Blue Grass Army Depot Directorate of Public Works, is gratefully acknowledged for his contributions to the planning and execution of this project. The authors also acknowledge Mark Puhalla, U.S. Army Engineer District–Savannah, Glenn Todd, Fort Benning Directorate of Public Works (DPW), and Milam Le Bleu, Kawakami Army Ammunitions Depot DPW, for assisting with the site evaluation.

The Commander of ERDC was COL Bryan S. Green and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

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1 Introduction

1.1 Problem statement

Water intrusion is a very common problem for Department of Defense (DoD) and Army building managers and maintainers. When water percolates down into soil and accumulates around a subgrade structure, such as a basement or underground bunker, it will attempt to reach a pressure equilibrium by finding a path through structure, either flowing through cracks, holes, or joints; or by infiltration through porous construction materials. During periods of heavy rain or snow-melt runoff, large volumes of water can seep through the subgrade portions of walls and floors in concrete structures, damaging or destroying the structure’s contents, corroding metal fixtures and equipment, and rotting wood. Water intrusion also corrodes the steel reinforcement in the concrete, degrading the facility’s structural integrity. High interior moisture resulting from water intrusion also nurtures the rapid growth of mold and mildew, producing poor air quality that can cause respiratory distress or disease in personnel working near these spaces.

In locations predominantly consisting of expansive clay soils, groundwater and water intrusion can create additional structural problems. Wetting/drying cycles of expansive clays impose excessive loading on subgrade walls and floors, creating stresses that can crack foundation walls and slabs. The resulting damage will increase maintenance and repair requirements and costs, including the need to replace the waterproofing membranes that were installed at construction time. The costs of both the resulting water damage and accompanying corrosion damage are excessive and must be reduced.

In terms of facility types operated by the U.S. Army, General Administration Buildings (FAC 6100)[*] and Enlisted Unaccompanied Personnel Housing (FAC 7210) have the highest overall corrosion maintenance cost. In

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[*] FAC (facility analysis categories) are DoD four-digit Real Property Asset Database (RPAD) codes for facilities.

Fiscal Year 2011 the total maintenance corrosion costs for General Administration Buildings was $104M and $90M for Unaccompanied Personnel Housing (Herzberg 2014).

Preventing water intrusion into basements and other subgrade structures is a centuries old issue for engineers. The most common method is a waterproofing membrane installed on the outside of the below-grade portion of the structure. However, these membranes can be damaged during construction, and any resulting leaks cannot be easily repaired.

Sump pumps can remove standing water from a basement, but they do not keep water out of the building. They are subject to failure under heavy use and often cannot prevent the accumulation of standing water during the wettest seasons.

The conventional solution for existing problem structures—trenching and installing drainage tiles—is labor-intensive, time-consuming, disruptive to facility operations, and subject to failure. This solution also may become ineffective over time as a result of local changes in runoff and drainage patterns due to new construction of pavements or other facilities. Instead of working directly on the building or the adjacent landscape, the Army could benefit from the application of less-intrusive technologies to divert or remove water from soil in the immediate vicinity of the building.

In 2006 the U.S. Army Engineer Research and Development Center (ERDC) patented an innovative electro-osmotic method and system for dewatering soils and other particulate materials (Morefield et al. 2006). It applies the well-known phenomenon of electro-osmotic flow to a specialized design that arranges an anode and cathode vertically within in a single well to extract moisture from surrounding soil. The DoD Corrosion Prevention and Control Program funded the Construction Engineering Research Laboratory (ERDC-CERL) to demonstrate and validate this technology as an effective and economical method for removing underground water from the immediate vicinity of an existing Army facility.

1.2 Objective

The objective of this project was to design, demonstrate, and validate the patented Intelligent Single-Well Electro-Osmotic Dewatering (ISWEOD) system in a field implementation to reduce the groundwater level near a building subject to destructive subgrade water intrusion.

1.3 Approach

The project began with development of a laboratory model to produce an enhanced production version of the ISWEOD system. System design is discussed briefly in Chapter 2 and fully documented in Appendix A.

The laboratory model provided criteria for site selection. Three sites were evaluated as potential demonstration locations: Kawakami Army Ammunition Depot, Japan; Fort Benning, GA; and Blue Grass Army Depot, KY. Blue Grass Army Depot (BGAD) was selected as the demonstration site because the soil conditions at Kawakami and Fort Benning were not suitable for the technology. The results of the site evaluations are presented Appendix B, and the site soil analyses are presented in Appendix C. The research team selected BGAD as the demonstration site for reasons given in the appendices.

The project team coordinated with the BGAD Directorate of Public Works (DPW) to select the specific area and building for the demonstration. Contractors installed monitoring wells nearby the selected building to monitor the water table level outside the influence of ISWEOD system operation. The system was then installed and monitored to collect data.

To determine the effectiveness of the electro-osmotic process, the research team tested four driving voltages. The system was evaluated operating at 0, 12, 24, and 40 volts. The 0 volt level was used only during evaluation and commissioning of the pumps (i.e., operation of the wells and pumps without electro-osmosis). The other operational voltages helped to determine the water-collection impact of wells in conjunction with electro-osmosis: higher driving voltages should collect more water and correspond positively to higher pumping rates.

1.4 Metrics

The following criteria were selected to determine the success of the demonstrated system:

1. Lowering of the water table in the vicinity of the ISWEOD wells
2. A positive correlation between increasing the electrode voltage and higher pumping rates
3. Reduction of water intrusion into the basement

To quantify ISWEOD performance, the system acquisition/control module recorded the baseline level of the water table in the vicinity of the ISWEOD wells using pressure transducers (i.e,. *piezometers*). These piezometers were installed beyond the area affected by the ISWEOD-produced electric fields.

The pumping rate of each ISWEOD well was determined by monitoring the number of pump cycles over a period of time.

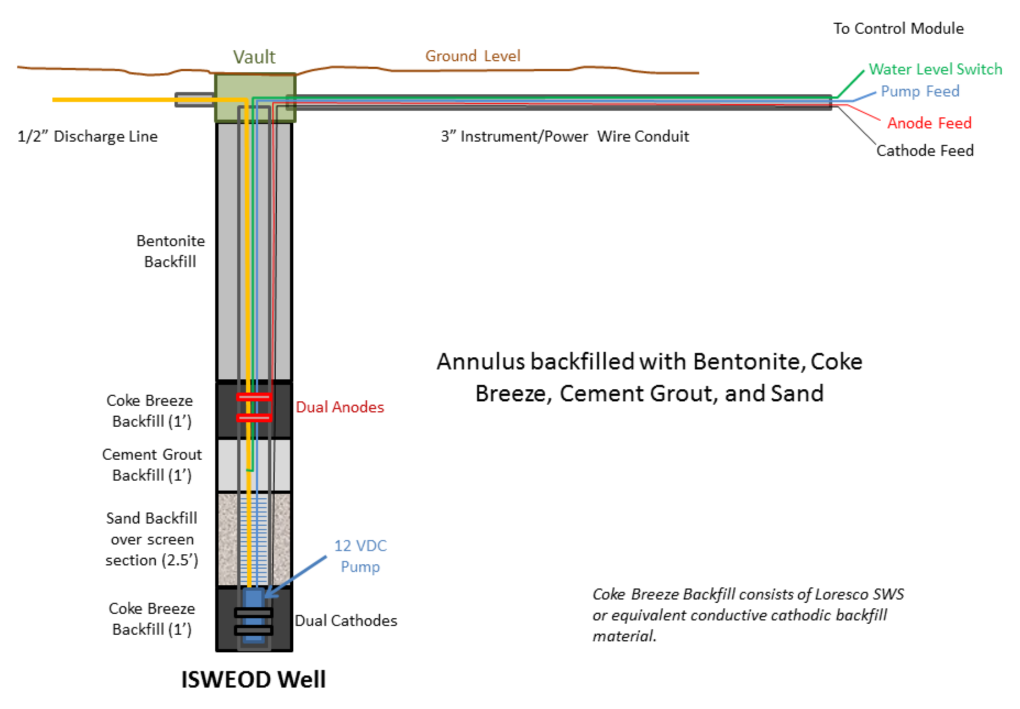
Quantitative validation of ISWEOD system performance according to the third criterion was not possible because of persistent drainage problems on the west side of the building, where rainwater would collect in the porous fill surrounding the building and drain to the basement along the wall and footers. (This issue is explained in section 3.1.3.)

2 Technical Investigation

2.1 Technology overview

The ISWEOD system design consists of a number of small, individual water-extraction wells that operate on principles of electro-osmotic flow. Electro-osmosis is the movement of a fluid though a porous medium, driven by an external electric field. The flow is initiated by the movement of positively charged ions (i.e., *cations*) present in the pore fluid of the medium; the water surrounding the cations moves with them (McInerney 2002). The wells are installed around the building perimeter using methods similar to boring post holes into the ground, and the design requires no building modifications. Each well uses a pair of primary electrodes fastened outside a vertical polyvinyl chloride (PVC) pipe, with the anode positioned above the cathode to force water that enters the well downward. In the initial ISWEOD system concept a pair of *guide electrodes* are installed near the primary electrodes to help extend the electric field further from the wells in order to increase the influence of the electro-osmotic field. In this implementation of the system the guide electrodes did not increase the system effectiveness and were replaced by redundant electrodes. Figure 1 shows a diagram of an individual well.

Figure 1. Design of the ISWEOD well.

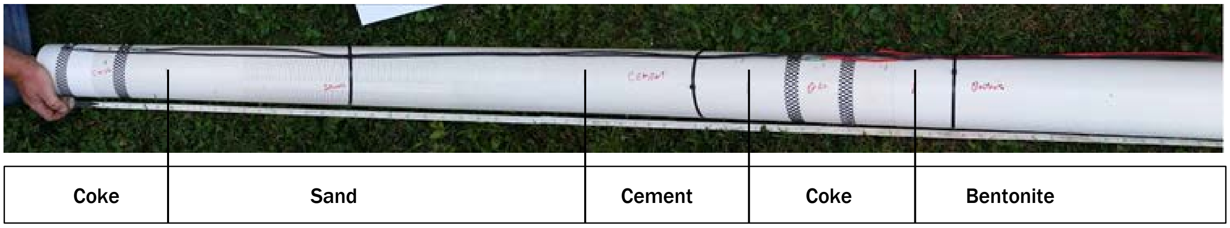


Each electrode consists of two bands of expanded titanium meshes with dimensionally stable oxide coatings, which can be seen near the middle and bottom of the well diagram. Each band is 1 in. wide and positioned 4 in. from the other. Each well contains two anodes and two cathodes, not only to help propagate the electro-osmotic current, but also to provide redundancy in case of damage to one or the other during installation or operation. The wells are installed with a cathodic protection backfill material (e.g., coke breeze) packed around the electrodes and fine sand around the well screens. A 1 ft long cement seal between the well screen sand pack and the anode zone coke fill electrically isolate the two electrodes. Bentonite chips are placed in the annulus above the anode coke zone to seal out surface water. The backfilling of an installed well is done in this order:

1. 0.5 ft of bentonite is placed at the bottom of boreholes that touch bedrock in order to isolate the well from the bedrock (not visible in Figure 1).
2. 1.5 ft of cathodic backfill material is placed to cover the cathode.
3. 2 ft of fine sand is placed to cover the well screen.
4. 1 ft of cement is placed to electrically isolate the area between electrodes (see explanation in Appendix A).
5. 1 ft of cathodic backfill material is placed to cover the anode.
6. The remaining area is filled with bentonite to limit surface water intrusion.

Backfill segments on the ISWEOD well are shown in Figure 2.

Figure 2. ISWEOD well, marked with backfill sections.



Flexible polyethylene tubing, 0.5 in. diameter, is attached to the pump discharge port and routed back up near the surface and then laterally to a nearby storm drain (see Figure 1 near top left).

An instrument/power wire conduit was placed to route feed wires for the anodes and cathodes, and to house conductors for the pump electrical power and a water-level switch connected to the master controller.

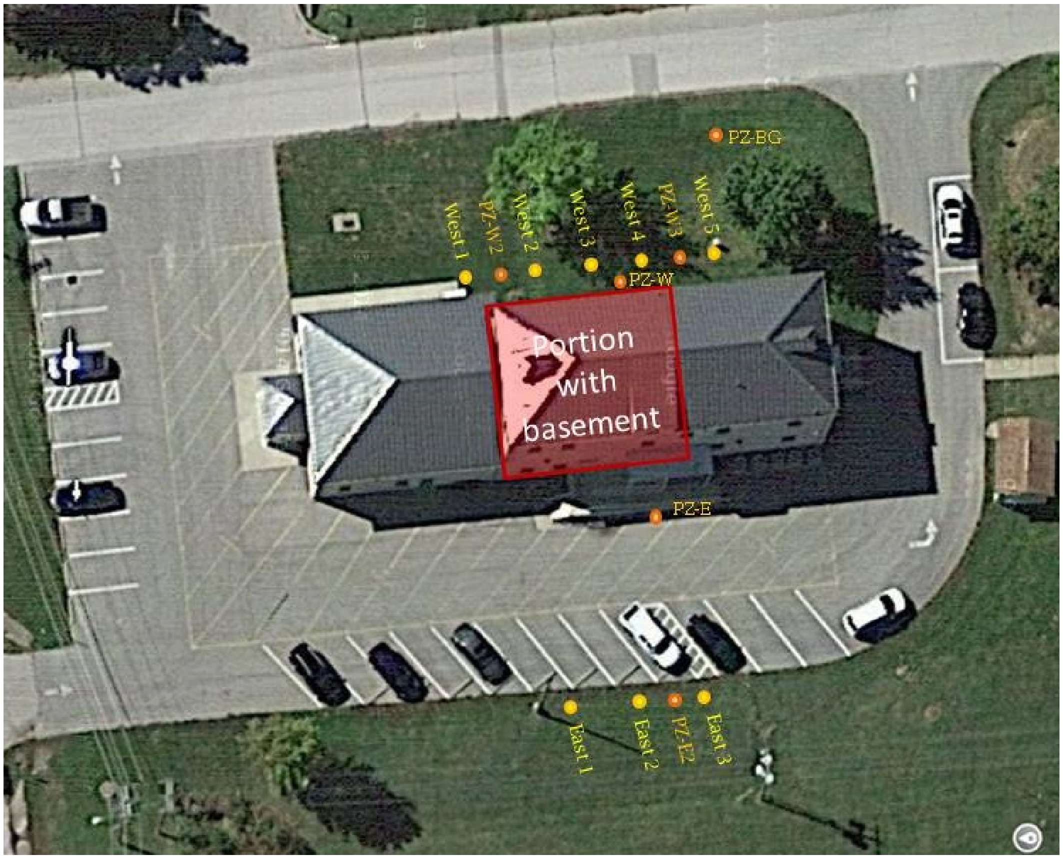
Each well is equipped with a water-level control switch. When the water level rises inside a well and makes contact with the level switch, the controller turns on the pump for a preset amount of time. The volume of water moved in each pump cycle is calculated using the calibrated pump flow rate and pumping time per cycle.

2.2 Field work and system installation

The ISWEOD well system, services, and piezometric monitoring wells were installed at BGAD Building S-3 between 21 September and 9 October 2015. A piezometric well consists of a small-diameter pipe, screened at or below the water table, designed to monitor and record the water table level using piezoelectric pressure transducers mounted inside the pipe. Eight ISWEOD dewatering wells and six piezometric wells were installed.

Five ISWEOD wells were placed on the west (grassy) side of the building and three were placed on the edge of the parking lot on the east side (Figure 3). The ISWEOD well locations are indicated by yellow dots, and the six piezometric well locations are indicated by orange dots.

Figure 3. ISWEOD and piezometric well locations at BGAD Building S-3.



One reference piezometric well, PZ-BG, was installed approximately 30 ft west of the ISWEOD system on the west side of the building to provide background (i.e., benchmark) water-table data beyond the influence of the ISWEOD wells (see Figure 3). Because the topology of the area indicates that water flows west to east across the site, both above and below the grade, the PZ-BG well is located “upstream” from the ISWEOD system.

The installation began with the boring of the ISWEOD and piezometer holes using an air-rotary drilling rig (Figure 4). The ISWEOD holes were drilled using an 8 in. bit. The boreholes were drilled to a depth of 12 ft. or bedrock refusal. (All three of the east-side boreholes reached bedrock). The preassembled ISWEOD wells were immediately installed, and the holes were backfilled as described in section.

Figure 4. Drilling rig.

The piezometer holes were drilled with a 4.5 in. bit. The piezometer wells were constructed of 5 ft lengths of 1 in. diameter PVC well screen with 7 ft of riser. To promote hydraulic connectivity (water transfer) the piezometer holes were backfilled with 6 ft of fine sand. The rest of the hole was filled with bentonite to prohibit surface water infiltration. Finally, piezoelectric pressure transducers were installed in each well.

Installation of the ISWEOD and piezometer wells are shown in Figure 5 and Figure 6. Installation of supporting elements is shown in Figure 7.

Figure 5. ISWEOD wells and piezometers during installation.

Figure 6. ISWEOD well installation on west side of building.

Figure 7. Vault, conduit, and drain line (tubing) installation.

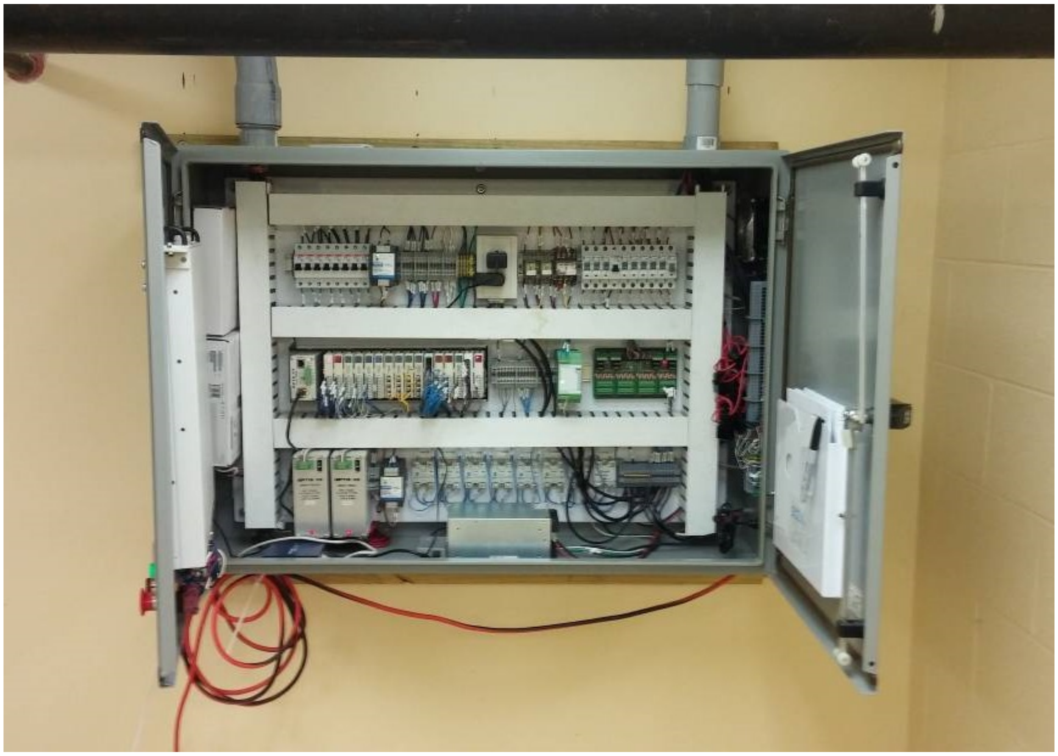
Each well required installation of anode and cathode lead wires, conductors for pump electrical power, conductors for a water-level sensor, and a pump water discharge line. Once the ISWEOD and piezometer wells were in place, a fiberglass vault (splice box) was cemented to the top of each PVC well pipe and set flush with the ground surface (see Figure 7). The vaults accommodate electrical and pump connections and access to the wells, and these are laid out to avoid interfering with grounds maintenance. The vaults were interconnected with PVC conduits which contained the electrical wires. The wires were routed to the master control cabinet located in the basement of Building S-3 (Figure 8). The pump discharge tubing was also buried and routed to the storm sewer (see Figure 7).

Figure 8. Master control cabinet in basement of building S-3.

The main electrical conduit on the west side entered the basement of the building through an abandoned 3 in. steel pipe. The 2.5 in. PVC conduit tightly fit inside the 3 in. pipe and required minimum sealant. On the east side of the building an abandoned water spigot and pipe were removed and the hole enlarged to accommodate the 2 in. conduit.

The ISWEOD system wiring was routed through the vaults and conduits into the master control unit cabinet, showing its contents in Figure 9.

Figure 9. Fully instrumented and wired master control unit.



The master control unit contains a direct current (DC) power supply for the electrodes, a 12 volt DC power supply for submersible pumps, voltage and current recorders, timers, and counters. The data are recorded and the pumps are controlled by the master control module, which is based on an OPTO 22[*] industrial automation system. The master control module also copies data to an onboard micro secure digital (SD) card that can be removed and mounted to an external desktop or laptop computer. The entire control system operates on 120 volts alternating current (AC).

The anode and cathode electrodes are energized by an adjustable (0–40 volt) DC power supply. The master control module switches the power supply on and off. It can be programmed to create a pulse waveform, which has been demonstrated to increase the effectiveness of electro-osmosis (McInerney 2002). The system measures and records the current on each anode.

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[*] Opto 22, Temecula, CA. http://www.opto22.com/site/about.aspx, accessed 23 October 2017.

The water collected in the ISWEOD wells is removed by the installed submersible pumps. They operate on 12 volts DC and are controlled by the master control module and level sensor.

During the demonstration period, the following data were recorded every 6 hours:

- Date and time
- Power supply voltage
- Power supply current
- Current to each of the eight ISWEOD anodes
- Number of pump cycles for each pump
- Water volume removed at each well
- Piezometer well water levels
- Cabinet temperature
- Room temperature and relative humidity

As stated previously, the volume of water removed for each pump cycle is calculated from the pump flow rate and pumping time. Each well has a water-level control switch. When the water level rises and makes contact with the level switch, the control module turns on the associated pump for a preset amount of time.

The pumps on the west side of the building lift 1 liter of water each cycle, and the east-side pumps move 0.5 liters per cycle. The east-side wells are not as deep as the west ones because the bottoms are set just above the bedrock, and the water table there is already lowered because of the building foundation and sump pumps. Therefore, they pump less water per cycle and the cycles are less frequent than they are for the west-side pumps.

2.3 Commissioning

The system was started on 30 October 2015 without the electrodes being energized so the researchers could collect baseline water level and pumping information and identify any problems with the data collection and recording system. The operations through November and December collected valuable trend data but also revealed issues causing water to collect in the vaults and leak into several piezometric wells. These problems negatively influenced the data because it takes several days for the piezometric well levels to re-equilibrate with the water table. The project team tried to fix the problem by drilling weep holes through the bottom of each vault. However, to fully resolve the problem the tops of the piezometric wells had to be sealed.

There also was a power failure, after which the system did not reboot properly. When the system did restart on 6 December, all collected data had been deleted from memory and the backup drive. However, data had been backed up to a laptop three weeks earlier, so only three weeks of data were lost. To prevent a recurrence of the problem, an uninterruptable power supply (UPS) was added to the controller module and data collection system. In the event of a power failure, the ISWEOD electrode power supply and pumps will shut down, but the data system will continue recording for up to three days. Also, a newer data controller with onboard backup was installed to make sure no data are lost in the future.

On 23 December the site was deluged with a torrential rain. Due to flooding on the west side of the building, water drained into and flooded the vault attached to the West 3 ISWEOD well, causing water to run into the master control cabinet through the electrical conduit. Afterword, more drains were added to the vaults to allow water to weep out more readily. However, the clayey soil onsite could prevent these drains from being totally effective during very heavy rains, so the conduit line from the west side into the data cabinet was sealed with expanding polyurethane foam to prevent a recurrence of water entering the master control cabinet. A drain hole was also drilled into the conduit for redundancy.

Leakage into the cabinet had affected two data system input cards, which affected the data for two of the piezometric west-side wells. Those input cards were dried out and continued to work with no further problems.

Prior to initiating full-time system operation, a stray voltage/current assessment was done at the site to make sure no buried utilities would be affected by the ISWEOD system. No interference was found, and operation began on 2 January 2016.

2.4 Operation

The system was operated at several electrode voltage levels, and performance was monitored for 11 months. Data from the master control module were downloaded monthly and evaluated.

The system was operated at 12, 24, 30, and 40 volts for various periods throughout the demonstration until shutdown on 22 November 2016. The system was operated the longest at 24 and 40 volts, with shorter periods of operation at 12 and 30 volts.

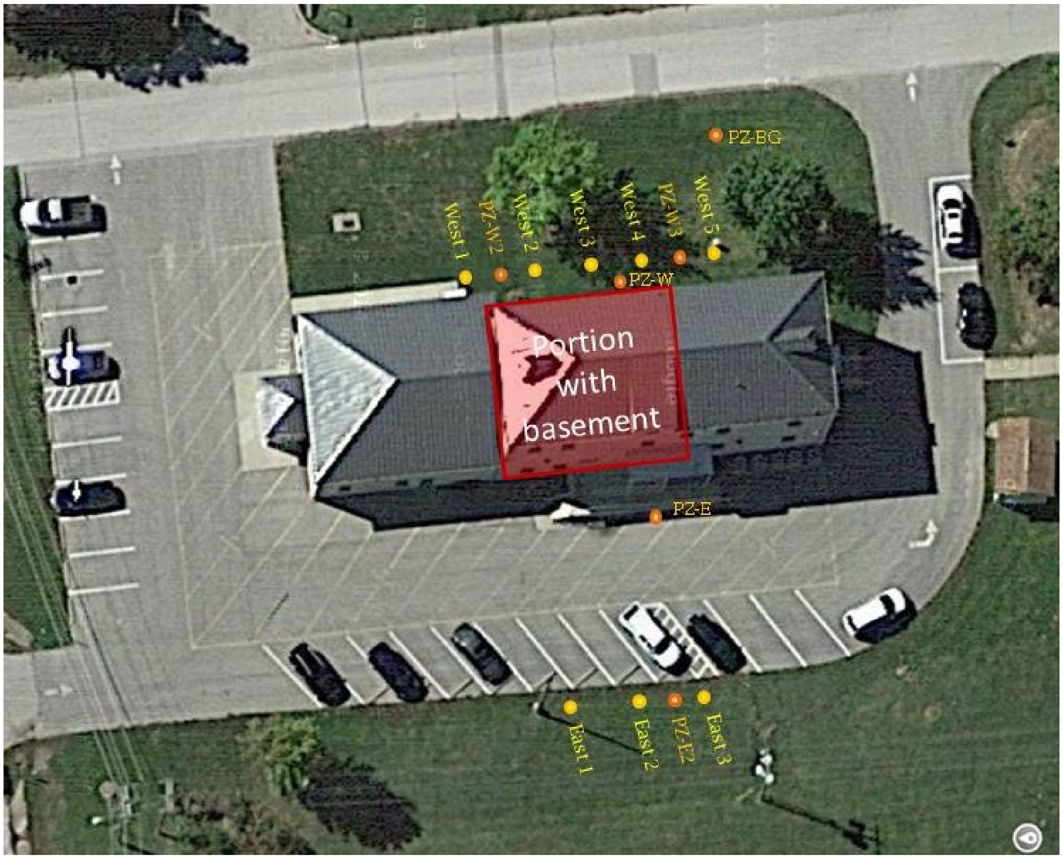
The first attempt to operate the complete system at 40 volts was not successful due to the lack of current capacity by the power supply. Near the end of the demonstration period, the east well electrodes were disconnected to allow the west wells to be operated at 40 volts until the end of the demonstration.

3 Discussion

3.1 Results

Evaluation of the data collected during the 13-month operation validates successful system performance for two of the three metrics listed in Chapter 1, section 1.4. Drainage and ponding issues at the demonstration site made it impossible to accurately assess project results for the third metric. For the reader's convenience in comparing the well designations with the text in this chapter, Figure 3 is repeated below for reference.

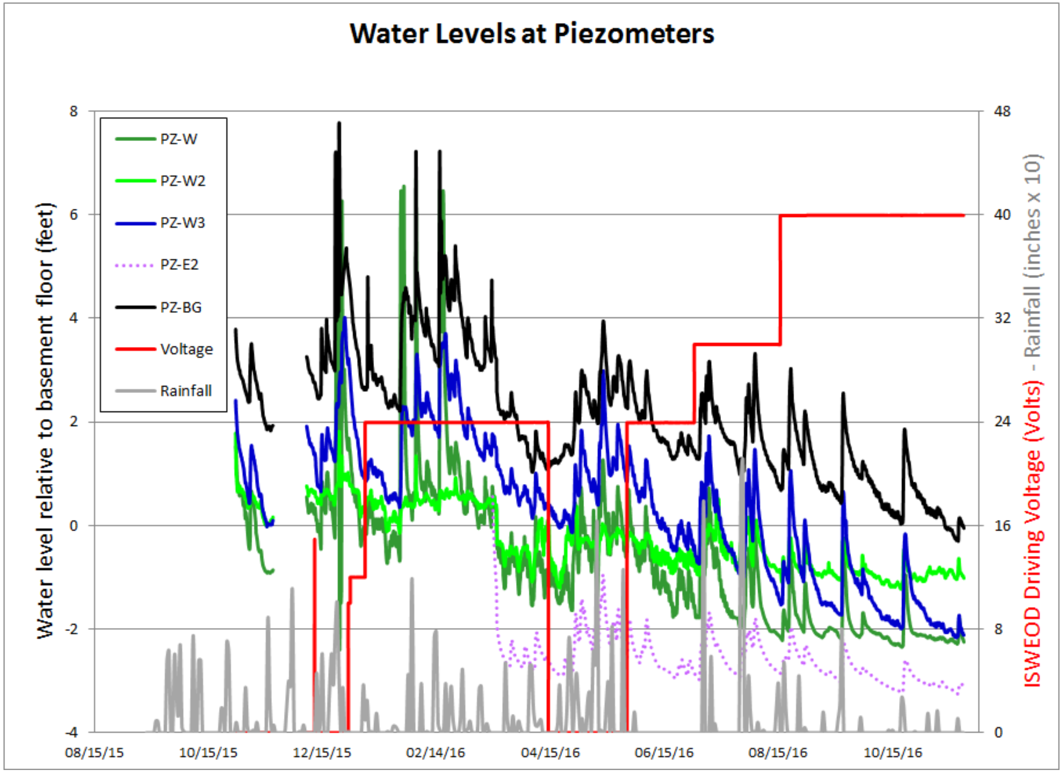
Figure 3 [reprinted]. ISWEOD and piezometric well locations at BGAD Building S-3.



3.1.1 Metric 1—water table level comparisons

Measurements of the water table near the ISWEOD wells show a lowering of the water table level attributable to operation of the ISWEOD system. Water level data collected by the piezometric wells are shown in Figure 10. One piezometric well (designated PZ-BG) was installed approximately 35 ft west of the ISWEOD system on the west side of the building. Unlike the others, this piezometric well was placed outside the lines of ISWEOD wells to collect background data on the water table level outside the direct influence of the dewatering system.

Figure 10. Piezometer well water levels during 13 month ISWEOD demonstration period.



Piezometer PZ-W2 is located on the west side of the building between ISWEOD wells West 1 and West 2, and piezometer PZ-W3 is located between ISWEOD wells West 4 and West 5. Both wells are about 15 ft from the foundation. Piezometer PZ-W is also located on the west side of the building but is only about 8 ft from the foundation.

Piezometer PZ-E was damaged and unusable. An individual data logger was installed in the piezometer well that is located between ISWEOD wells East 2 and East 3 on the east side of the parking lot located on the east side of building. This piezometer is designated PZ-E2.

ISWEOD driving voltages are shown in red in Figure 10. The electrodes were operated at 0, 12, 24, 30 and 40 volts for various periods throughout the demonstration. The local rainfall data are also shown in the figure. Rainfall amounts are multiplied by a factor of 10 in order to make the data visible on the plot.

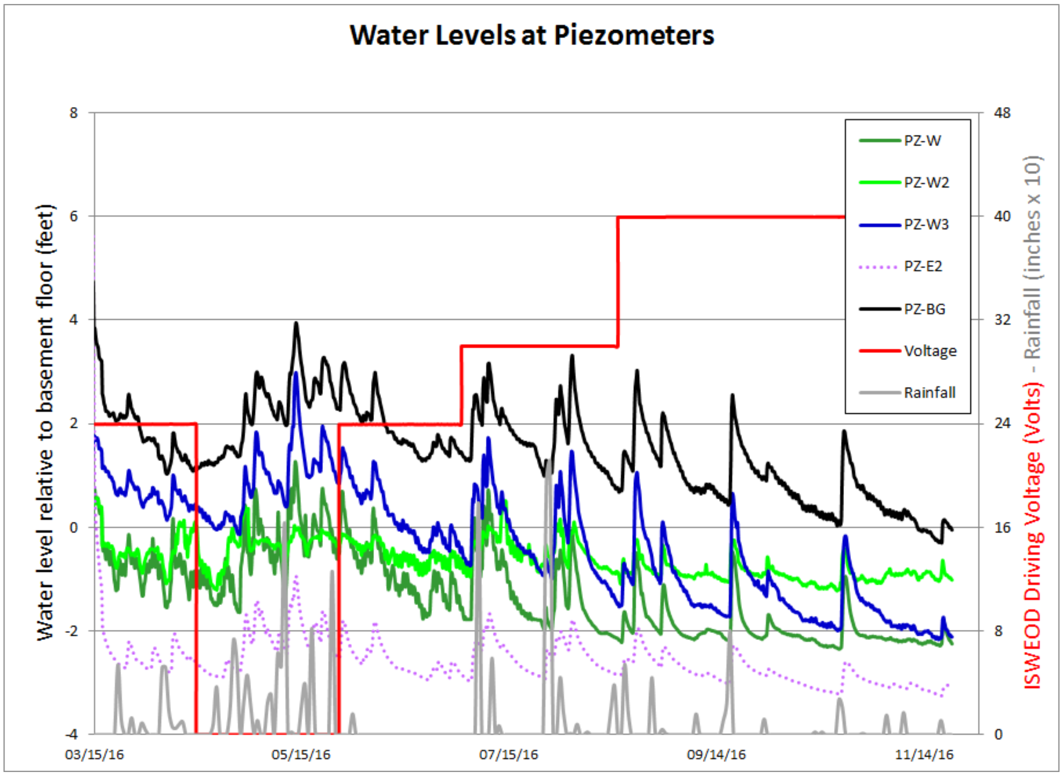
Much of the water level data collected before March 2016 exhibit erratic readings because rainwater was leaking into the piezometric wells. The piezometers were installed under flush-mount vaults and initially vulnerable to flooding when the vault filled with water. This condition was finally corrected by sealing the tops of the piezometer wells with caps and plumbers putty in mid-March 2016.

The response to rainfall is evident. All piezometric wells show an abrupt increase in water level after a large rainfall followed by a gradual reduction.

All piezometers indicate a reduced water-table level relative to the background level measured by PZ-BG. Most of this effect is probably due to the soil and gravel fill on that side of the building, which allows quick collection and easy movement of the water near the surface. This water is then directed toward the building drainage system. The background piezometer (PZ-BG) is about 35 ft from the building, the ISWEOD system and piezometer wells (PZ-W2 and PZ-W3) are about 15 ft from the building, and piezometer PZ-W is 8 ft from the building. The small data set from November 2015, when neither the pumps nor the electro-osmotic component of the ISWEOD system were operating, clearly indicates that the water levels decrease nearer to the building.

Even though the building's surrounding soil conditions and drainage system has a large influence on the water levels in the soil, the effect of the ISWEOD system on lowering the water levels can be observed in the data. In Figure 11 the water level data set has been zoomed in to show only the final eight months of testing. This span of time documents the period when the ISWEOD system was operating with no surface water leakage into the piezometric wells and the data set is unaffected by power interruptions that had compromised data collection during earlier months.

Figure 11. Piezometer well water levels during ISWEOD demonstration, final eight months.



From April through May 2016 the ISWEOD system driving voltage was zero, and only the ISWEOD well pumps were operating. There were several rain events during this period, but the action of the pumps alone does not appear to have much effect on the water levels. However, during the periods when the ISWEOD system driving voltage was turned on (i.e., electro-osmosis was active), the water levels around the ISWEOD wells and the building dropped slightly faster than the background level. There is not much effect at 24 volts, but it becomes noticeable at 30 and 40 volts.

The water level nearest the building on the west side, as measured by PZ-W, dropped faster when the ISWEOD system was operating and with higher driving voltages. This well is about 7 ft from PZ-W3, which is between ISWEOD wells West 4 and West 5 (see Figure 3 or the copy of it at the top of this chapter). Note the period when the driving current is set to 40 volts. After a rainfall, the water levels rise in all piezometer wells and then fall off. The water level in well PZ-W falls faster than the water level in PZ-W3 or the level in the background well PZ-BG.

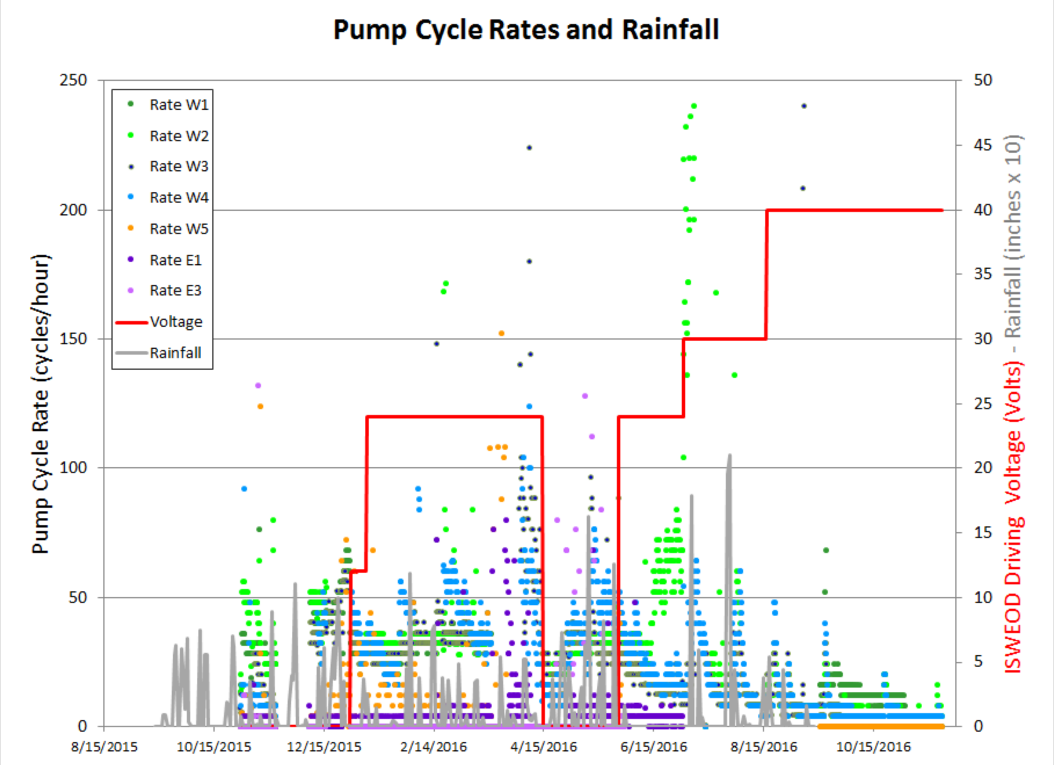
3.1.2 Metric 2—pump rates and driving voltage

The data indicate a slight dependence of pump rates on the ISWEOD driving voltage.

Figure 12 shows the pump rates and ISWEOD driving voltages over the 13-month demonstration period. The wells on the west side of the building are about 15 ft from the foundation and the wells on the east side are at the east edge of the parking lot (see Figure 3 or the copy of it at the top of this chapter).

ISWEOD driving voltages are shown in red in Figure 12. The electrodes were operated at 0, 12, 24, 30 and 40 volts for various periods throughout the demonstration. The local rainfall is also shown, again with amounts multiplied by ten in order to make the data visible on the plot.

Figure 12. Pumping frequency for each ISWEOD well during 13 month ISWEOD demonstration period.



The original pumps did not last for the entire demonstration period. Over the 10 months of operation, 7 of the 8 ISWEOD well pumps failed. These were relatively low-cost pumps. At three locations, the original pumps were replaced with higher-cost ones and these were found to be more reliable than the originals.

Due to the failing pumps, some of the pump cycle data were removed from the data set to avoid the inclusion of misleading, erroneous measurements. When a pump failed, the pump circuitry would call for the pump to turn on continuously and the pump cycle rates would jump significantly, so the erroneous data were ignored in the analysis.

Figure 13 shows the pump rates and ISWEOD driving voltages for the final eight months of the demonstration period, and Table 1 summarizes the pump cycle data accounting only for the periods of proper operation. Wells operated with 12 volts applied for only 10 days, and this period of time was not sufficient to produce enough useable data to properly evaluate this voltage level in comparison with the other voltage levels.

Figure 13. Pumping frequency for each ISWEOD well, final eight months.

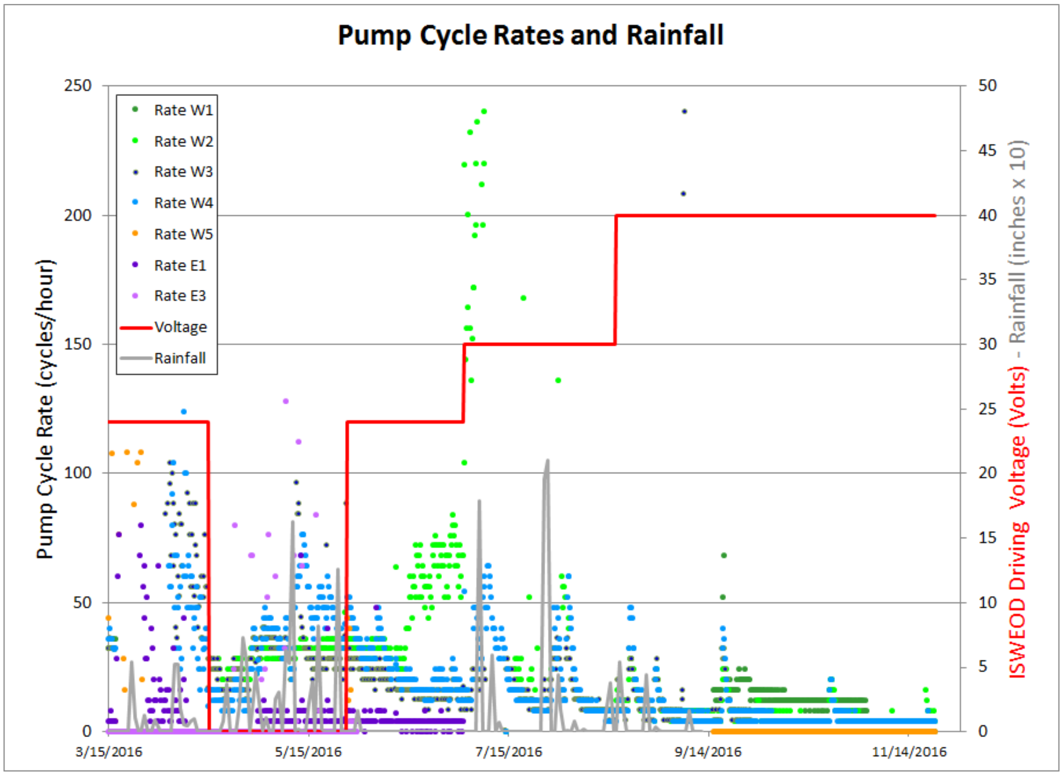


Table 1. Nominal pump rates (cycles per day) for the ISWEOD system.

	0 Volts	24 Volts	40 Volts
West 1	38.4	31.6	13.3
West 2	39.4	56.9	7.0
West 3	34.8	36.1	16.8
West 4	25.8	32.3	6.7
West 5	4.5	8.2	0.8
West Totals	142.9	165.1	65.3
East 1	4.3	6.5	Off
East 2	7.3	10.2	Off
East 3	4.3	0.4	Off
East Totals	15.9	17.1	

When under the influence of the ISWEOD electric field, the pump rates should increase because more water is being drawn into and removed from the wells. Rates should also increase with increasing voltage.

For the pumps that were run effectively, the average pump rates for each voltage step are listed in Table 1. The 24-volt condition shows a slight increase from the 0-volt condition but the 40-volt condition does not. This result is probably attributable to the fact that 40-volt run condition occurred during a summer/fall dry spell (see Figure 13). The basement was dry during the dry spell because rainfall events were insignificant. In fact, during the last two months of operation (when the driving current was 40 volts) there was only one rain event amounting to barely more than 0.25 in. During this time the groundwater levels reported by all piezometers dropped to, or below, the level of the basement floor, including the background piezometer PZ-BG. Consequently, some ISWEOD wells did not record any cycles during that time.

3.1.3 Metric 3—basement water intrusion

A reduction in basement water intrusion attributable to ISWEOD system operation could not be confirmed or adequately assessed due to a persistent drainage issue on the west side of the building. This issue caused surface water to bypass the wells, instead collecting and draining to the basement along the wall and footers. Four specific problems were noted:

- The ground on the west side of the building slopes slightly toward the building and there is a low spot against the foundation.
- The fill around the building appears to consist of soil and gravel that would allow quick movement of water through the ground to the building foundation.
- The entire west side yard would flood periodically, indicating that the nearby storm sewer could not drain runoff fast enough during some rain events.
- A clogged downspout in the area temporarily contributed to runoff issues, but the site maintenance detail cleared the downspout.

As a result of these problems, the basement had significant water infiltration within hours of a rain event, but the infiltration would stop within a few days.

If the cause of the infiltration had been groundwater only, there would have been a much longer lag time between rain events and basement infiltration, and the infiltration would have been more persistent and continual. However, the lack of reduction in basement water intrusion cannot be taken to imply that the ISWEOD infiltration metric was either met or not met.

3.2 Lessons learned

3.2.1 Site selection

The effectiveness of the ISWEOD system is very dependent on soil conditions. It functions most effectively in dense, clayey soils of low permeability that do not drain readily, and are present in large enough amounts around a structure to create infiltration problems. This principle was validated during the evaluation of three candidate sites for the project, as documented in Appendix A. The site evaluated at KAAD was not suitable because soil samples showed that the soil around the ECM was very sandy, probably local backfill material consisting of volcanic rock. That type of soil cannot effectively support electro-osmotic flow. Soil sampling around the proposed Fort Benning site showed a thin clay zone 1.5–2.0 ft thick between the surface and a sandy aquifer below. The clay layer is located 8–10 ft below grade, and the large water problem there is likely due to the foundation penetrating the clay zone. ISWEOD technology would not work effectively in these conditions because the entire subgrade structure is not surrounded by the clay zone.

The results of the soil analysis at the BGAD site showed good subgrade clay content, and the clay layer completely surrounded the building. Therefore, the site was properly selected for this demonstration project. The disadvantage of the site was that the soil at grade on the west side of the building consisted of soil and gravel fill that allowed quick collection and easy movement of the water toward the foundation. Also, the grade on the west side of the building sloped slightly toward the building, terminating in a low spot against the foundation. These conditions directed rainwater toward the building. Such issues can been corrected with proper landscaping.

3.2.2 Implementation details

This was a demonstration project to validate the functionality and costs of a prototype system. In permanent field implementations the system should be designed with ruggedized components for reliability over the long term. The results of this project point to two specific areas requiring focused design attention: pump reliability and conduit watertightness.

A successful implementation of the ISWEOD system requires the use of small, reliable, and affordable pumps or an alternative pumping system to remove the water from the wells. If pumps are specified, they must be able to operate reliably under the requirement for frequent on/off cycles in order to maintain system design water levels. The Proactive Poseidon 12-volt pumps did not last for the entire test. Over the 10 months of operation, 7 of the 8 pumps failed. These were low-cost pumps in their class, at $260 each. In three wells the low-cost pumps were replaced with higher-cost 12-volt pumps—the Proactive Abyss model, which cost $1,300 each. These were observed to be more reliable than the original pumps. If many ISWEOD wells are required, the costs of the pumps could become prohibitive. A vacuum-based or siphon system that runs continuously could be tested. A suitable multi-head suction pump could also be considered in future designs.

All vaults and wells must be watertight at the surface to prevent rainwater and runoff from entering the system. Leakage can cause electrical faults or overload pumps. In such cases, ISWEOD wells will perform much unnecessary work pumping away surface water before dewatering the soil around the foundation, and piezometric monitoring wells will return erroneous water table results. During the demonstration, these problems were corrected by improving the water seals. In a working application, system designers should specify durable and long-lasting watertight seals at all joints and fittings where ingress could occur.

4 Economic Summary

4.1 Costs and assumptions

The total project costs were $755,876. A rough breakdown of project expenses is presented in Table 2.

Table 2. Breakdown of total project costs.

Description	Amount
Labor	$173,910
Materials	--------------
Contract	$549,857
Travel	$12,109
Reporting	$15,000
Navy participation	$5,000
Total	$755,876

The field demonstration costs for this CPC project are shown in Table 3.

Table 3. Project field demonstration costs.

Item	Description	Amount
1	Project Management and Execution Labor	$185,271
2	Project Management and Execution Travel	$21,243
3	Soil Boring and Soil Analysis (3 sites)	$24,936
4	ISWEOD Laboratory Development	$36,455
5	ISWEOD Field Development	$85,908
6	BGAD Well Drilling and Installation Support	$67,050
7	BGAD ISWEOD System Fabrication, including materials	$73,466
8	BGAD Travel for Installation	$22,620
9	BGAD Monitoring	$12,313
10	BGAD Data Analysis and Reporting	$20,595
	Total	$549,857

Baseline costs (Alternative 1), new system costs (Alternative 2), and new system benefit cost savings (Alternative 2) are listed in Table 4.

Table 4. Costs used in ROI computation.

	Baseline				New System Cost				New System Benefit		
	Install Sump Pump System	Operate	Maintain	Total	Install ISWEOD System	Operate	Maintain	Total	Lost Productivity	Damage	Total
1	80,000	180	500	80,680	165,000	150	500	165,650	25,000	5,000	30,000
2		180	500	680		150	500	650	25,000	5,000	30,000
3		180	500	680		150	500	650	25,000	5,000	30,000
4		180	500	680		150	500	650	25,000	5,000	30,000
5		180	500	680		150	500	650	25,000	5,000	30,000
6		180	500	680		150	500	650	25,000	5,000	30,000
7		180	500	680		150	500	650	25,000	5,000	30,000
8		180	500	680		150	500	650	25,000	5,000	30,000
9		180	500	680		150	500	650	25,000	5,000	30,000
10		180	500	680		150	500	650	25,000	5,000	30,000
11		180	5,500	5,680		150	2,500	2,650	25,000	5,000	30,000
12		180	500	680		150	500	650	25,000	5,000	30,000
13		180	500	680		150	500	650	25,000	5,000	30,000
14		180	500	680		150	500	650	25,000	5,000	30,000
15		180	500	680		150	500	650	25,000	5,000	30,000
16		180	500	680		150	500	650	25,000	5,000	30,000
17		180	500	680		150	500	650	25,000	5,000	30,000
18		180	500	680		150	500	650	25,000	5,000	30,000
19		180	500	680		150	500	650	25,000	5,000	30,000
20		180	500	680		150	500	650	25,000	5,000	30,000
21		180	5,500	5,680		150	2,500	2,650	25,000	5,000	30,000
22		180	500	680		150	500	650	25,000	5,000	30,000
23		180	500	680		150	500	650	25,000	5,000	30,000
24		180	500	680		150	500	650	25,000	5,000	30,000
25		180	500	680		150	500	650	25,000	5,000	30,000
26		180	500	680		150	500	650	25,000	5,000	30,000
27		180	500	680		150	500	650	25,000	5,000	30,000
28		180	500	680		150	500	650	25,000	5,000	30,000
29		180	500	680		150	500	650	25,000	5,000	30,000
30		180	500	680		150	500	650	25,000	5,000	30,000

The economic analysis assumes the installation of 25 water-removal systems at typical Army administration-type buildings. This category of buildings was selected for the analysis because dry, usable basements are important to the missions these facilities support. Every square foot of these buildings needs to be effectively utilized. Due to mission growth and overcrowding, the basements in these buildings are needed either for office space or storage of office equipment, supplies, and/or files. The U.S. Army has more than 7,400 general-purpose administration buildings (Army Real Property Category Code 61050), and many of these have basements. The very conservative number of 25 buildings was chosen for the economic analysis because of the limitations of soil type and distribution in which this technology will function effectively. We focused this analysis on buildings with basements, but this technology applies to buildings of any type, including those with crawl spaces and on-slab construction. In these cases, the application will be building stabilization. Buildings constructed on clayey soils, especially expansive clays, are subject to movement due to changing water content in the soil, and ISWEOD technology can be used to limit the range of water-content fluctuations.

4.1.1 Alternative 1 (basement sump pumps)

A standard basement water-removal system using sump pumps is installed inside the basement. The work includes making a trench in the concrete floor around the perimeter, installing drain pipe, filling the trench and refinishing the floor. Interior floor drains may be installed if necessary for multi-point water collection. Sump tanks and sump pumps are installed. The number of tanks and pumps depends on the size of the basement and the amount of water to be removed.

The following assumptions are made in computing the costs of this type of basement dewatering system for a typical commercial-type building such a military administration building:

- The initial installation cost is $80,000.
- The cost to operate the system (electricity) is $180 per year, and the system-maintenance cost is $500 per year.
- Major maintenance (e.g., pump replacement) will be required every ten years.

4.1.2 Alternative 2 (ISWEOD ground dewatering)

For computing the ROI, the following assumptions are made concerning the ISWEOD system:

- The initial system cost is $165,000.
- The cost to operate the system (electricity) is $150 per year, and the maintenance cost is $500 per year.
- Major maintenance (e.g., pump replacement) will be required every ten years.

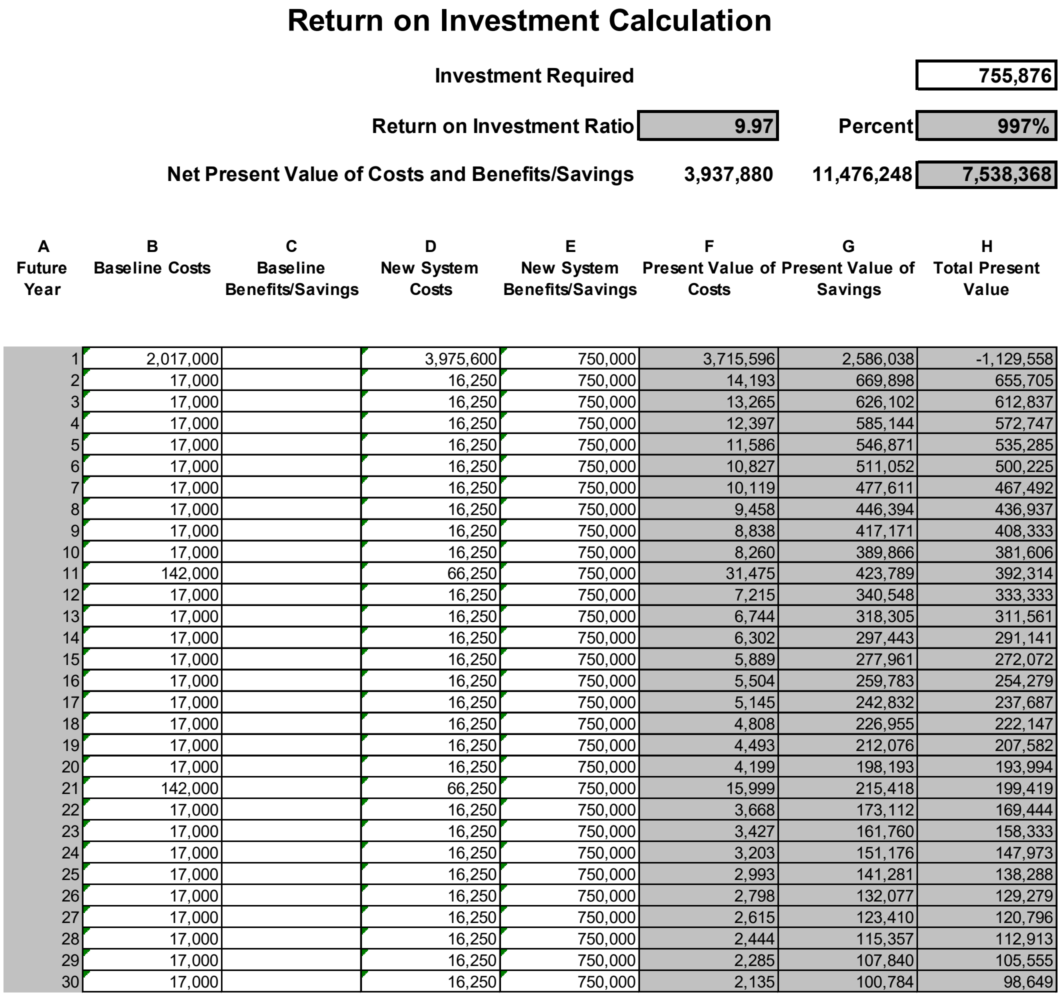
As the ISWEOD system removes water exterior to the basement, it prevents water from entering the basement and, therefore, helps to reduce indoor humidity. This function provides a benefit of $25,000 per year in helping to avoid lost productivity due to occupant health issues (e.g., mold allergies), and $5,000 of moisture damage to equipment (e.g., corrosion), office supplies, and other stored materials.

Initial purchase and installation of one ISWEOD system is not included in Year 1 of the ROI computation because the system is accounted for under project costs.

4.2 Projected return on investment (ROI)

The ROI for this technology was computed using methods prescribed by Office of Management and Budget (OMB) Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Comparing the costs and benefits of the two alternatives, the 30-year return on investment is projected to be about 9.97, as shown in and Table 5.

Table 5. ROI computation.



Return on Investment Calculation

Investment Required			**755,876**
Return on Investment Ratio	**9.97**	**Percent**	**997%**
Net Present Value of Costs and Benefits/Savings	**3,937,880**	**11,476,248**	**7,538,368**

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	2,017,000		3,975,600	750,000	3,715,596	2,586,038	-1,129,558
2	17,000		16,250	750,000	14,193	669,898	655,705
3	17,000		16,250	750,000	13,265	626,102	612,837
4	17,000		16,250	750,000	12,397	585,144	572,747
5	17,000		16,250	750,000	11,586	546,871	535,285
6	17,000		16,250	750,000	10,827	511,052	500,225
7	17,000		16,250	750,000	10,119	477,611	467,492
8	17,000		16,250	750,000	9,458	446,394	436,937
9	17,000		16,250	750,000	8,838	417,171	408,333
10	17,000		16,250	750,000	8,260	389,866	381,606
11	142,000		66,250	750,000	31,475	423,789	392,314
12	17,000		16,250	750,000	7,215	340,548	333,333
13	17,000		16,250	750,000	6,744	318,305	311,561
14	17,000		16,250	750,000	6,302	297,443	291,141
15	17,000		16,250	750,000	5,889	277,961	272,072
16	17,000		16,250	750,000	5,504	259,783	254,279
17	17,000		16,250	750,000	5,145	242,832	237,687
18	17,000		16,250	750,000	4,808	226,955	222,147
19	17,000		16,250	750,000	4,493	212,076	207,582
20	17,000		16,250	750,000	4,199	198,193	193,994
21	142,000		66,250	750,000	15,999	215,418	199,419
22	17,000		16,250	750,000	3,668	173,112	169,444
23	17,000		16,250	750,000	3,427	161,760	158,333
24	17,000		16,250	750,000	3,203	151,176	147,973
25	17,000		16,250	750,000	2,993	141,281	138,288
26	17,000		16,250	750,000	2,798	132,077	129,279
27	17,000		16,250	750,000	2,615	123,410	120,796
28	17,000		16,250	750,000	2,444	115,357	112,913
29	17,000		16,250	750,000	2,285	107,840	105,555
30	17,000		16,250	750,000	2,135	100,784	98,649

The original ROI estimate from the Project Management Plan (PMP) was 20.29. The difference between that estimate and the one presented here is explained by a thorough revision of the assumptions used in the ROI computation. Major changes in the cost assumptions are listed below:

- Baseline system
  - Installation of an interior sump pump system increased to $80,000 from $3,000 because of increased building size and inclusion of installation of perimeter drain tile and patching of cracks
  - Sump pump system operation costs increased to $180 per year from $75
  - Sump pump system maintenance costs decreased to $500 from $10,000 because the PMP included non-system maintenance costs such as water removal and yearly crack repair which will not be required with a quality sump pump system
  - Pump replacement cost increased to $5,000 from $3,000 but the pump lifetime was increased to 10 years from 5 due to better quality pumps
- New system
  - Installation of an ISWEOD system increased to $165,000 from $85,000 because data are now available on actual installation costs
  - ISWEOD system operation costs were not included in PMP
  - ISWEOD system maintenance costs were not included in PMP

5 Conclusions and Recommendations

5.1 Conclusions

5.1.1 Blue Grass Army Depot demonstration

Evaluation of the data during the 13-month demonstration at BGAD shows that the system was successful when evaluated against two of the three metrics stated in section 1.4.

Measurements of the water table in the vicinity of the ISWEOD wells show a lowering of the water table due to operation of the ISWEOD system, satisfying the first metric. Even though the building's drainage system has a large influence on the water levels in the soil, the effect of the ISWEOD system on lowering the water table level was observed in the data. During the periods when the ISWEOD system driving voltage was turned on (i.e., electro-osmosis was active), the water levels around the ISWEOD wells and the building dropped slightly faster than the background level as measured beyond the direct influence of the system. Little effect was observed at the 24-volt driving current, but the effect became noticeable at 30 and 40 volts.

A slight dependence on pump rates relative to the ISWEOD driving voltage was observed in the data, satisfying the second metric. For the pumps that were run effectively, the average pump rates at the 24-volt driving condition show a slight increase from the 0-volt condition.

The third metric for ISWEOD system success could not be confirmed or adequately assessed because of persistent drainage problems on the west side of the building. The ground surface contours and other problems caused water to collect and drain to the basement along the wall and footers. The ISWEOD system was not designed to prevent infiltration caused by undesirable runoff patterns, so ISWEOD effects on total basement infiltration could not be distinguished from the ponding of runoff in the basement.

5.1.2 ISWEOD system development

Pilot performance evaluations of the original ISWEOD design based upon the electrical and hydraulic characteristics of soil samples from KAAD showed that the system is unlikely to perform as required in that environment (see Appendix A). Based on the limited projection of the voltage field from the ISWEOD wells, it appears the electro-osmotic assistance was minimal at the pilot test locations. The preliminary design for KAAD was to have ISWEOD wells placed 24 ft apart along each side of the bunker. With the effective voltage field projecting only a few inches from the well, there would be no significant electro-osmotic influence.

The original system design was modified for application at a BGAD site with expansive clay soil. Based on the increase in pump rates and the improved projection of the voltage field, it appears that the modified design adds electro-osmotic assistance to the well water removal. With the original design the best performance was 5% of the driving voltage at 1.5 ft. The performance of the revised design was 4% to 10% at 3 ft—a large improvement over the original system. The performance improvement can be attributed to increasing the electrode surface area and placing an insulator in the borehole between the anode and cathode.

The design for BGAD was to have ISWEOD wells placed 12 ft apart along each side of the building. With the voltage field of the modified ISWEOD system projecting several feet from each well, effective electro-osmotic influence was expected. The electro-osmotic influence on water removal was confirmed in the demonstration, but the effect was not as great as predicted. The effectiveness of electro-osmosis is directly affected by the driving voltage applied to the electrodes, the electrode size, and the electrode spacing. All these effects were observed during ISWEOD system development. Because this was the first field demonstration of the system, these parameters were probably not optimized for the site.

5.2 Recommendations

5.2.1 Applicability

The modified ISWEOD system shows good potential for reducing and possibly eliminating water intrusion in many below-grade structures. Its best use will be in retrofitting an existing structure where standard repair would involve more expensive and intrusive methods such as excavation around the foundation and installation or repair of a an exterior drainage system. When soil characteristics are appropriate—denser, clayey soils are better—the modified ISWEOD system will be a safe and cost-effective method of preventing water intrusion by lowering the water table surrounding the structure.

One of the most beneficial applications will be for older, overcrowded military administration buildings. Every square foot of this building space needs to be utilized cost-effectively, including the basement, in order to control facility life-cycle costs. In older buildings where basement utilization has been abandoned due to moisture-related problems, reclaiming these spaces would provide considerable benefits.

Because the ISWEOD system removes excessive water from the soil outside the basement, the resulting decrease or elimination of subgrade infiltration reduces interior humidity that can contribute to occupant health issues (e.g., mold allergies) and prevent moisture damage to equipment (e.g., corrosion) and stored materials. ISWEOD technology complements another electro-osmotic technology called electro-osmotic pulse (McInerney 2002). EOP technology reduces moisture intrusion through concrete using electrodes installed in the below-grade concrete walls and floors of the building, and protrude into the adjacent soil.

5.2.2 Implementation

ISWEOD technology is not recommended for full implementation at this time. Technical issues remain, as discussed below in section 5.2.3.

No DoD unified facilities criteria or specification documents directly apply to this water-removal technology. The one that most closely applies is Unified Facilities Guide Specification (UFGS) 33 26 00.00 10, Relief Wells. This guide specification covers the requirements for relief wells to be constructed near dams or levees to relieve the excess hydrostatic pressures created by the presence of pervious strata close to the surface. However, because this document specifically addresses dams and levees, it would be best to develop a new UFGS for ISWEOD technology when it is suitable for DoD-wide implementation. For that future effort, UFGS 33 26 00.00 10 could serve as a content model for an ISWEOD guide specification.

ISWEOD design guidance could be included in a future Unified Facilities Criteria (UFC) document addressing the general application of electro-osmotic water-movement technologies. In addition to ISWEOD technology, the document could address EOP technology.

5.2.3 Future work

Lessons learned during the pilot and demonstration tests show several topics needing further work.

The efficacy of water removal by electro-osmosis is very dependent on the characteristics of the soil. Therefore, the range of ISWEOD system performance efficiency should be determined for common soil types with greater or lesser clay content.

A more reliable and energy-efficient pumping system should be developed. Instead of installing individual pumps in each well, a vacuum-based or a continuously operating siphon system should be investigated to reduce costs and service interruptions. A multi-head suction pump could also be considered.

The effectiveness of electro-osmotic water removal is directly affected by the driving voltage on the electrodes, the electrode size, and the electrode spacing. The optimum combination of values for these three parameters should be determined. Such a study could be performed using computer modeling to develop a design matrix.

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Appendix A: Optimizing the Intelligent Single-Well Electro-Osmotic Dewatering System

Pilot evaluation of the ISWEOD system for possible use at the Kawakami Arsenal, Japan (munitions bunker)

Introduction

Terran Corporation was commissioned to develop and implement a trial application of the Intelligent Single Well Electro-Osmotic Dewatering (ISWEOD) system, designed and patented by the United States Army Corps of Engineers (USACE). A pilot test was performed to determine the effectiveness of the ISWEOD system in Kawakami Army Ammunitions Depot (KAAD) soil conditions.

Electro-osmosis is the movement of a fluid though a porous medium due to an external electric field. The flow is initiated by the movement of cations (positively charged ions) present in the pore fluid of clay or a similar porous medium; the water surrounding the cations moves with them (McInerney 2002).

The simplified velocity equation for the fluid is:

$$V_e = \frac{\varepsilon \xi E}{4\pi \nu l} \qquad \text{Eq 1}$$

where

V_e = flow velocity of fluid (m/s)
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).

The external electric field is applied by placing the porous medium between two electrodes, an anode (the positive electrode) and a cathode (the

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* The difference of potential between the plates of a hypothetical capacitor used to model the diffuse layer in the porous medium.

negative electrode), and applying an electric potential (voltage) to the electrodes.

In the ISWEOD system the well casing has at least one anode and one cathode mounted in a manner to direct water toward the well collection screen (see Figure 1 in main report) using electro-osmosis. An anode is placed above the well screen while a cathode is placed below the well screen. Near the primary anode, a series of guide electrodes are placed to help project the electric field out from the well and into the soil, resulting in dewatering of a larger area.

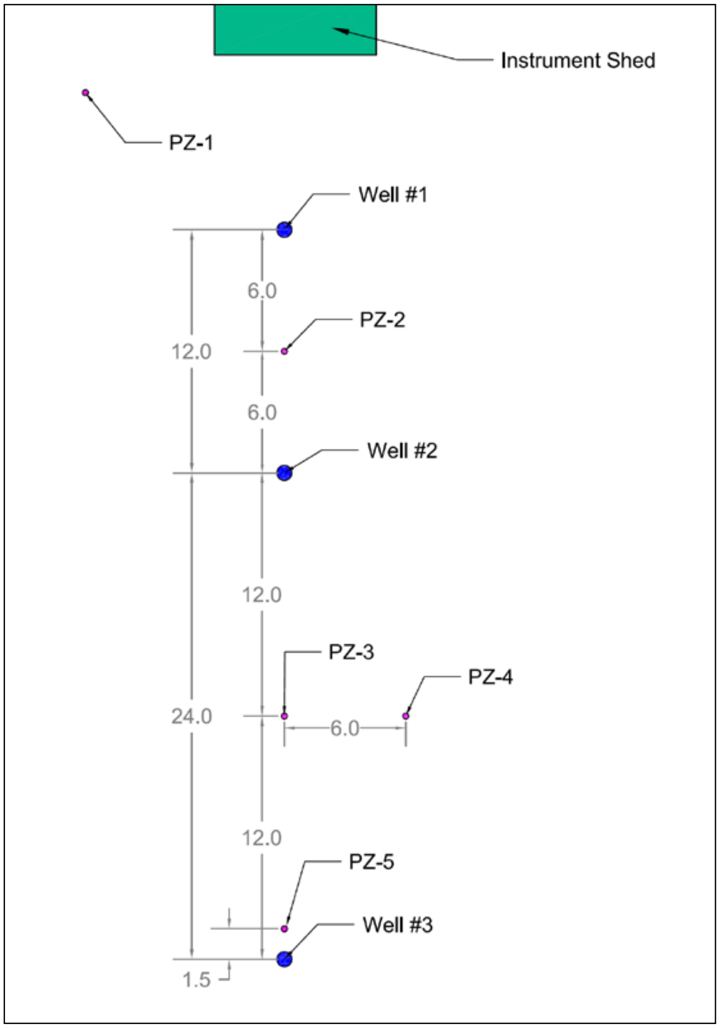
A series of three ISWEOD wells was installed at a test site to evaluate the design and identify any issues with installation and operations ahead of a potential installation at KAAD.

Pilot site design

The pilot test site soils consisted of clay and silt sediment with a thickness of about 12 ft overlaying limestone bedrock. There were small veins of sand inter-bedded within the clay and silt. The soil becomes saturated at approximately 3 ft below grade. A running stream immediately next to the site, with its normal surface about 4–5 ft below grade, provides recharge/discharge for the adjacent sediments.

The pilot site used three ISWEOD wells and five piezometer wells as shown in Figure A1. The ISWEOD wells were placed with 24 ft and 12 ft spacing. Wells 1 and 2 were placed 12 ft apart and Wells 2 and 3 were placed 24 ft apart to model the preliminary design for KAAD. Piezometer PZ-1 was placed 8 ft north of the ISWEOD installation and toward the creek to perform as a background water level monitor. Piezometer PZ-2 was placed between Wells 1 and 2, and PZ-3 was placed between Wells 2 and 3. PZ-4 was also placed between Wells 2 and 3 but was moved 6 ft off-center from PZ-3. PZ-5 (added later) was installed 18 in. from Well 3 to help determine the electric field strength close to an ISWEOD well.

Figure A1. Plan view of ISWEOD pilot site (dimensions in feet).



The ISWEOD and piezometer wells were placed nominally 8 ft below grade so the water table would be approximately at the elevation of the primary anode. Photographs of the pilot site are shown in Figure A2 and Figure A3.

Figure A2. Photograph of ISWEOD pilot site.

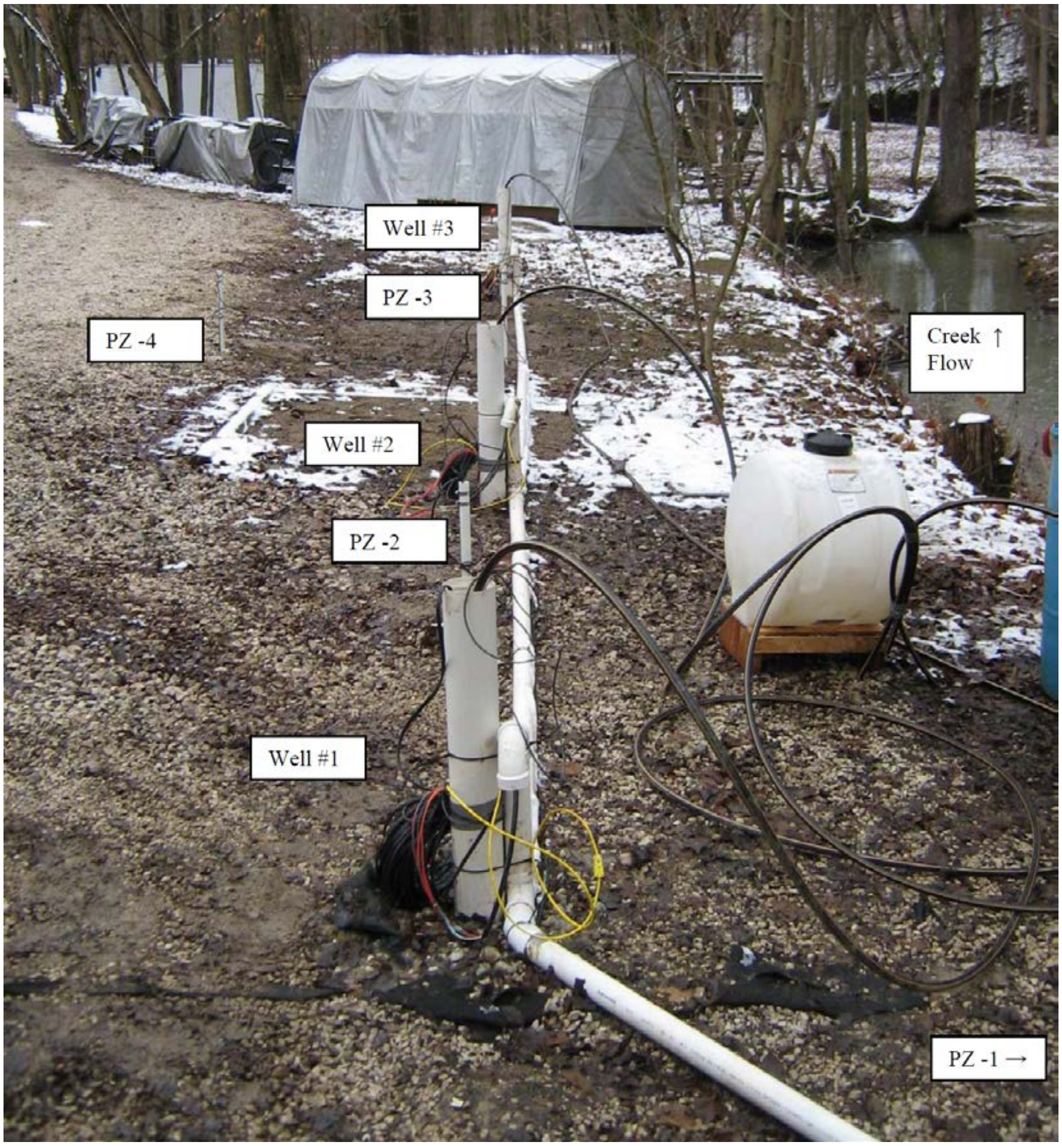
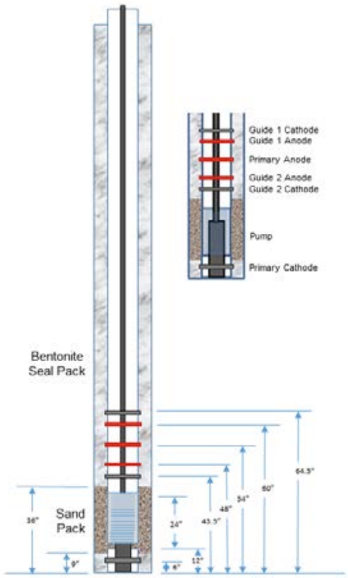


Figure A3. Photograph of ISWEOD pilot site showing piezometer (PZ-5) 18 in. from Well 3 (foreground).

The 10 ft long ISWEOD wells were constructed of two pieces of 4 in. schedule 80 PVC well pipe, with the lower section containing a 2 ft section of 0.010 in. slot well screen installed 1–3 ft from the bottom. The top section of well pipe is simply a riser. There is a 5 in. sump at the bottom of the well and a 12 volt pump placed in each well to remove water.

The schematic of an individual ISWEOD well is shown in Figure A4. Each well is equipped with a series of electrodes and guide electrodes. The electrodes consist of a 1 in. wide band of a dimensionally stable anode (DSA) expanded metal mesh. The DSA was a titanium base metal with an oxide coating. The primary cathode is placed 6 in. from the bottom of the well and the primary anode is located 54 in. from the bottom, or 48 in. above the cathode. A DC voltage is applied between the primary anode and cathode to produce electro-osmotic flow in the surrounding soil.

Figure A4. Schematic of ISWEOD showing electrode locations.

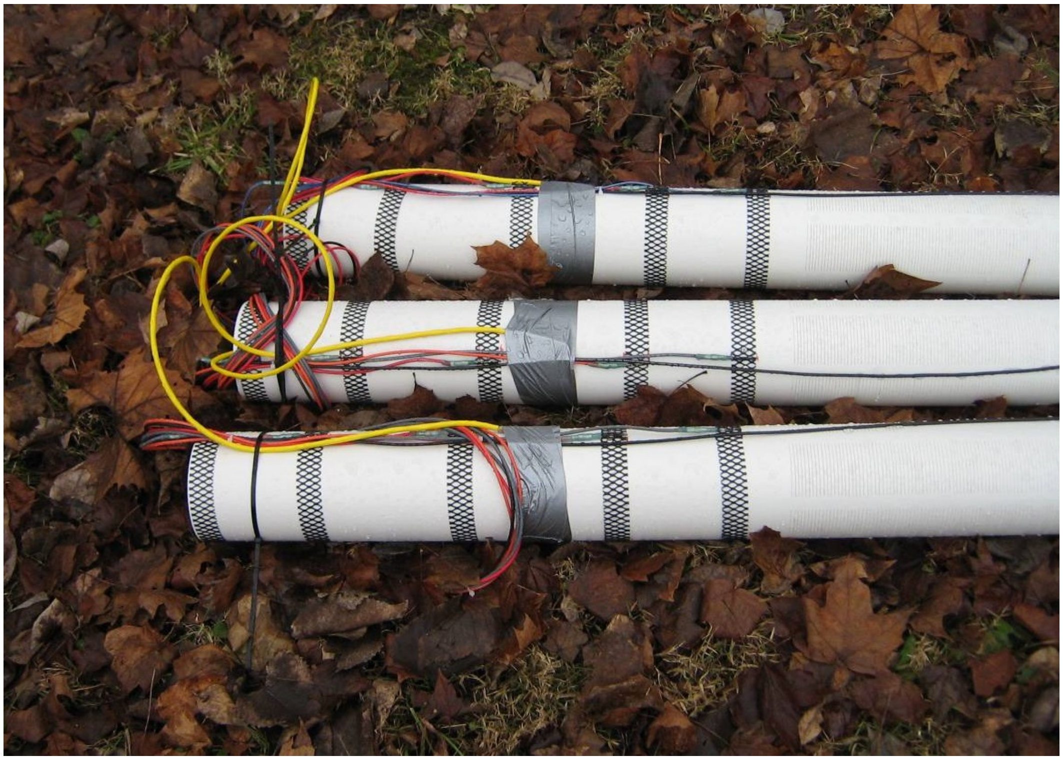


The guide anodes straddle the primary anode and were placed at 48 in. and 60 in. from the bottom, while the guide cathodes were placed 4.5 in. above and below the guide anodes at 43.5 in. and 64.5 in. from the bottom. A variable DC voltage was applied between the guide anodes and cathodes to influence the “throw” of the primary electric field.

The wells were backfilled with a fine sand pack around the well screens and bentonite chips around the well casing to make good electrical contact with the surrounding soil and to seal out surface water infiltration.

A photograph of a section of the ISWEOD wells and electrodes is shown in Figure A5 (compare with inset to Figure A4).

Figure A5. Photograph of ISWEOD wells and electrodes, from left to right: guide 1 cathode, guide 1 anode, primary anode, guide 2 anode, and guide 2 cathode (primary cathode is out of the picture at far right).



The piezometer wells were 10 ft long, made from a 1 in. diameter PVC pipe, with the bottom 5 ft including a 0.010 slotted screen to allow water to enter. All of the piezometers, except the background one (PZ-1), contain stainless steel electrode bands fastened to the pipe at 0, 1, 2, 3, 4, 5 and 7 ft from the bottom to measure voltage difference by depth. The voltage difference will indicate ISWEOD well electric field strength at the location of the piezometer. A photograph of the piezometric wells is shown in Figure A6.

Figure A6. Photograph of the piezometric wells with electric field measurement bands placed every foot from the bottom up to 5 ft then at 7 ft.

A data acquisition and control system (Opto 22) was placed in a nearby utility shed to control the electrode power supplies (rectifiers) and dewatering pumps, and to monitor water levels, voltage, current, temperature, and pumping activity at the wells. The data acquisition system recorded the information to a removable universal serial bus (USB) storage drive. Electric field measurements were made manually by referencing each metal band potential to the bottom-most band. The bands were connected to color coded wires that ran to the surface for researcher access. The color codes, from bottom to top (soil surface), are: white (bottom), yellow (+1 in.), orange (+2 in.), red (+3 in.), brown (+4 in.), green (+5 in.) and blue (+7 in.).

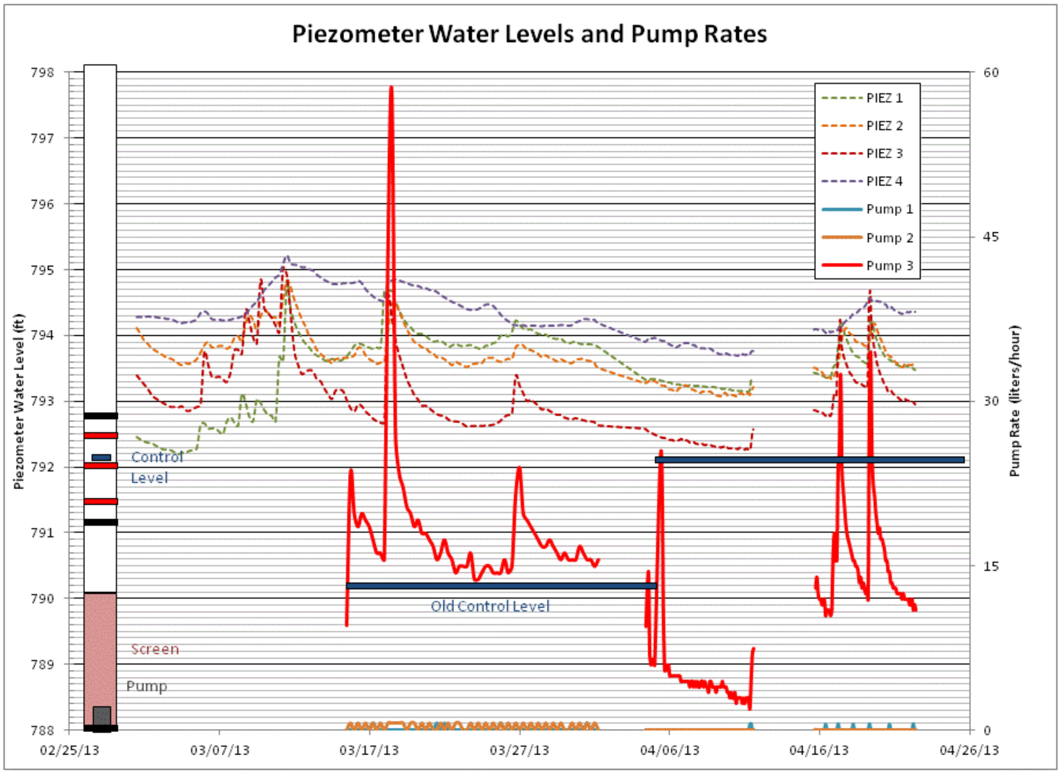
To assure safe operation of the data system and to prevent an excessive voltage difference at the soil surface, the cathodes and data system were grounded (connected to earth) at the local electric panel.

Results

The system began operation on 27 February 2013 and continued for almost two months while adjustments were made to operations as piezometer water levels were monitored. Figure A7 shows the water levels and well pumping rates during the initial operating period. Increases in well water levels indicate rain events.

For the first two weeks, the water levels were monitored to establish background conditions. Pump control of water levels began 15 March 2013. Even though the wells were installed at the same depth and within close proximity, the pumping rates were vastly different during this operational period. Well 3 produced water regularly and at any water control level. Well 2 produced almost no water after the initial pump-down, and Well 1 produced very little water.

Figure A7. Water level and pump rate trends during initial operating period for ISWEOD pilot test.



If the pumps or ISWEOD system are more effective in removing water than simple soil drainage, then the water levels in the piezometer wells will decrease faster following a rain event during the pump and ISWEOD operating periods than during the control period (27 February – 14 March).

The primary rectifier was energized two weeks after the pumps were activated. Soon after the primary electrode rectifier was put on line, the primary current dropped from 1.3 amps to 0.2 amps within hours. There was concern that the anodes were no longer in contact with water and so the water level control set point was raised 2 ft from the top of the well screen zone to a level slightly above the primary anode in an attempt to keep the anodes wet. The impact on the piezometer water levels was minor.

The guide electrode rectifier was energized on 17 April. Various combinations of rectifier voltages and cycle times for the guide electrode were evaluated, but no discernible changes in pumping rates or water levels were observed compared to the control period (17 February – 14 March). The data system was improved to allow infinite timing loops for the primary and guide electrodes as well as pumping times and volumes.

On April 22 the voltage differences at the piezometers were measured to evaluate the electric field strength at various primary and guide electrode voltages. The conditions tested are shown in Table A1. Prior to testing, the system was operated for five days with the primary electrode current at 100 volts and the guide electrodes at 25 volts. The two rectifiers were operated synchronously with a pulse cycle of 30 seconds "on" and 10 seconds "off." Well 3 was pumping regularly and produced 317 gallons (1,200 liters) while Well 1 produced only 2.11 gallons (8 liters) and Well 2 produced no water over the five days of operation. There was 0.5 in. of rain during this period.

Table A1. Rectifier settings for measuring the electric field strength.

Condition	Primary Rectifier Setting	Guide Rectifier Setting	Comment
1	100.00 volts (0.11 amps)	0.00 volts (0.00 amps)	
2	100.00 volts (0.11 amps)	25.00 volts (1.25 amps)	
3	100.00 volts (0.11 amps)	50.00 volts (2.43 amps)	
4	100.00 volts (1.50 amps)	0.00 volts (0.00 amps)	Two guide electrodes electrically connected to primary anode

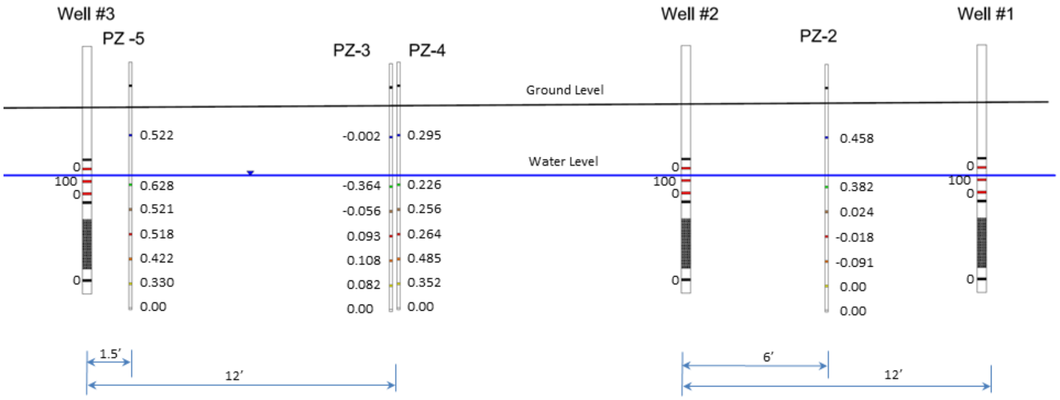
Figure A8 – Figure A11 list the voltages measured at each piezometer electrode band relative to the lowest electrode band (see Figure A6) during the field testing. The well and piezometer locations and depths in those figures are drawn to scale. Recall that PZ-4 is not co-located with PZ-3 but is actually 6 feet from it and perpendicular to the line of the ISWEOD wells (Figure A1).

The primary anodes were operated at +100 volts for all cases. For the fourth case, the guide electrode rectifier was turned off and two guide anodes on each ISWEOD well were electrically connected to the primary anode to increase the anode surface area by a factor of three.

Figure A8. Electric field measurements for rectifier condition 1.

VOLTAGE FIELD MEASUREMENTS

Primary at 100 volts DC, 0.11 amps
Guide at 0 volts DC
Cathodes grounded

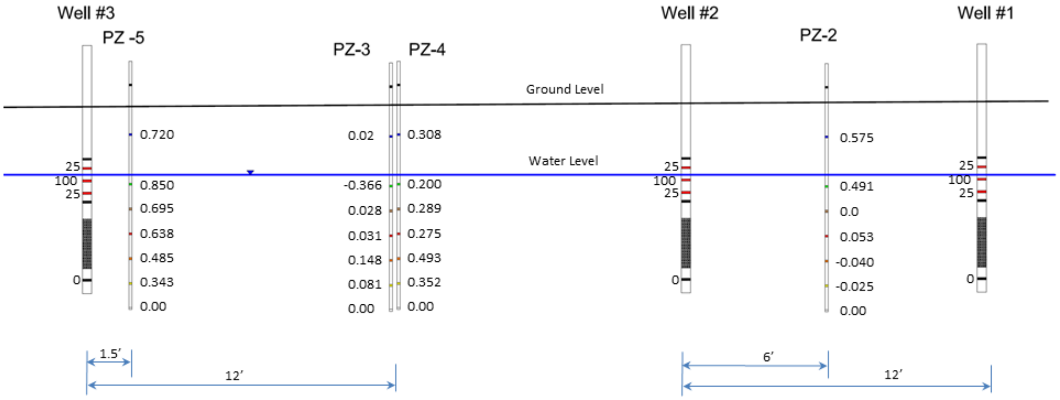


April 22, 2013

Figure A9. Electric field measurements for rectifier condition 2.

VOLTAGE FIELD MEASUREMENTS

Primary at 100 volts DC, 0.11 amps
Guide at 25 volts DC, 1.25 amps
Cathodes grounded

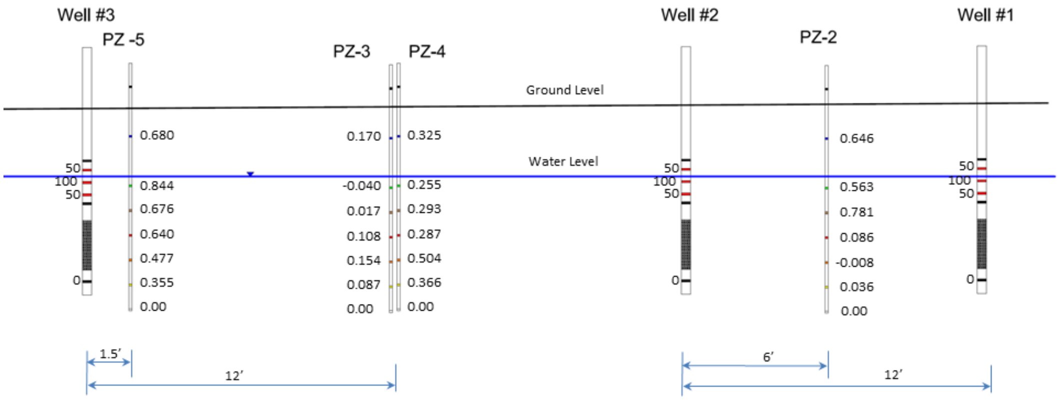


April 22, 2013

Figure A10. Electric field measurements for rectifier condition 3.

VOLTAGE FIELD MEASUREMENTS

Primary at 100 volts DC, 0.11 amps
Guide at 50 volts DC, 2.43 amps
Cathodes grounded

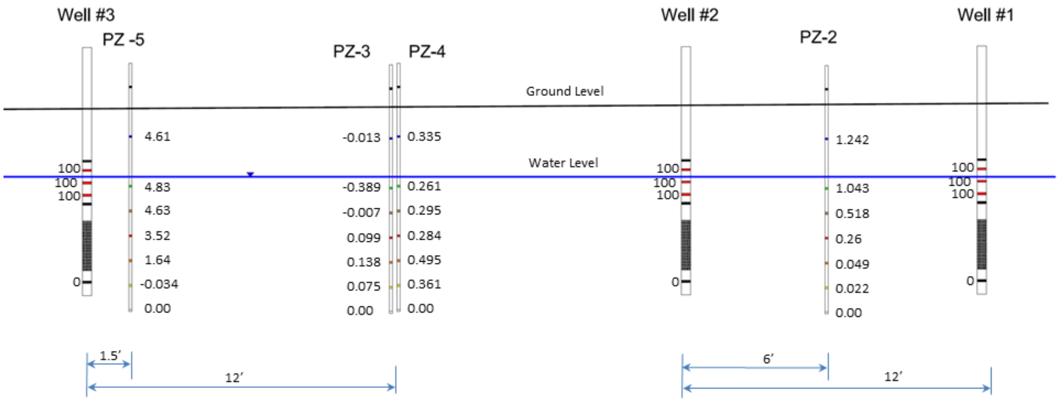


April 22, 2013

Figure A11. Electric field measurements for rectifier condition 4.

VOLTAGE FIELD MEASUREMENTS

Primary at 100 volts DC, 1.50 amps
Guide at 0 volts DC
Anodes Jumpered (3 anode bands)



April 22, 2013

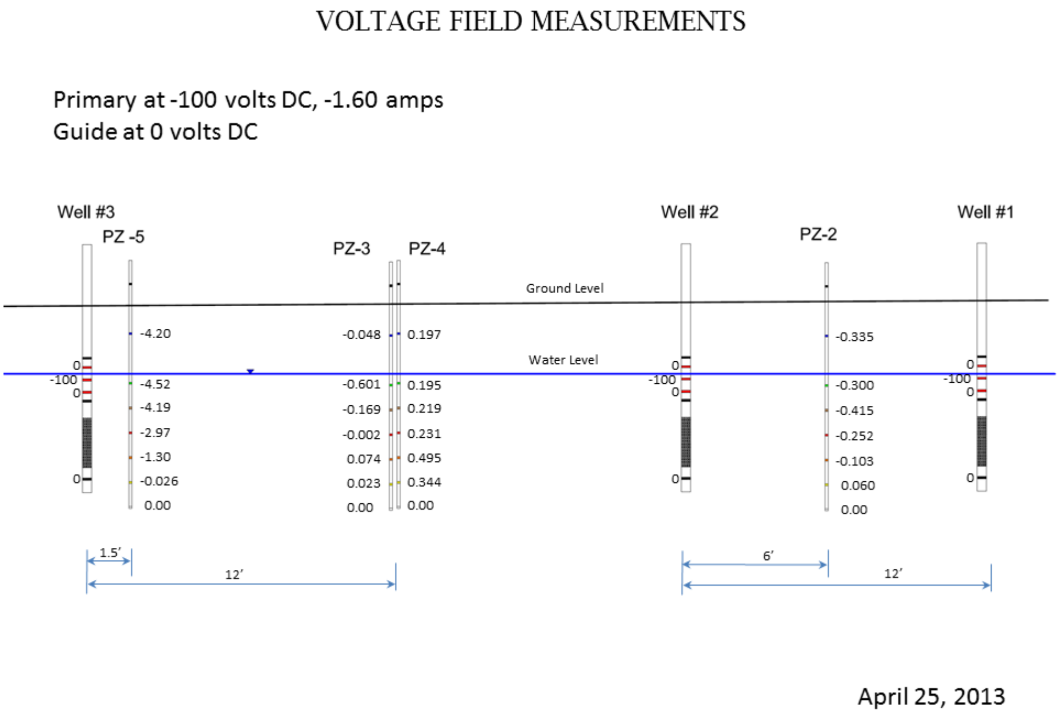
Based on the vertical voltage potentials (electric fields) at each piezometer, the voltage field does not project significantly outward from each ISWEOD well. Measured at 18 in. away (PZ-5), the difference is less than 1 volt top-to-bottom when the primary electrodes are at a 100 volt difference. Tying in the secondary electrodes had a measurable effect on the electric fields at +100 volts, but the voltage difference was only 5 volts at 18 inches.

The electric fields at 6 and 12 ft from the ISWEOD wells show virtually no influence regardless of operating parameters. Most of the measured values can be considered to be "noise." Measurements taken without the ISWEOD system operating captured values that varied only by ±0.5 volts.

A major operational concern was the rapid decrease in electrical current when the electrodes were first energized. As noted, the current dropped from 1.2 to 0.2 amps within hours of operation, possibly indicating over-drying of the soil in contact with the anode. This interpretation is supported by the effect on the current when the guide and primary anodes were connected in order to triple the anode surface area. The result was a sizeable increase in the current and a slower subsequent decrease.

To determine the possibility of anode-drying issues, the polarity was reversed for 8 hours prior to voltage-field mapping. The reversed polarity electrically switches the anode and cathode, with the lower electrode now functioning as the anode. The anode is now below the water table and therefore always wet. Figure A12 presents the electric field readings under reversed polarity.

Figure A12. Electric field measurements for the reverse polarity condition.



Under the reversed polarity configuration of the primary electrodes with no secondary voltage (zero guide electrode voltage), PZ-5 at 18 in. from Well 3 measures -4.5 volts compared to 0.6 volts for the normal polarity. However, even a magnitude of 4.5 volts is a significant reduction from the 100 volts at the well electrodes and indicates a lack of electric field projection. A measurement with secondary electrodes activated at -25 volts showed no substantial change. This result suggests that drying at the anode is an issue, but a minor one compared to the lack of electric field projection.

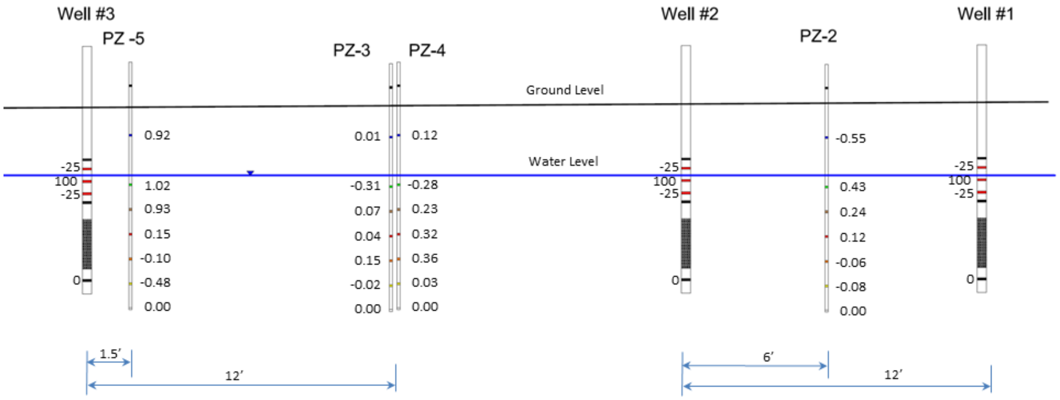
Two additional tests were undertaken at the pilot site to investigate the effects of reversing the polarity of the secondary electrodes and arranging the anodes and cathodes to operate in a crisscross configuration. The crisscross configuration test was performed after the pilot site was fully rehydrated by pumping water into the wells for one week raising the water table back above all the electrodes.

Figure A13 shows the electric field strengths under reversed polarity of the secondary electrodes, and it should be compared to Figure A9 which shows results when operating in the normal configuration.

Figure A13. Electric field measurements for reversed polarity of secondary electrodes.

VOLTAGE FIELD MEASUREMENTS

Primary at 100 volts DC, 0.49 amps
Guide at -25 volts DC, -1.5 amps

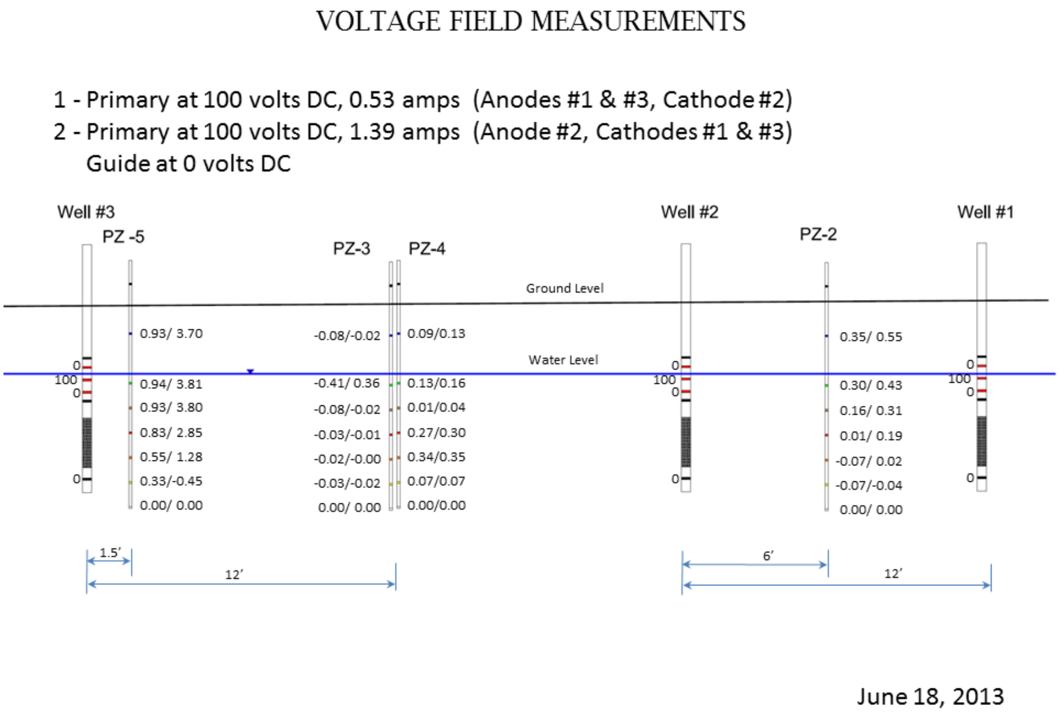


May 29, 2013

This test showed no improvement over the normal configuration, and relative performance was worse as indicated by the large decrease in the electric fields.

A test was performed with the system operating in a “crisscross” configuration that energized the anodes at Well 1 and Well 3 with the cathode at Well 2 for 10 seconds. Then, the anode at Well 2 was energized with the cathodes at Well 1 and Well 3 for 10 seconds. Figure A14 shows the field strength mapping for the crisscross configuration. This figure should be compared to Figure A8, which shows results when operating in the normal configuration.

Figure A14. Electric field measurements for cross-electrode configuration.



VOLTAGE FIELD MEASUREMENTS

1 - Primary at 100 volts DC, 0.53 amps (Anodes #1 & #3, Cathode #2)
2 - Primary at 100 volts DC, 1.39 amps (Anode #2, Cathodes #1 & #3)
Guide at 0 volts DC

June 18, 2013

Under the reversed polarity configuration of the primary electrodes with no secondary voltage from the guide electrodes, PZ-5 at 18 in. from Well 3 measures -4.5 volts compared to 0.6 volts for normal polarity. However, even a magnitude of 4.5 volts is a significant reduction from the 100 volts at the well electrodes, and indicates a lack of electric field projection.

The crisscross configuration provided no significant improvement over normal operation. Although the electric field showed an increase at Pz-5 compared to normal operation, it was still less than 4 volts with the system operating at 100 volts.

Pilot test report for modified ISWEOD wells for use at Blue Grass Army Depot (Building)

Introduction

After finding a suitable test location at the Blue Grass Army Depot (BGAD) in Richmond, KY, a decision was made to modify the ISWEOD design to increase its effectiveness before installation at BGAD.

A second pilot test program was performed to determine the effectiveness of the modified ISWEOD wells in field conditions and to optimize the operation. The modified ISWEOD well contains one anode and one cathode on the same well stem in a manner to direct water downward using electro-osmosis. The anode was placed above the well screen and the cathode is placed below the well screen. The anode and cathode were enlarged to increase the electrical current flow and the electric field projection into the soil. An electrical insulating cement seal was placed between the anode and cathode to minimize current flow in the backfilled region and force the current to flow out and away from the probe. This technique was not used in the first pilot test that included the guide electrodes because the close spacing of the electrodes prevented accurate placement of the cement seal.

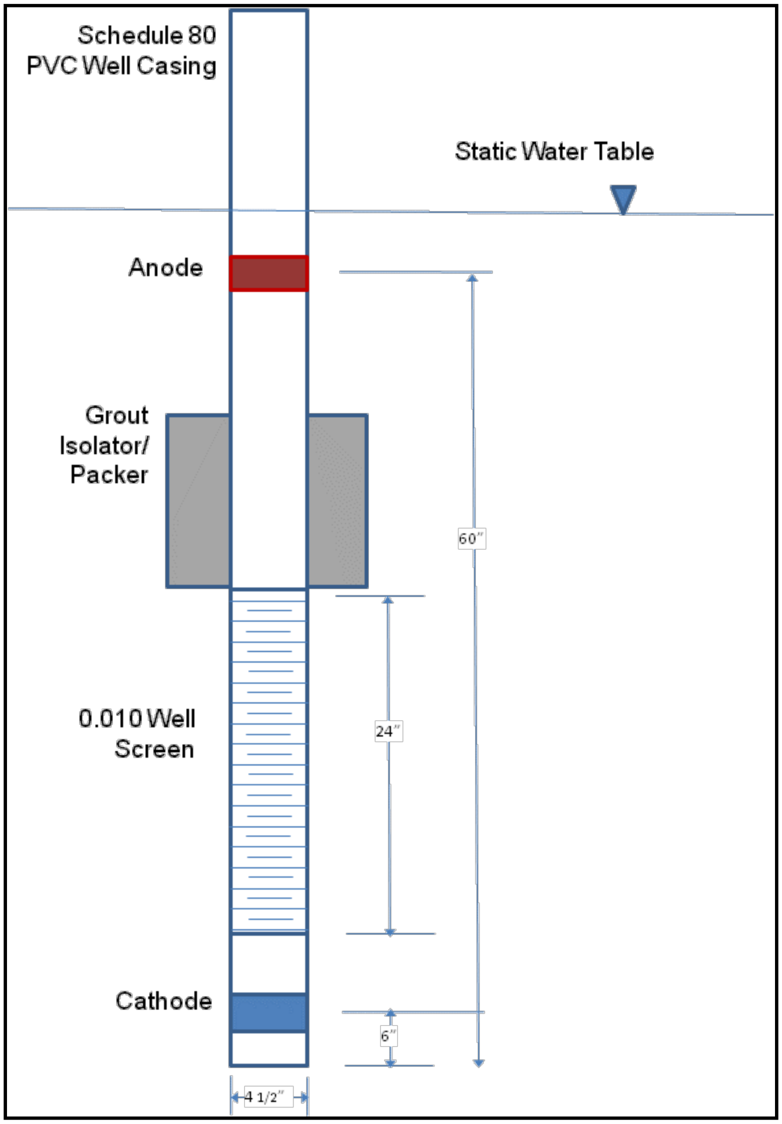
A series of three modified ISWEOD wells was installed at a second pilot test site to evaluate the well design and resolve any issues with installation and operations ahead of the installation at the BGAD. The location for this test was the same general location as the initial pilot test. The layout for the second pilot was modified slightly from the first, tailoring it for the conditions at the BGAD site.

Second pilot site design

The second pilot test site soil consisted of clay and silt sediment with a thickness of around 12 ft overlaying limestone bedrock. There were small veins of sand inter-bedded within the clay and silt. The soil became saturated at approximately 3 ft below grade. A running stream immediately next to the site, with a normal water surface about 4–5 ft below grade, provided recharge/discharge for the adjacent sediments.

The second pilot site design consisted of three ISWEOD wells and five piezometers. The 10 ft ISWEOD wells were constructed of two pieces of 4 in. schedule 80 PVC well pipe with the lower section containing a 2 ft section of 0.010 slot well screen installed at 1–3 ft from the bottom. The top section of well pipe was a riser, and a 5 in. sump was located at the bottom of each well with a 12 volt pump (Proactive Poseidon 12 volt pump from ECT Manufacturing, Inc., Hamilton, NJ) to remove water. Figure A15 shows the installation of the modified ISWEOD wells.

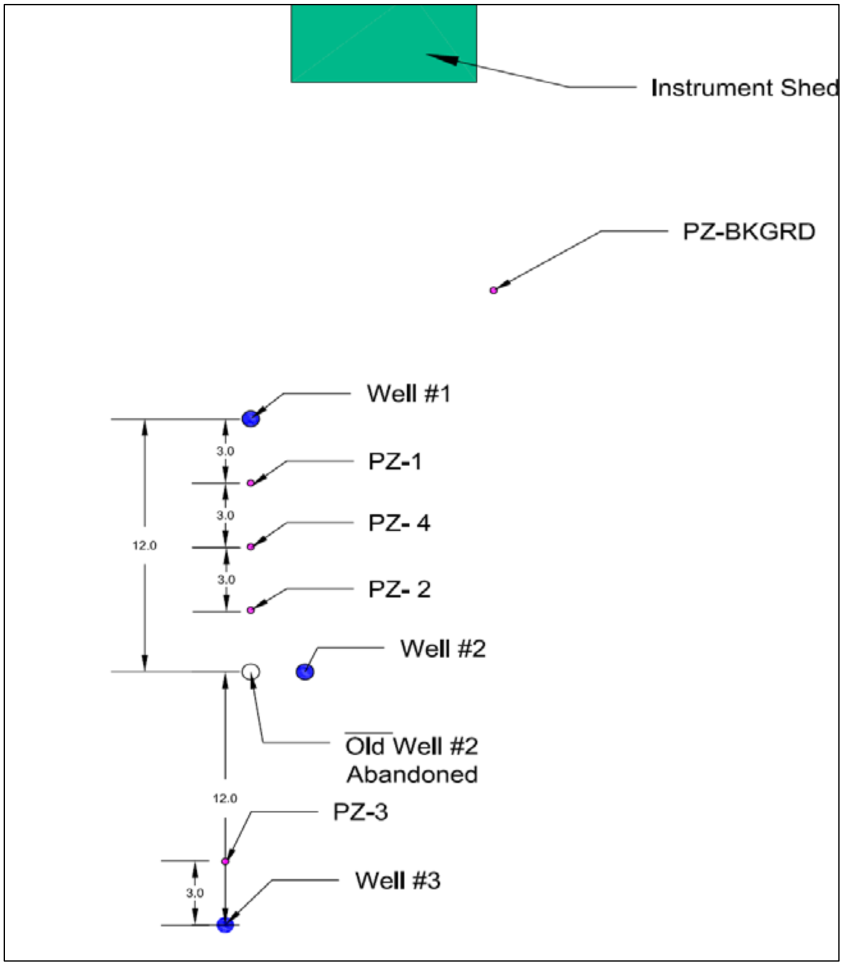
Figure A15. Schematic of modified ISWEOD well.



Each well was equipped with an anode and cathode electrode. Each electrode consisted of two electrically parallel 1 in. wide bands of expanded DSA metal titanium with an oxide coating (Water Star, Inc.) separated by 4 in. The multiple electrode bands help to distribute the current and provide redundancy against damage to one or the other during installation or operations. The cathode was placed nominally at 9 ft below grade while the anode was placed nominally 4 ft below grade. The wells were backfilled with a cathodic protection material (Loresco SWS coke breeze) packed around the electrodes and with fine sand placed externally around the well screens (see Figure 1 in main report). A 1 ft thick cement seal was placed between the sand pack and the coke breeze. Bentonite chips were placed in the annulus above the coke breeze to seal out surface water infiltration.

The ISWEOD wells and water-level piezometers were installed according to the arrangement shown in Figure A16. The wells were placed 12 ft apart. Piezometer PZ-BKGRD was placed 10 ft north and east of the installation to perform as a background water-level monitor. PZ-1, PZ-2, and PZ-3 were placed 3 ft from Wells 1, 2, and 3 respectively. PZ-4 was placed halfway between Well 1 and 2. The wells and piezometers were placed nominally 9 ft below grade so the water table would be approximately at the elevation of the anode.

Figure A16. Plan view of second ISWEOD pilot site.



Well 2 was installed improperly. During installation, the borehole was overdrilled and made connection with an artesian zone below, causing water to continually run out the top of the well. The well was removed, the borehole sealed with bentonite, and a new Well 2 was installed 5 ft east of the original location.

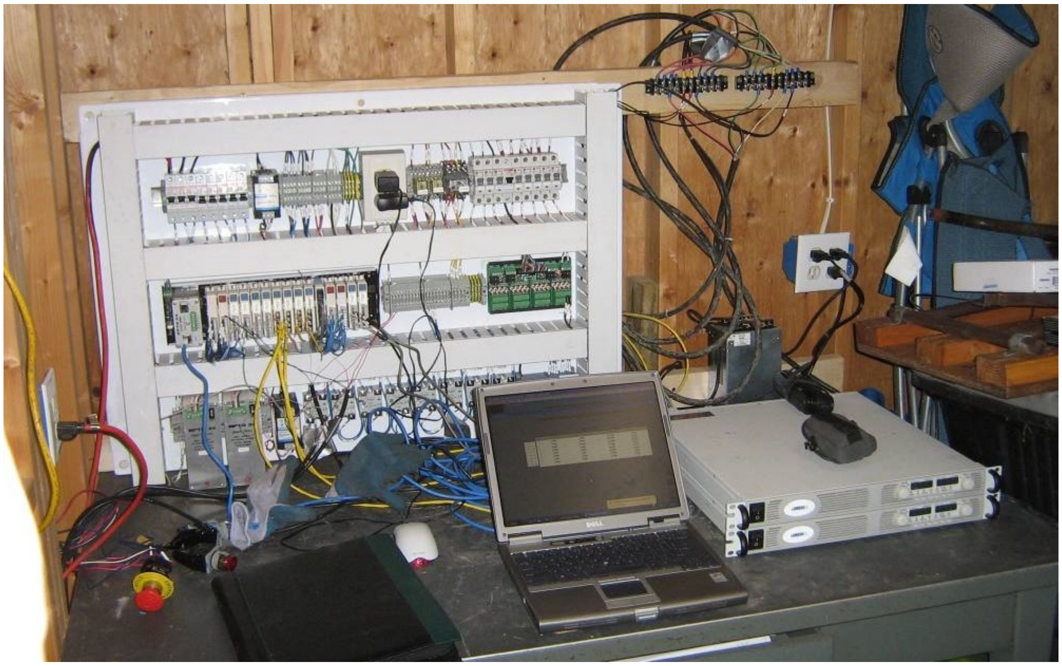
The piezometers were 10 ft long and made with 1 in. diameter PVC. The bottom 5 ft consisted of 0.010 slotted well screen. All of the piezometers except the background one (PZ-BKGRD) contain stainless steel bands fastened to the pipe at 0, 1, 2, 3, 4, 5, 7, and 9 ft (similar to those shown in Figure A6) to measure electric field strength by depth. Water-level transducers (Telog) were placed in each of the piezometers for recording water table levels. Pictures of the wells and piezometers, as installed, are shown in Figure A17 and Figure A18.

Figure A17. Photograph showing complete layout of second pilot test site. PZ-BKGRD is closest, followed (near to far) by Well 1, PZ-1, PZ-4, PZ-2, Well 2 (off line with others), PZ-3, and Well 3.

Figure A18. Field installation showing (near to far) Well 1 and PZ-1, PZ-4, and PZ-2.

A data acquisition and control system (Opto 22) was located in a nearby utility shed to control the ISWEOD power supplies and dewatering pumps, and monitor water levels, voltage, current, temperature, and pumping activity (Figure A19). Electric field measurements were made manually by referencing each metal band potential to the bottom-most band on the piezometers. The bands were connected to color-coded wires running to the surface for access. The color codes, from bottom to top (soil surface), were as follows: white (bottom), yellow (+1 in.), orange (+2 in.), red (+3 in.), brown (+4 in.), green (+5 in.) and blue (+7 in.).

Figure A19. Photograph of the data acquisition and monitoring system.



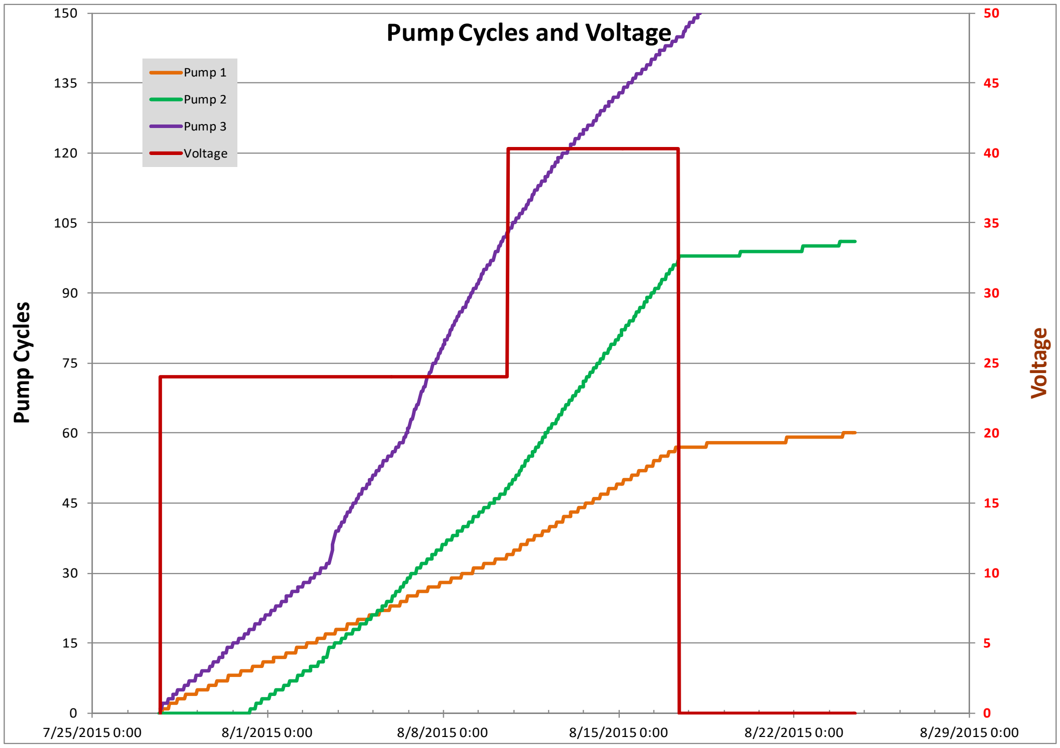
To assure safe operation of the data system and to prevent an excessive voltage difference at the soil surface, the cathodes and data system were grounded (connected to earth) at the local electric panel.

Results

The system began operation on 11 June and continued until 24 August 2015. Adjustments were made to the data system and operations while water levels were monitored. Each ISWEOD well had a 12 volt pump controlling the water level 6 ft below grade (the water table was 2 to 3 ft below grade). The pumps were turned on with a contact switch (LIDA DSA wire loop) triggered by high water and ran for a fixed duration. Each pump cycle equated to 1 liter of water removed.

While the electrodes were energized (at either 24 or 40 volts), the pump cycles increased in Wells 1 and 2. Well 3 appeared to be more influenced by rainfall during this period (Figure A20).

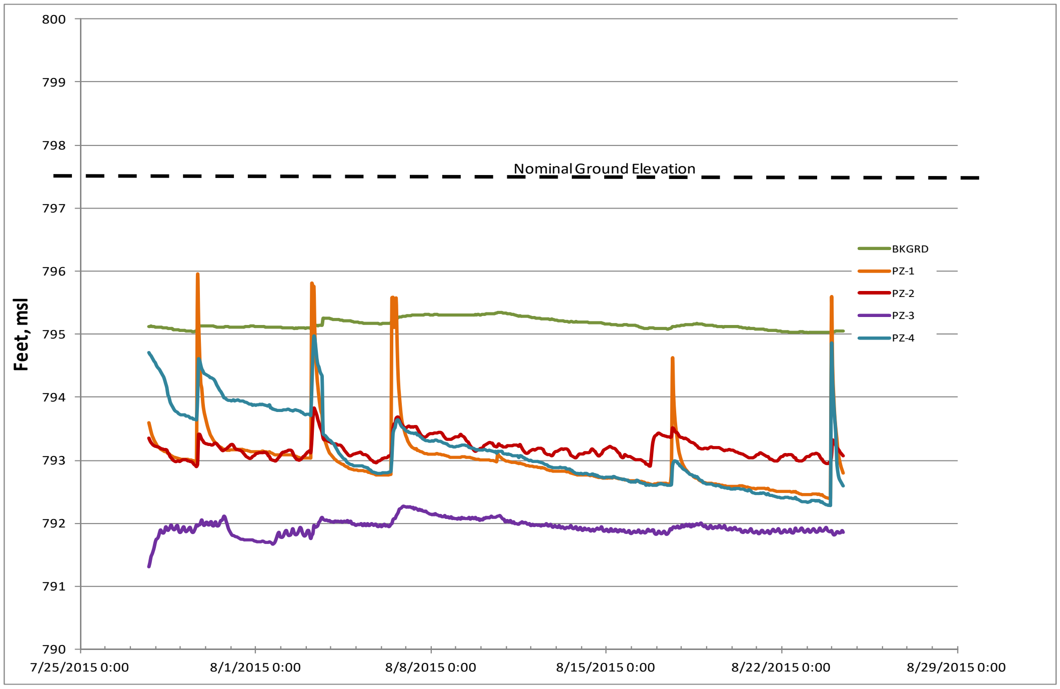
Figure A20. Pump cycles and electrode voltage.



There was a noticeable increase in the pumping rates at 40 volts versus 24 volts. Since the BGAD site soil has clay content as high, or higher than the test location, this system design was expected to be effective at removing water there. The system was turned off August 17. When the rectifier was turned off the pumping rates of Wells 1 and 2 were greatly reduced, indicating the effectiveness of the electro-osmotic assistance to the water collection.

The piezometers PZ-1, PZ-2, PZ-3, and PZ-4 show a decrease in the water table versus the background piezometer (Figure A21), which can be attributed to water removal by the ISWEOD pumps. Both hydraulic and electro-osmotic forces acted to direct water to the ISWEOD wells. Spikes in the data for PZ-1, PZ-2, and PZ-4 indicate rainfall events. Recovery after these events should be faster when the electrodes are energized and the electro-osmotic flow is assisting in water removal. The system operated at 24 volts from 27 July through 10 August and 40 volts from 10 August through 17 August. The first three rainfall events occurred while the system electrodes were energized, the last two events occurred when the electrodes were not energized. While the pump cycles show a correlation with ISWEOD voltages, this correlation is not evident in the piezometer data.

Figure A21. Water levels at piezometers.



Voltage measurements were taken using the conducting bands on the piezometers. Measurements were made manually by referencing each metal band to the bottom-most band. Figure A22 and Figure A23 show plots of these measurements for each piezometer location and driving voltage.

Figure A22. Field strength at piezometers for 24 volt driving voltage.

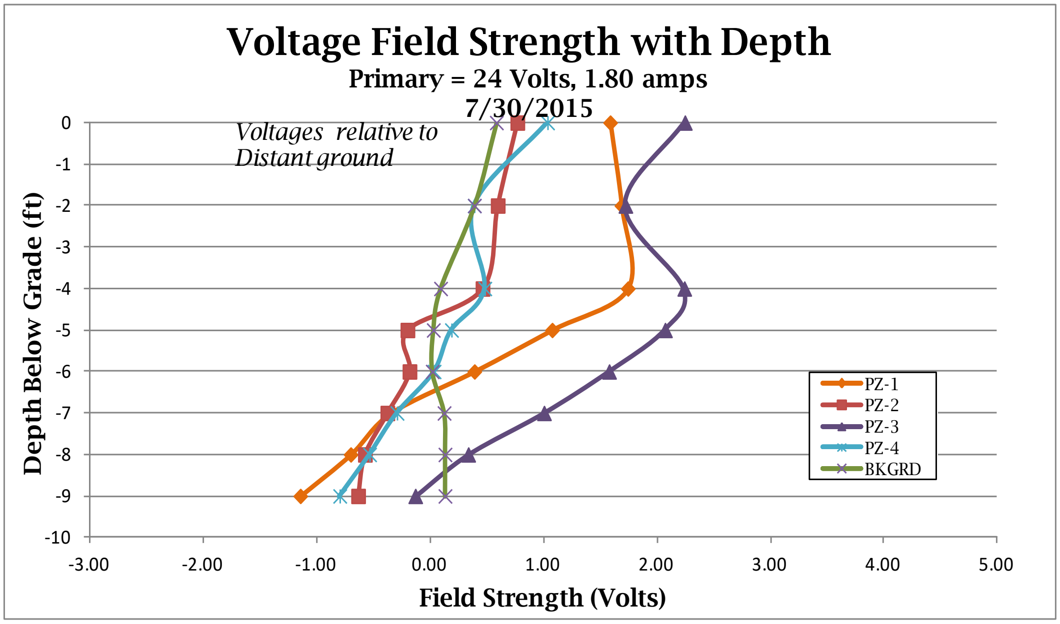
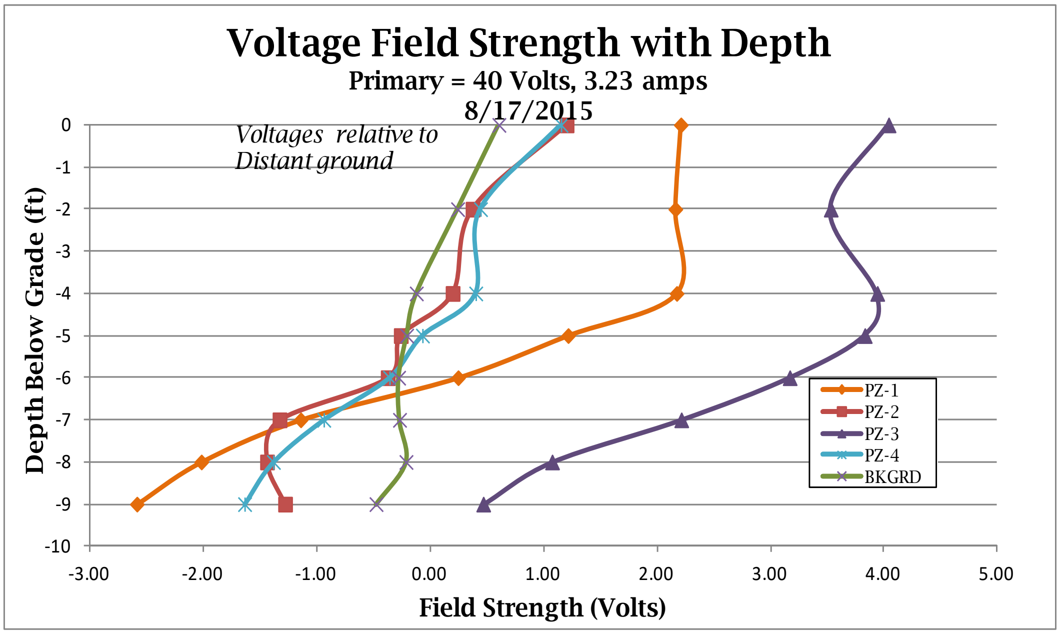


Figure A23. Field strength at piezometers for 40 volt driving voltage.



At 24 volts applied to the ISWEOD electrodes, the voltage profiles at the piezometers 3 ft away from the probes (PZ-1 and PZ-3) show values of 1–2 volts throughout the top 5 ft of soil (Figure A22). This is the same range in the soil as the ISWEOD electrodes. (On these plots each ISWEOD anode is located at about 0 depth and each cathode is at about -5 ft.) 1–2 volts is 4% to 8% of the driving voltage. At 40 volts, the voltage profiles double to 2–4 volts throughout the top 5 ft of soil (Figure A23). This is 5% to 10% of the driving voltage.

With the original design, even though the system was operating at 100 volts, the best performance was 5% of the driving voltage at 1.5 ft. The new design performance of 4%–10% at 3 ft is a large improvement over 5% at 1.5 ft. This improvement is exceptional because the field does not decrease linearly with distance, but has an inverse distance (1/r) dependence. So to have the field increase while also doubling the distance is a tremendous improvement over the original design. The improvement can be attributed to increasing the electrode surface area and placing an isolator in the borehole between the anode and cathode.

Conclusions for optimization studies

Kawakami Arsenal design (munitions bunker)

The performance of the pilot test configuration is probably a good indication of what would be expected at Kawakami using the same basic design be used. Based upon the electrical and hydraulic characteristics of the soil samples from KAAD, the tested system is unlikely to perform any better at dewatering munitions bunkers there, and may possibly perform worse.

Based on the limited projection of the voltage field from the ISWEOD wells, it appears the electro-osmotic assistance was minimal at the pilot test location. A voltage field probe placed 1.5 ft from a well showed the field potential to be 5 volts (best case) or less when the ISWEOD well was operating at 100 volts. The voltage field probes placed 6 ft away or more showed no effect from the ISWEOD electrodes. The preliminary design for Kawakami was to have ISWEOD wells placed 24 ft apart along each side of the bunker. With the effective voltage field projecting only a few inches from the well, there would be no significant electro-osmotic influence. The issue may be the limited electrode surface area with respect to the poor soil electrical conductivity. The limited electrode surface area can be increased by using a larger-diameter well. However, it is doubtful enough surface area could be added to overcome the poor soil electrical conductivity. The water removal will be primarily a function of straight hydraulic dewatering (pumping only) with insignificant electro-osmotic enhancement.

Blue Grass Army Depot design (administrative building)

Based on the increase in pump rates and the improved projection of the voltage field, it appears that the new design added electro-osmotic assistance to the well water removal. With the original design the best performance was 5% of the driving voltage at 1.5 ft. The new design performance of 4%–10% at 3 ft is a large improvement over 5% at 1.5 ft. The improvement can be attributed to increasing the electrode surface area and placing an isolator in the borehole between the anode and cathode.

The preliminary design for the Blue Grass Army Depot was to have ISWEOD wells placed 12 ft apart along each side of the building. With the voltage field projecting several feet from each well, effective electro-osmotic influence was expected.

Appendix B: Site Selection

Three sites were evaluated as potential demonstration locations: Kawakami Army Ammunition Depot, Japan; Fort Benning,GA; and Blue Grass Army Depot, KY. Blue Grass Army Depot was selected as the demonstration site because the soil composition at Kawakami and Fort Benning was not suitable for supporting electro-osmotic well technology.

Kawakami Army Ammunition Depot (KAAD)

The Kawakami Army Ammunition Depot, Japan, was the initial site proposed for the Intelligent Single-Well Electro-Osmotic Dewatering (ISWEOD) System demonstration. A photograph of the proposed site is shown in Figure B1. A site survey was conducted and soil samples were collected and shipped to a laboratory for evaluation.

Figure B1. Kawakami earth-covered magazine (ECM).

The contractor, Terran Corporation, received soil samples from KAAD 19 June 2013. Three sample depths were provided: 0–1.5 meters, 1.5–2.2 meters, and 2.2–3.0 meters. The soil samples were tested for electrical conductivity and sent to a geotechnical laboratory for particle size determination and soil classification (see Appendix C). The soil is classified as silty sand to silty loam with extremely low electrical conductivity.

Table B1 presents the soil characteristics for each sample. The very low electrical conductivity is consistent with the high amount of gravel and sand. Typically, soils with high electrical conductivity either have dissolved solids content (brine/salts) or tend to be rich in silt or clay. Soils with high gravel or sand content and lower water content tend to be less electrically conductive.

Table B1. Soil conditions at KAAD.

Parameter \ Depth (ft)	0–5.0	5.0–7.2	7.2–9.8
Soil Classification	Silty Sand	Sandy Loam	Silty Loam
Electrical Conductivity (S/m)	0.003	0.007	0.026
Gravel (%)	10.3	23.1	15.4
Sand (%)	63.9	45.1	42.9
Silt (%)	20.5	21.3	30.6
Clay (%)	5.6	10.1	11.1
Hydraulic Conductivity (cm/sec)*	$6\text{x}10^{-5}$	$2\text{x}10^{-5}$	$9\text{x}10^{-6}$
Moisture (%)	16.8	16.5	20.0

* Conservative estimate based on particle size analysis.

Hydraulic conductivity estimates based on the particle size analysis provide an order of magnitude approximation. Even with a slight bias toward the lower end of the conductivity estimates, these samples indicate hydraulically conductive soil above which electro-osmosis would be effective ($1\text{x}10^{-5}$ cm/sec upper limit).

Information from the soil borings, along with the local topography, geology of the island, and local water tables, was assembled into a site conceptual model to help determine the suitability of the site for ISWEOD technology. The following conclusions are based on the model:

1. The top 5 ft of soil consists of sandy fill material which easily passes water but remains saturated because of lack of drainage.
2. Below that there is a 2 ft thick layer of sandy loam material that is also saturated and easily passes water.
3. The lower layer consists of silty loam that contains a bit more silt than the layer above, with possibly enough silt for electro-osmosis to overcome hydraulic forces.
4. The area appears to be a bowl shaped region, filled with sandy material, that fills with water from precipitation. Local drainage is by gravity to lower areas and then by storm sewers.

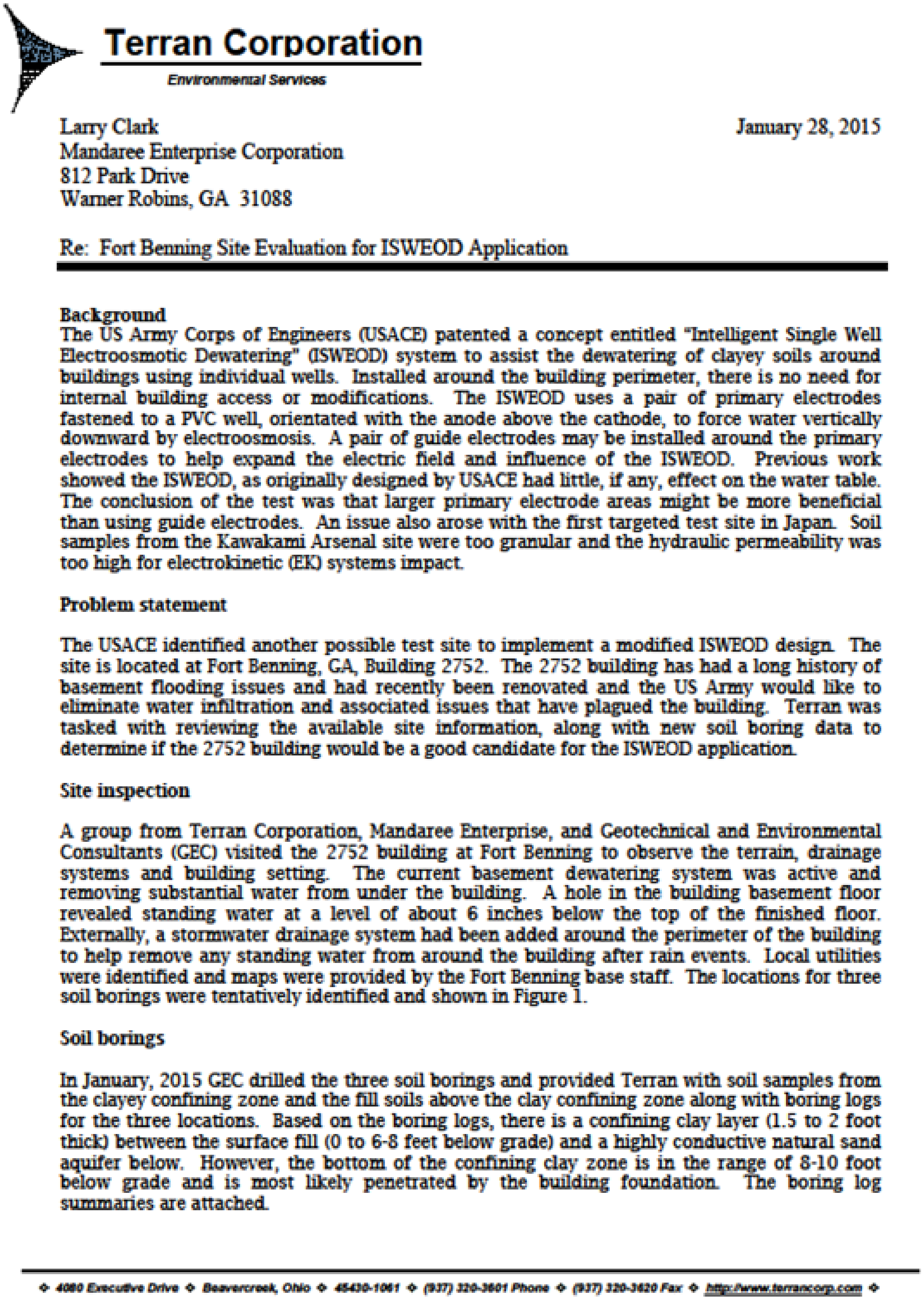
5. The bunker at KAAD is in one of the lower areas. With the soil being sandy, the electro-osmotic process will not be effective at removing the water below the bunker. Water will be removed most effectively using traditional gravity drainage systems.

Based on both visual observation during the site survey and soil laboratory test results, it was determined that the fill around the target ECMs consisted of crushed volcanic gravel and sand with no clay content. This material had very high hydraulic conductivity and low electrical conductivity, leading us to conclude that the KAAD native soil and site conditions would not be compatible with ISWEOD technology.

Fort Benning, GA

The area surrounding Building 2752 at Fort Benning, GA, was also evaluated as a potential demonstration site. Water was entering the basement, affecting the operations of the above-grade portions of the building and preventing the basement from being used. A site survey was conducted and soil samples collected. The soil samples showed a clay zone 1.5–2.0 ft thick between the surface and a sandy aquifer below. The clay layer is 8–10 ft below the surface and the serious water problem is probably due to the foundation penetrating the clay zone. It was decided that the ISWEOD technology would not be effective in these conditions. The letter report describing the analysis of the soil samples and site conditions is reproduced in Figure B2.

Figure B2. Fort Benning, GA site evaluation [continued to next two pages].



Terran Corporation
Environmental Services

Larry Clark
Mandaree Enterprise Corporation
812 Park Drive
Warner Robins, GA 31088

January 28, 2015

Re: Fort Benning Site Evaluation for ISWEOD Application

Background

The US Army Corps of Engineers (USACE) patented a concept entitled "Intelligent Single Well Electroosmotic Dewatering" (ISWEOD) system to assist the dewatering of clayey soils around buildings using individual wells. Installed around the building perimeter, there is no need for internal building access or modifications. The ISWEOD uses a pair of primary electrodes fastened to a PVC well, orientated with the anode above the cathode, to force water vertically downward by electroosmosis. A pair of guide electrodes may be installed around the primary electrodes to help expand the electric field and influence of the ISWEOD. Previous work showed the ISWEOD, as originally designed by USACE had little, if any, effect on the water table. The conclusion of the test was that larger primary electrode areas might be more beneficial than using guide electrodes. An issue also arose with the first targeted test site in Japan. Soil samples from the Kawakami Arsenal site were too granular and the hydraulic permeability was too high for electrokinetic (EK) systems impact.

Problem statement

The USACE identified another possible test site to implement a modified ISWEOD design. The site is located at Fort Benning, GA, Building 2752. The 2752 building has had a long history of basement flooding issues and had recently been renovated and the US Army would like to eliminate water infiltration and associated issues that have plagued the building. Terran was tasked with reviewing the available site information, along with new soil boring data to determine if the 2752 building would be a good candidate for the ISWEOD application.

Site inspection

A group from Terran Corporation, Mandaree Enterprise, and Geotechnical and Environmental Consultants (GEC) visited the 2752 building at Fort Benning to observe the terrain, drainage systems and building setting. The current basement dewatering system was active and removing substantial water from under the building. A hole in the building basement floor revealed standing water at a level of about 6 inches below the top of the finished floor. Externally, a stormwater drainage system had been added around the perimeter of the building to help remove any standing water from around the building after rain events. Local utilities were identified and maps were provided by the Fort Benning base staff. The locations for three soil borings were tentatively identified and shown in Figure 1.

Soil borings

In January, 2015 GEC drilled the three soil borings and provided Terran with soil samples from the clayey confining zone and the fill soils above the clay confining zone along with boring logs for the three locations. Based on the boring logs, there is a confining clay layer (1.5 to 2 foot thick) between the surface fill (0 to 6-8 feet below grade) and a highly conductive natural sand aquifer below. However, the bottom of the confining clay zone is in the range of 8-10 foot below grade and is most likely penetrated by the building foundation. The boring log summaries are attached.

Conceptual Site Model

Information from the three new soil borings, along with historical boring logs from nearby monitoring wells, historical water level measurements and site reconnaissance was assembled in to a site conceptual model to help determine the applicability of the ISWEOD system at Building 2752. The following are conclusions based on the conceptual model:

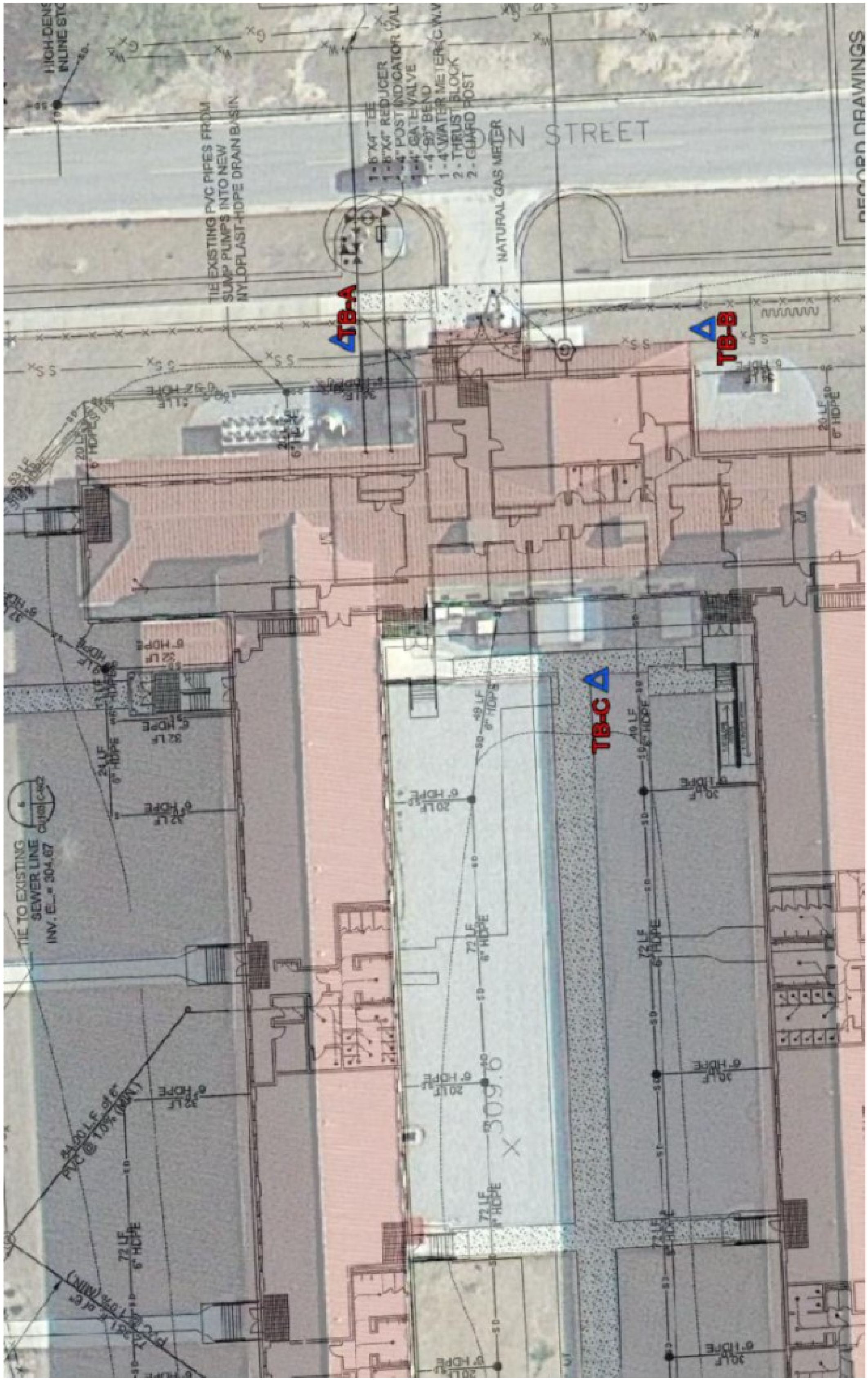
1. The top 6 to 8 feet of soil consists of sandy fill material which is easily drained.
2. There is a 1.5 to 3 foot thick layer of clayey material below the fill that retards drainage and acts as a limited confining zone.
3. Below the clay layer is a highly conductive aquifer that appears to be semi-confined with a potentiometric surface at or above the top of the clay layer (positive hydrostatic pressure caused by higher elevations of groundwater upgradient of the building site being forced under the confining clay layer).
4. Any breach or long-term saturation of the limited confining clay layer would allow groundwater, under pressure, to rise up into the fill zone (or basement of the building).
5. It is likely the excavations for the Building 2752 basement and foundations breached the bottom of the confining clay layer.

Conclusions

Based on the site visit, soil boring logs and historical information, it appears the 2752 building is not a good candidate site for testing the ISWEOD functionality. First, the clay zone is too thin to allow proper vertical separation of the primary anode and cathode. Second, the excavation for the building basement most likely punctured through the limited confining layer allowing groundwater to surge up into the sub-basement drainage zone, and in turn into the basement. Third, the amount of water being pumped by the current dewatering system indicates flow rate beyond the capability/capacity of the ISWEOD systems. A well designed pumping system installed around the perimeter of the basement would lower the water table below the basement foundation. This pumping system would remove any water above the confining clay layer and discharge it to the sanitary or storm sewer system, depending on permit allowances and contaminant levels, or pumped to an on-site storage for irrigation or other non-potable use.

Submitted by,

Chris Athmer P.E.
Terran Corporation


TB-A
TB-B
TB-C
STREET
RECORD DRAWINGS
NATURAL GAS METER
TIE EXISTING PVC PIPES FROM SUMP PUMPS INTO NEW NYLOPLAST HDPE DRAIN BASIN
TIE TO EXISTING SEWER LINE INV. EL.= 304.67
HIGH-DENS INLINE STO
72 LF 6" HDPE
20 LF 6" HDPE
32 LF 6" HDPE
30 LF 6" HDPE
309.6

Blue Grass Army Depot (BGAD), KY

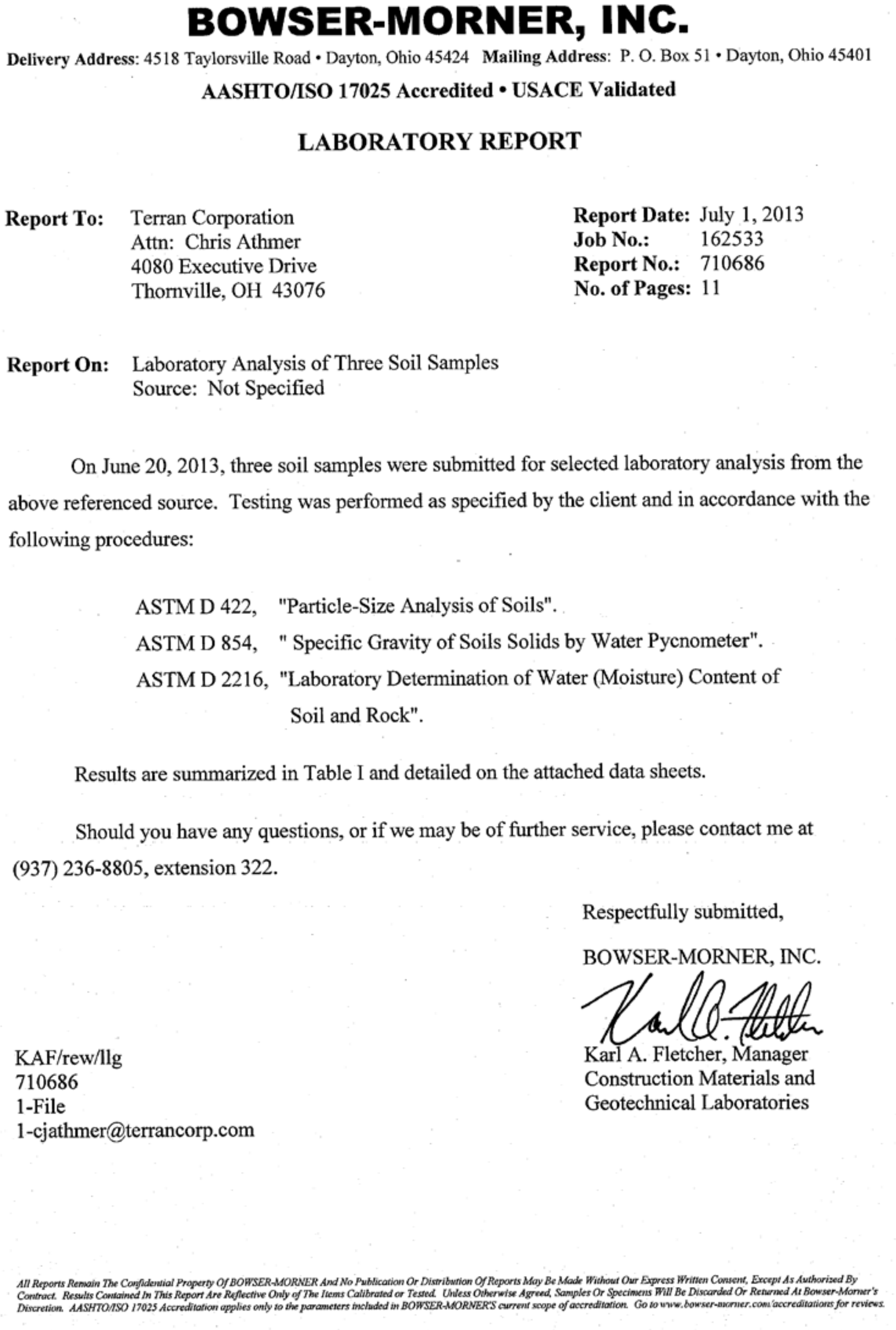
Building S-3 at the Blue Grass Army Depot (BGAD) has a long history of water-intrusion problems in the basement. A number of efforts have been made to address the problem, including installation of two sump pumps. Additionally, an area of the basement floor had been excavated to install drainage tile to increase the flow of water to one of the sump pumps.

The area surrounding Building S-3 was evaluated. A site survey was performed and soil samples were taken. The results of the analysis showed the soil to have a good clay content and, therefore, to be a candidate for the ISWEOD system demonstration.

In evaluating BGAD as a candidate location, piezometers were installed at the two locations (Figure B3) where soil samples were taken. The piezometers were monitored to assess the water table. The ground water table was found to be approximately 4 ft above the basement floor on the west side, or up gradient, of the building. The groundwater level on the east side, or down gradient side, was approximately equal to the basement floor level, indicating the basement and sump system are controlling the local water table. The ISWEOD system using electro-osmotic dewatering wells should be capable of lowering the water table 4–5 ft, providing additional capacity to handle even the heaviest rain events. This would allow the water table to be maintained below the basement level to reduce water intrusion.

Figure B1. Satellite view showing were soil samples were taken and piezometers were installed at BGAD.

Appendix C: Analysis of Soil Samples from Kawakami, Japan



BOWSER-MORNER, INC.

Delivery Address: 4518 Taylorsville Road • Dayton, Ohio 45424 **Mailing Address:** P. O. Box 51 • Dayton, Ohio 45401

AASHTO/ISO 17025 Accredited • USACE Validated

LABORATORY REPORT

Report To:	Terran Corporation Attn: Chris Athmer 4080 Executive Drive Thornville, OH 43076	**Report Date:** **Job No.:** **Report No.:** **No. of Pages:**	July 1, 2013 162533 710686 11

Report On: Laboratory Analysis of Three Soil Samples
Source: Not Specified

On June 20, 2013, three soil samples were submitted for selected laboratory analysis from the above referenced source. Testing was performed as specified by the client and in accordance with the following procedures:

ASTM D 422, "Particle-Size Analysis of Soils".
ASTM D 854, " Specific Gravity of Soils Solids by Water Pycnometer".
ASTM D 2216, "Laboratory Determination of Water (Moisture) Content of Soil and Rock".

Results are summarized in Table I and detailed on the attached data sheets.

Should you have any questions, or if we may be of further service, please contact me at (937) 236-8805, extension 322.

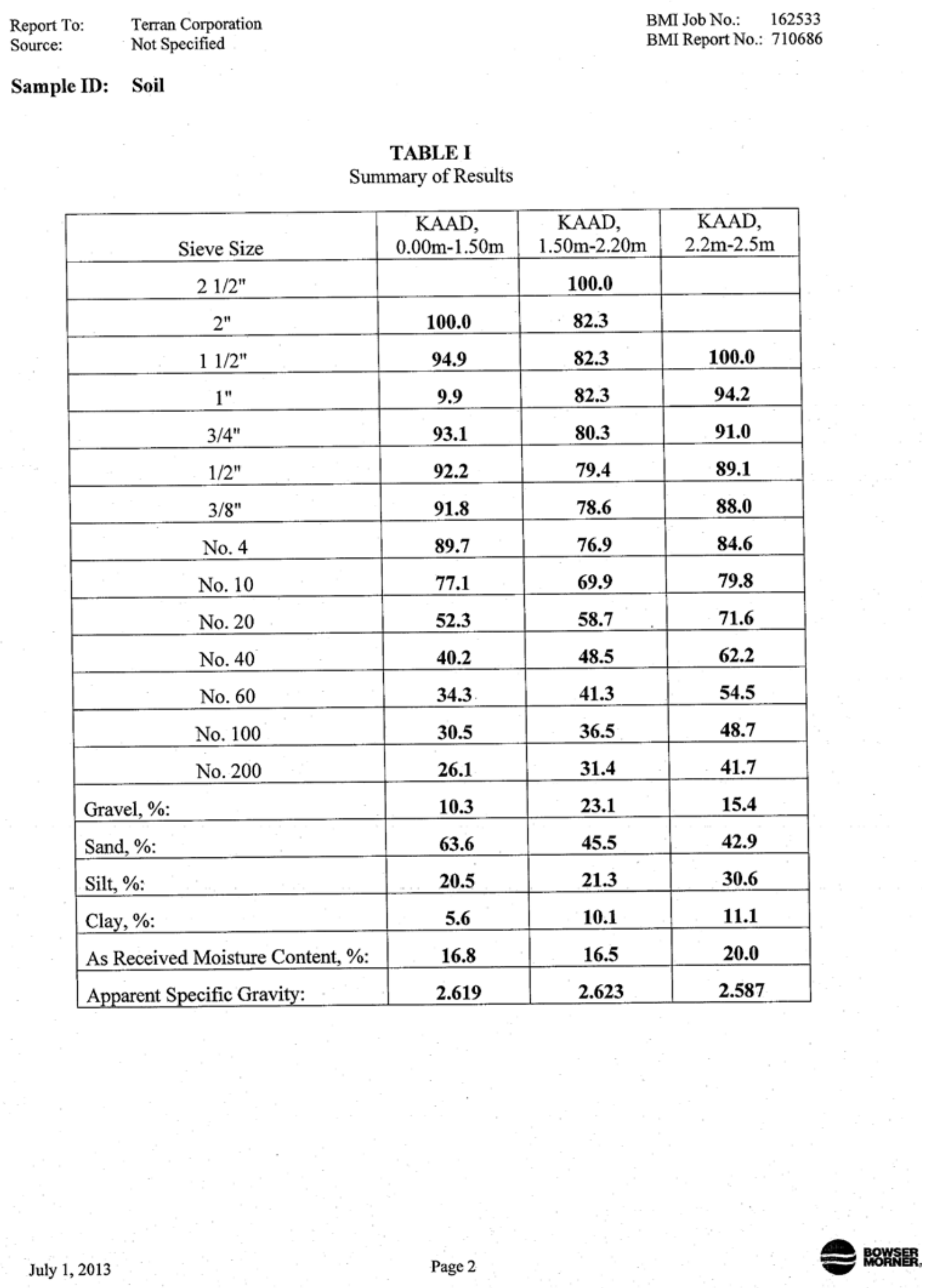
Respectfully submitted,

BOWSER-MORNER, INC.

Karl A. Fletcher

Karl A. Fletcher, Manager
Construction Materials and
Geotechnical Laboratories

KAF/rew/llg
710686
1-File
1-cjathmer@terrancorp.com



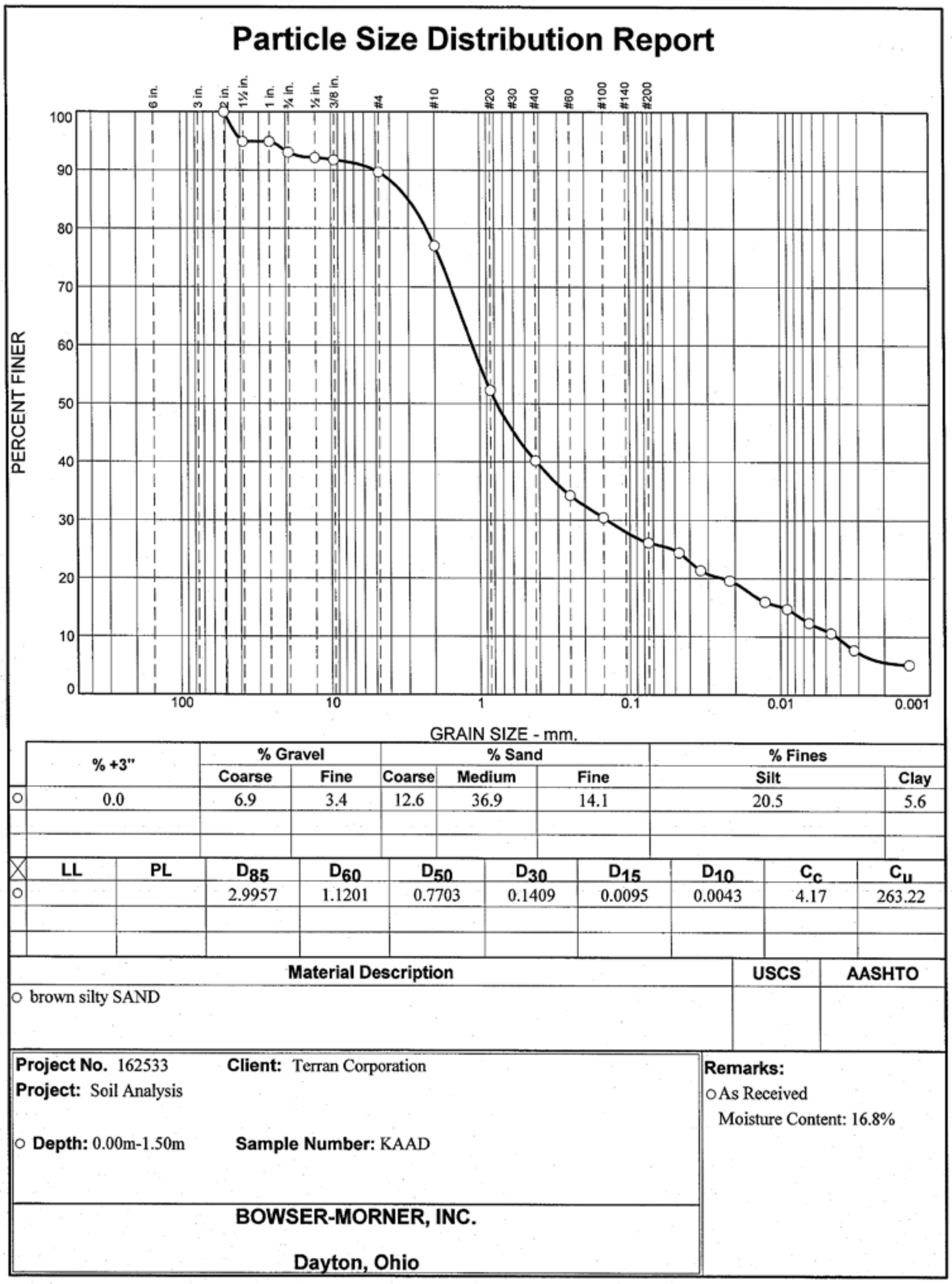
Report To: Terran Corporation
Source: Not Specified

BMI Job No.: 162533
BMI Report No.: 710686

Sample ID: Soil

TABLE I
Summary of Results

Sieve Size	KAAD, 0.00m-1.50m	KAAD, 1.50m-2.20m	KAAD, 2.2m-2.5m
2 1/2"		**100.0**	
2"	**100.0**	**82.3**	
1 1/2"	**94.9**	**82.3**	**100.0**
1"	**9.9**	**82.3**	**94.2**
3/4"	**93.1**	**80.3**	**91.0**
1/2"	**92.2**	**79.4**	**89.1**
3/8"	**91.8**	**78.6**	**88.0**
No. 4	**89.7**	**76.9**	**84.6**
No. 10	**77.1**	**69.9**	**79.8**
No. 20	**52.3**	**58.7**	**71.6**
No. 40	**40.2**	**48.5**	**62.2**
No. 60	**34.3**	**41.3**	**54.5**
No. 100	**30.5**	**36.5**	**48.7**
No. 200	**26.1**	**31.4**	**41.7**
Gravel, %:	**10.3**	**23.1**	**15.4**
Sand, %:	**63.6**	**45.5**	**42.9**
Silt, %:	**20.5**	**21.3**	**30.6**
Clay, %:	**5.6**	**10.1**	**11.1**
As Received Moisture Content, %:	**16.8**	**16.5**	**20.0**
Apparent Specific Gravity:	**2.619**	**2.623**	**2.587**



Particle Size Distribution Report

	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	6.9	3.4	12.6	36.9	14.1	20.5	5.6

☒	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			2.9957	1.1201	0.7703	0.1409	0.0095	0.0043	4.17	263.22

Material Description	USCS	AASHTO
○ brown silty SAND		

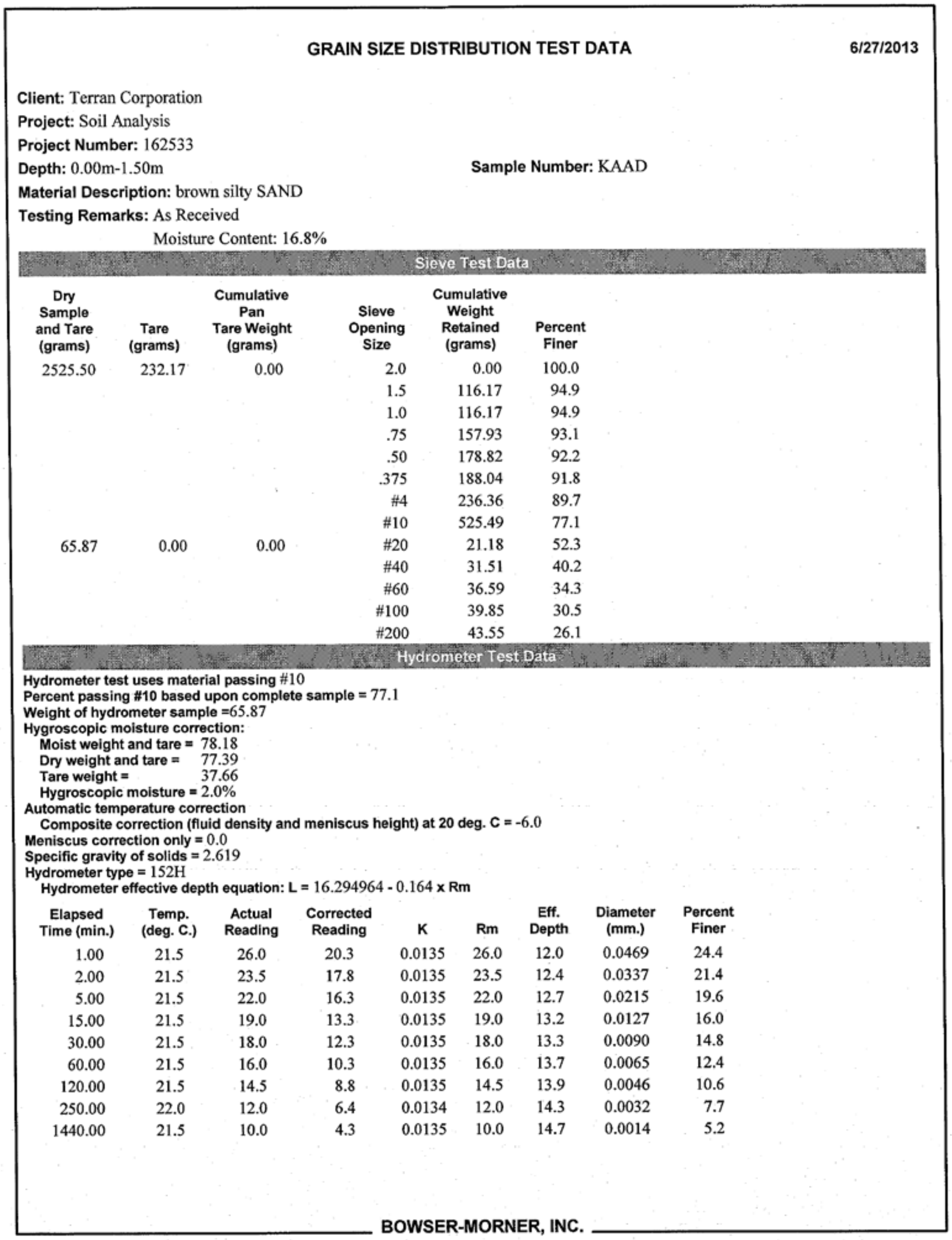
Project No. 162533 **Client:** Terran Corporation
Project: Soil Analysis

○ **Depth:** 0.00m-1.50m **Sample Number:** KAAD

BOWSER-MORNER, INC.

Dayton, Ohio

Remarks:
○As Received
Moisture Content: 16.8%



GRAIN SIZE DISTRIBUTION TEST DATA

6/27/2013

Client: Terran Corporation
Project: Soil Analysis
Project Number: 162533
Depth: 0.00m-1.50m **Sample Number:** KAAD
Material Description: brown silty SAND
Testing Remarks: As Received
Moisture Content: 16.8%

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
2525.50	232.17	0.00	2.0	0.00	100.0
			1.5	116.17	94.9
			1.0	116.17	94.9
			.75	157.93	93.1
			.50	178.82	92.2
			.375	188.04	91.8
			#4	236.36	89.7
			#10	525.49	77.1
65.87	0.00	0.00	#20	21.18	52.3
			#40	31.51	40.2
			#60	36.59	34.3
			#100	39.85	30.5
			#200	43.55	26.1

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 77.1
Weight of hydrometer sample =65.87
Hygroscopic moisture correction:
Moist weight and tare = 78.18
Dry weight and tare = 77.39
Tare weight = 37.66
Hygroscopic moisture = 2.0%
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.619
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	21.5	26.0	20.3	0.0135	26.0	12.0	0.0469	24.4
2.00	21.5	23.5	17.8	0.0135	23.5	12.4	0.0337	21.4
5.00	21.5	22.0	16.3	0.0135	22.0	12.7	0.0215	19.6
15.00	21.5	19.0	13.3	0.0135	19.0	13.2	0.0127	16.0
30.00	21.5	18.0	12.3	0.0135	18.0	13.3	0.0090	14.8
60.00	21.5	16.0	10.3	0.0135	16.0	13.7	0.0065	12.4
120.00	21.5	14.5	8.8	0.0135	14.5	13.9	0.0046	10.6
250.00	22.0	12.0	6.4	0.0134	12.0	14.3	0.0032	7.7
1440.00	21.5	10.0	4.3	0.0135	10.0	14.7	0.0014	5.2

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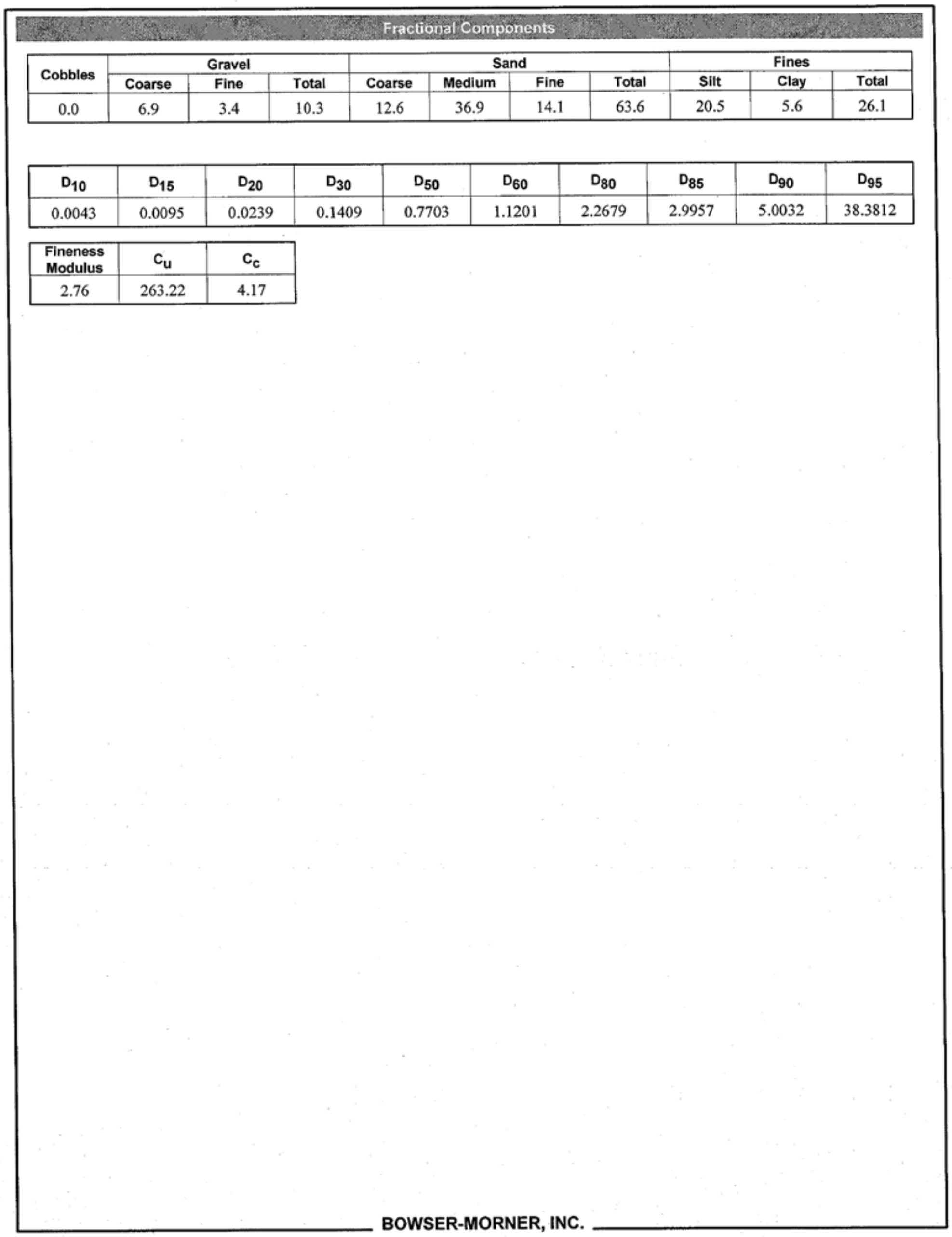

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	6.9	3.4	10.3	12.6	36.9	14.1	63.6	20.5	5.6	26.1

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0043	0.0095	0.0239	0.1409	0.7703	1.1201	2.2679	2.9957	5.0032	38.3812

Fineness Modulus	C_u	C_c
2.76	263.22	4.17

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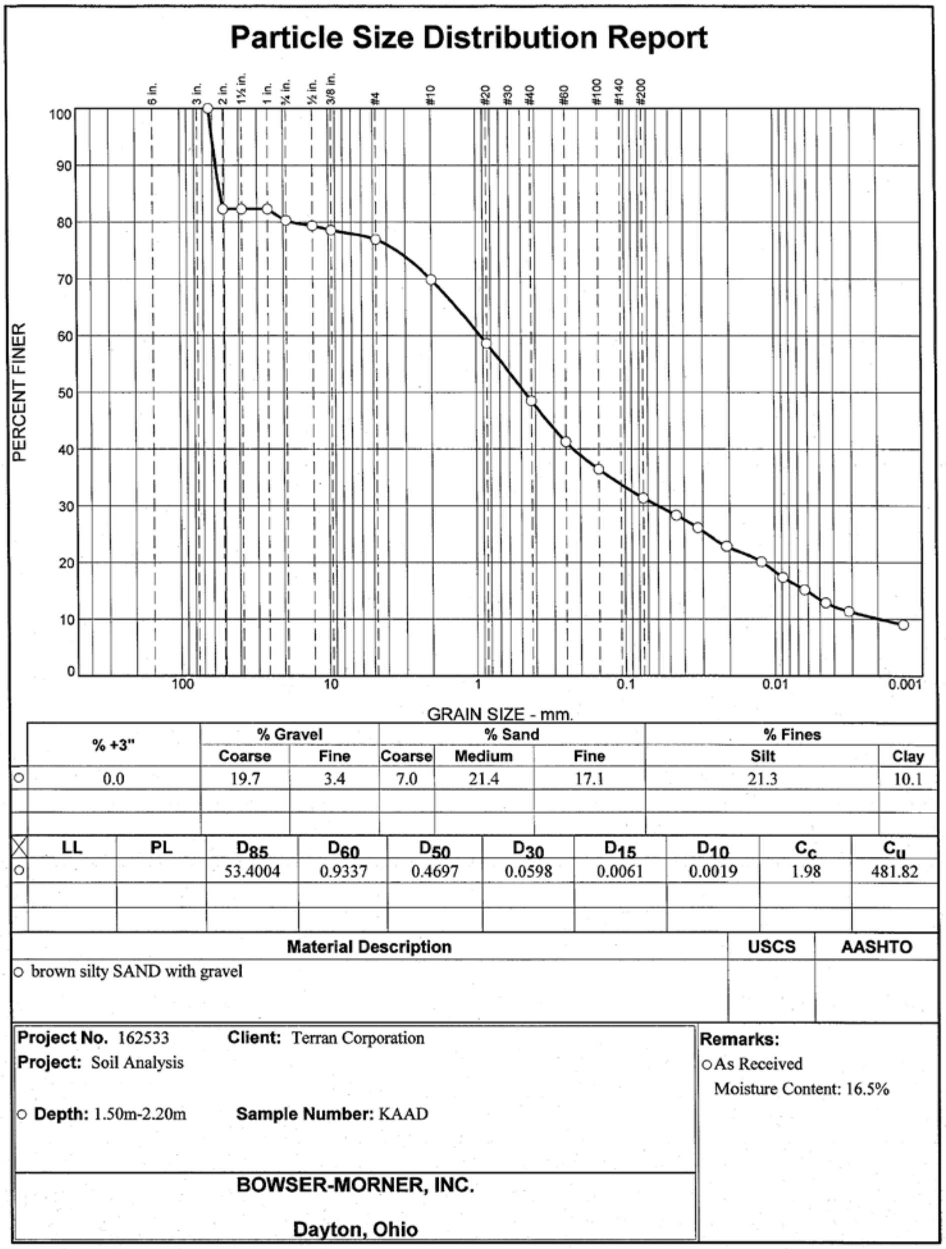


Particle Size Distribution Report

	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	19.7	3.4	7.0	21.4	17.1	21.3	10.1

☒	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			53.4004	0.9337	0.4697	0.0598	0.0061	0.0019	1.98	481.82

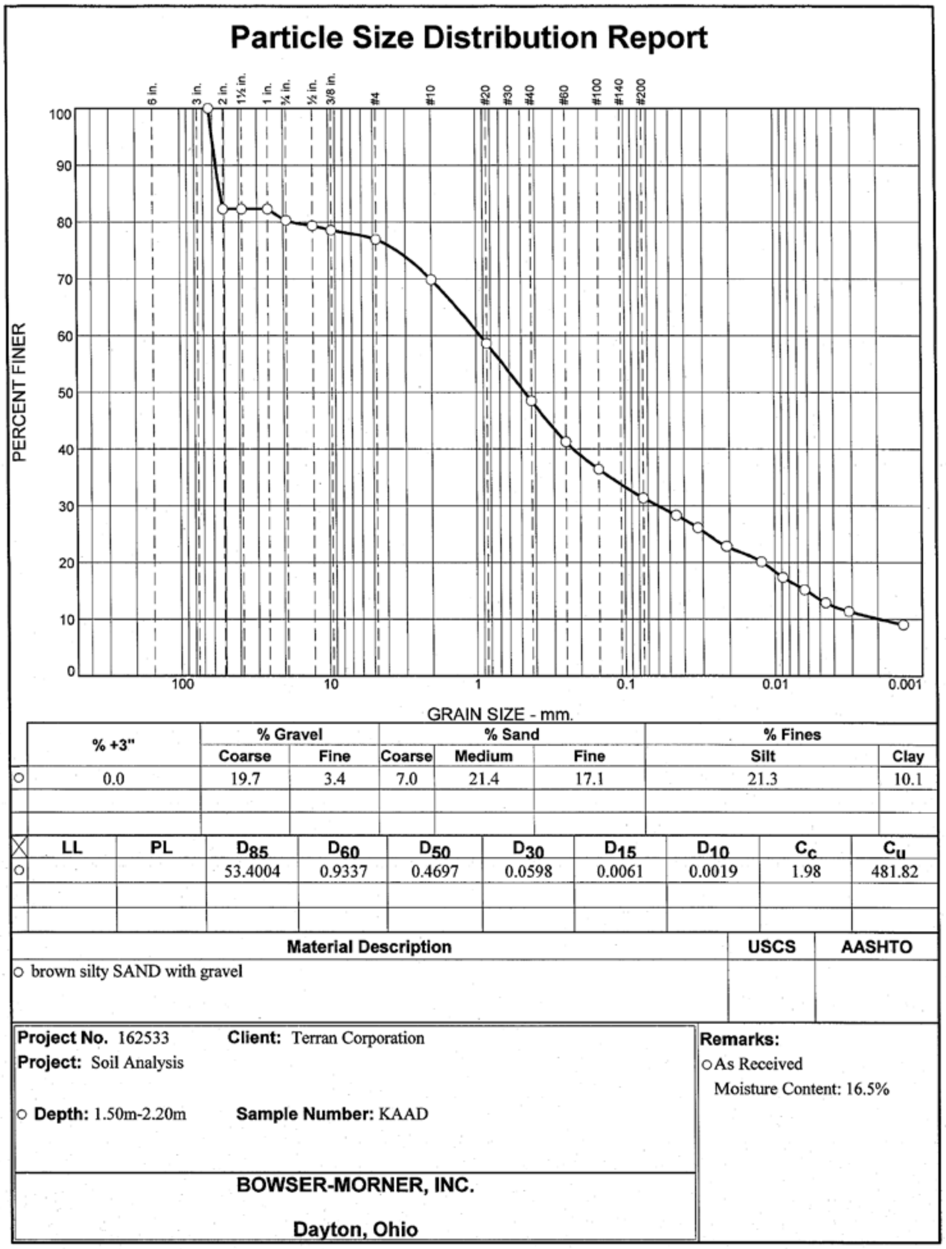
Material Description	USCS	AASHTO
○ brown silty SAND with gravel		

Project No. 162533 **Client:** Terran Corporation
Project: Soil Analysis

○ **Depth:** 1.50m-2.20m **Sample Number:** KAAD

BOWSER-MORNER, INC.
Dayton, Ohio

Remarks:
○As Received
Moisture Content: 16.5%



Particle Size Distribution Report

	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	19.7	3.4	7.0	21.4	17.1	21.3	10.1

☒	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			53.4004	0.9337	0.4697	0.0598	0.0061	0.0019	1.98	481.82

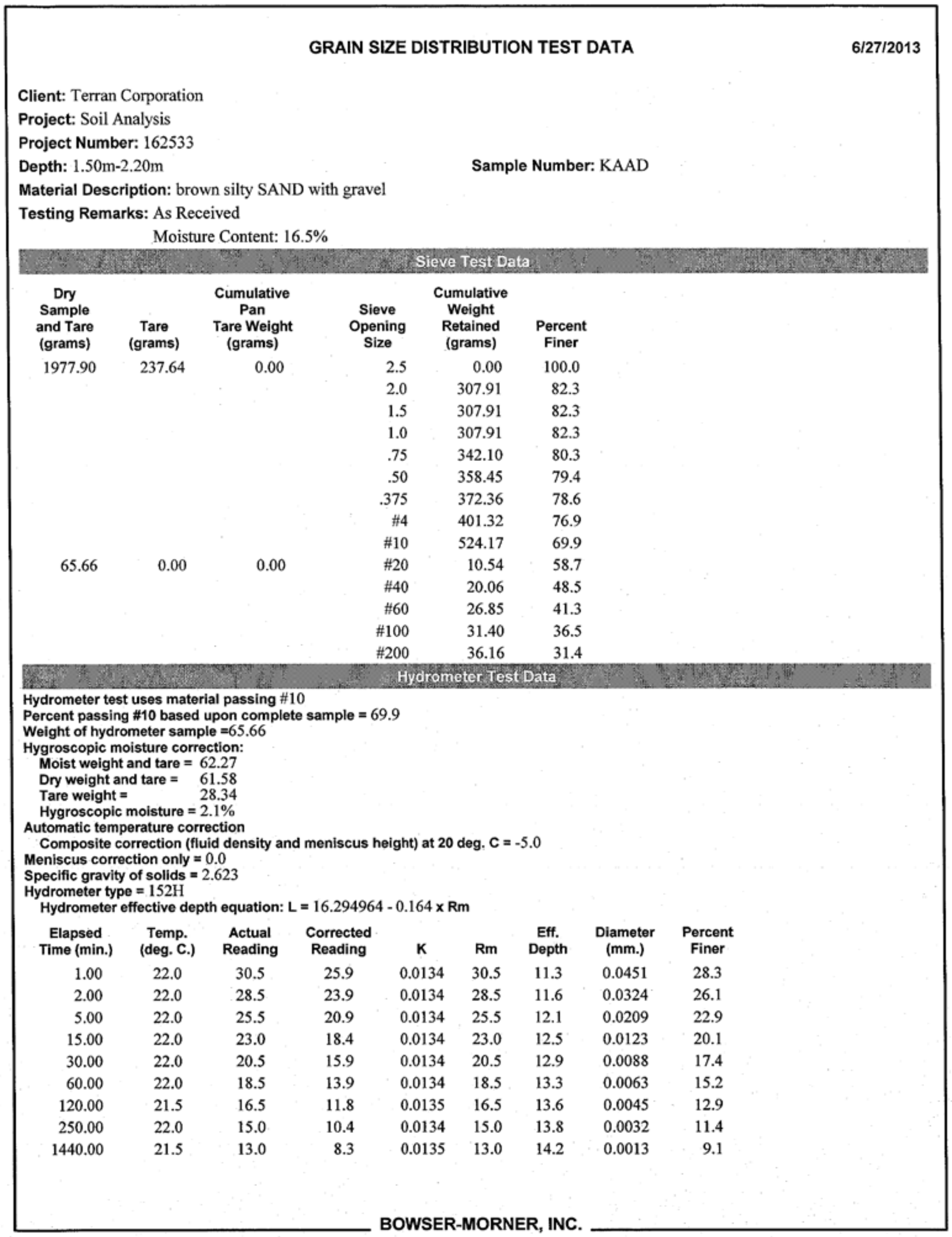
Material Description	USCS	AASHTO
○ brown silty SAND with gravel		

Project No. 162533 **Client:** Terran Corporation
Project: Soil Analysis

○ **Depth:** 1.50m-2.20m **Sample Number:** KAAD

BOWSER-MORNER, INC.
Dayton, Ohio

Remarks:
○As Received
Moisture Content: 16.5%



GRAIN SIZE DISTRIBUTION TEST DATA

6/27/2013

Client: Terran Corporation
Project: Soil Analysis
Project Number: 162533
Depth: 1.50m-2.20m **Sample Number:** KAAD
Material Description: brown silty SAND with gravel
Testing Remarks: As Received
Moisture Content: 16.5%

Sieve Test Data

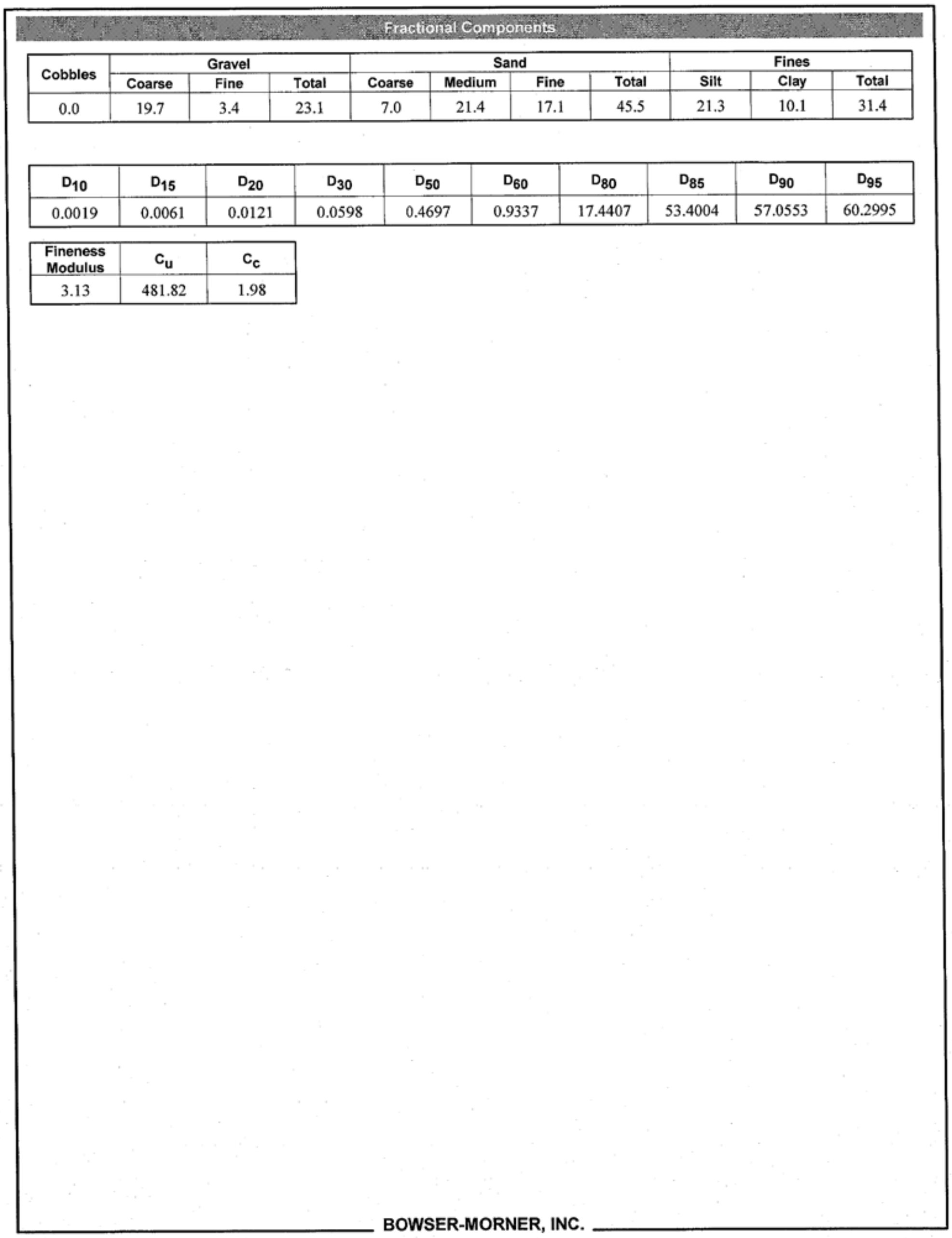
Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
1977.90	237.64	0.00	2.5	0.00	100.0
			2.0	307.91	82.3
			1.5	307.91	82.3
			1.0	307.91	82.3
			.75	342.10	80.3
			.50	358.45	79.4
			.375	372.36	78.6
			#4	401.32	76.9
			#10	524.17	69.9
65.66	0.00	0.00	#20	10.54	58.7
			#40	20.06	48.5
			#60	26.85	41.3
			#100	31.40	36.5
			#200	36.16	31.4

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 69.9
Weight of hydrometer sample =65.66
Hygroscopic moisture correction:
Moist weight and tare = 62.27
Dry weight and tare = 61.58
Tare weight = 28.34
Hygroscopic moisture = 2.1%
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -5.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.623
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	22.0	30.5	25.9	0.0134	30.5	11.3	0.0451	28.3
2.00	22.0	28.5	23.9	0.0134	28.5	11.6	0.0324	26.1
5.00	22.0	25.5	20.9	0.0134	25.5	12.1	0.0209	22.9
15.00	22.0	23.0	18.4	0.0134	23.0	12.5	0.0123	20.1
30.00	22.0	20.5	15.9	0.0134	20.5	12.9	0.0088	17.4
60.00	22.0	18.5	13.9	0.0134	18.5	13.3	0.0063	15.2
120.00	21.5	16.5	11.8	0.0135	16.5	13.6	0.0045	12.9
250.00	22.0	15.0	10.4	0.0134	15.0	13.8	0.0032	11.4
1440.00	21.5	13.0	8.3	0.0135	13.0	14.2	0.0013	9.1

BOWSER-MORNER, INC.



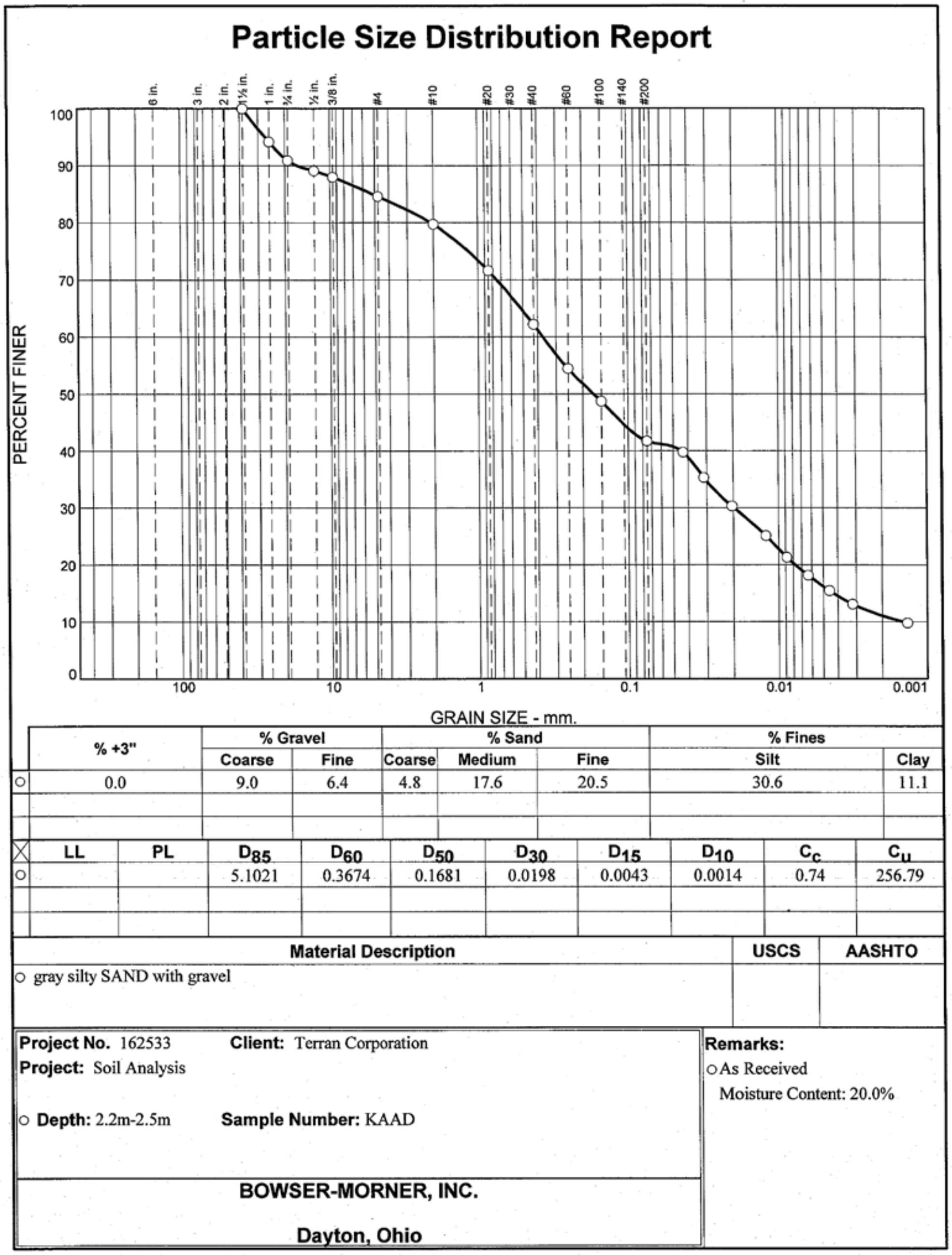
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	19.7	3.4	23.1	7.0	21.4	17.1	45.5	21.3	10.1	31.4

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0019	0.0061	0.0121	0.0598	0.4697	0.9337	17.4407	53.4004	57.0553	60.2995

Fineness Modulus	C_u	C_c
3.13	481.82	1.98

BOWSER-MORNER, INC.



Particle Size Distribution Report

	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0.0	9.0	6.4	4.8	17.6	20.5	30.6	11.1

☒	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			5.1021	0.3674	0.1681	0.0198	0.0043	0.0014	0.74	256.79

Material Description	USCS	AASHTO
○ gray silty SAND with gravel		

Project No. 162533 **Client:** Terran Corporation

Project: Soil Analysis

○ **Depth:** 2.2m-2.5m **Sample Number:** KAAD

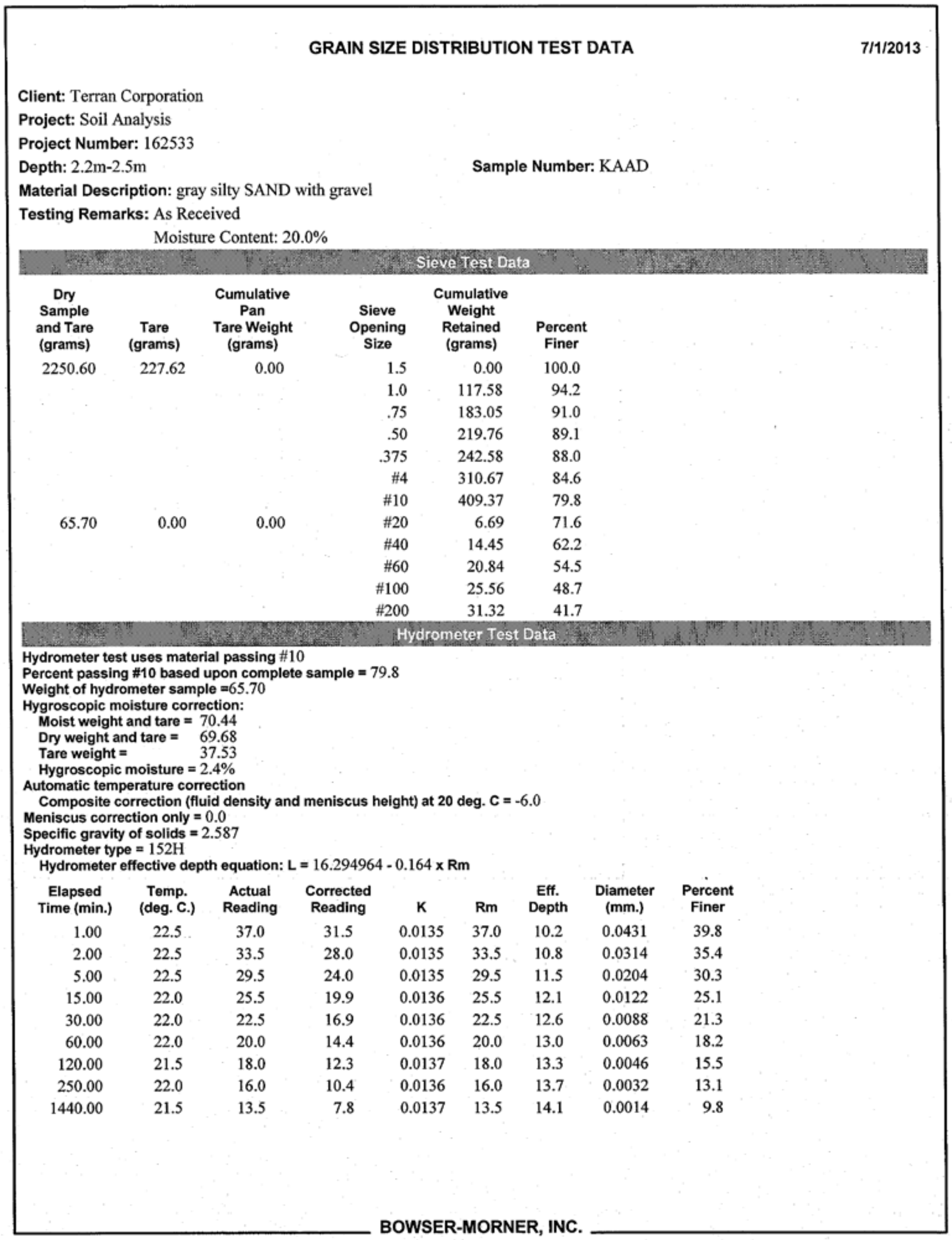
Remarks:

○As Received

Moisture Content: 20.0%

BOWSER-MORNER, INC.

Dayton, Ohio



GRAIN SIZE DISTRIBUTION TEST DATA

7/1/2013

Client: Terran Corporation
Project: Soil Analysis
Project Number: 162533
Depth: 2.2m-2.5m **Sample Number:** KAAD
Material Description: gray silty SAND with gravel
Testing Remarks: As Received
Moisture Content: 20.0%

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
2250.60	227.62	0.00	1.5	0.00	100.0
			1.0	117.58	94.2
			.75	183.05	91.0
			.50	219.76	89.1
			.375	242.58	88.0
			#4	310.67	84.6
			#10	409.37	79.8
65.70	0.00	0.00	#20	6.69	71.6
			#40	14.45	62.2
			#60	20.84	54.5
			#100	25.56	48.7
			#200	31.32	41.7

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 79.8
Weight of hydrometer sample =65.70
Hygroscopic moisture correction:
Moist weight and tare = 70.44
Dry weight and tare = 69.68
Tare weight = 37.53
Hygroscopic moisture = 2.4%
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.587
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	22.5	37.0	31.5	0.0135	37.0	10.2	0.0431	39.8
2.00	22.5	33.5	28.0	0.0135	33.5	10.8	0.0314	35.4
5.00	22.5	29.5	24.0	0.0135	29.5	11.5	0.0204	30.3
15.00	22.0	25.5	19.9	0.0136	25.5	12.1	0.0122	25.1
30.00	22.0	22.5	16.9	0.0136	22.5	12.6	0.0088	21.3
60.00	22.0	20.0	14.4	0.0136	20.0	13.0	0.0063	18.2
120.00	21.5	18.0	12.3	0.0137	18.0	13.3	0.0046	15.5
250.00	22.0	16.0	10.4	0.0136	16.0	13.7	0.0032	13.1
1440.00	21.5	13.5	7.8	0.0137	13.5	14.1	0.0014	9.8

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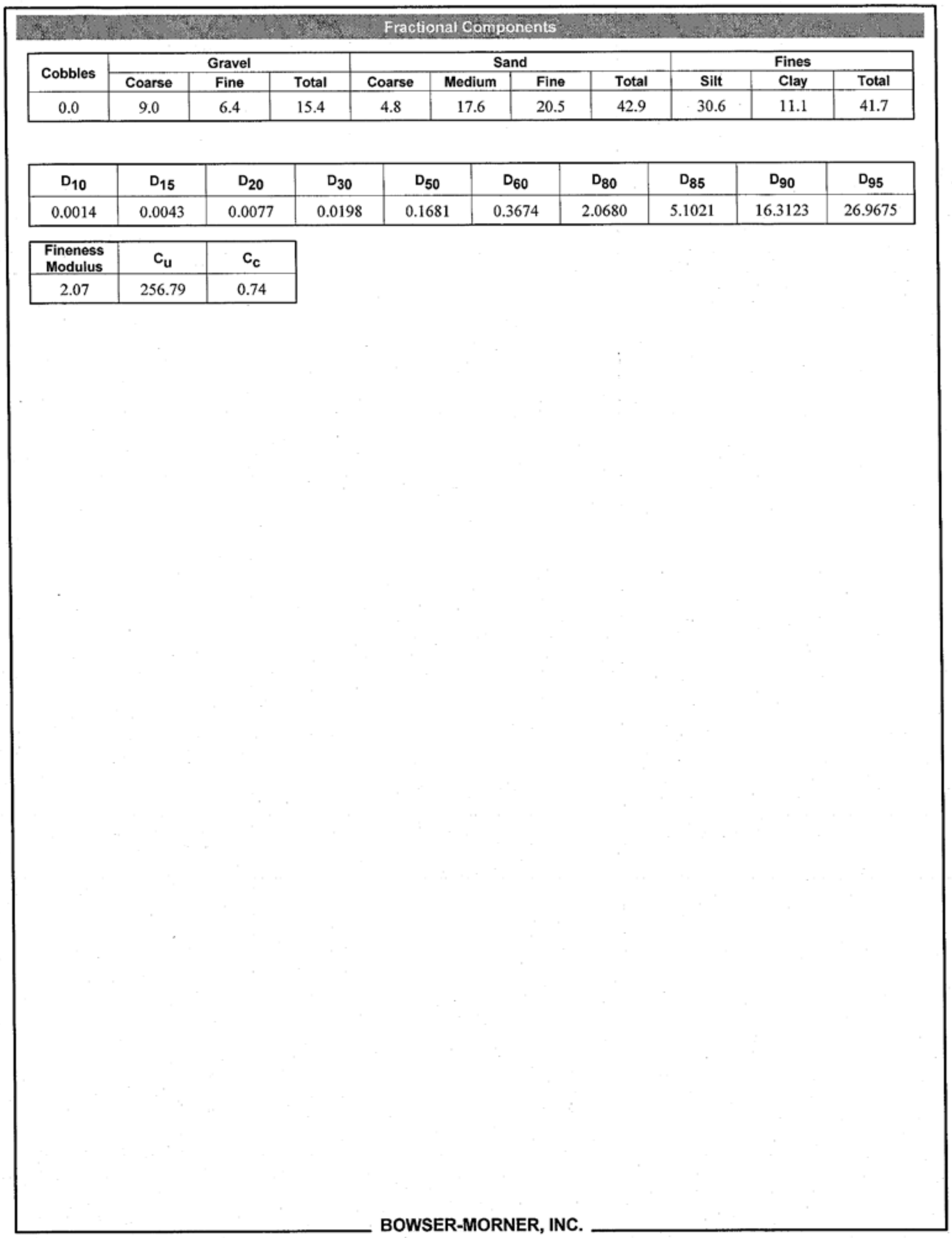

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	9.0	6.4	15.4	4.8	17.6	20.5	42.9	30.6	11.1	41.7

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0014	0.0043	0.0077	0.0198	0.1681	0.3674	2.0680	5.1021	16.3123	26.9675

Fineness Modulus	C_u	C_c
2.07	256.79	0.74

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Michael K. McInerney, Christopher Athmer, and Lawrence Clark

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14. ABSTRACT

When precipitation, runoff, and snowmelt percolate into soil and overload existing drainage infrastructure, the water table around building foundations can rise and infiltrate through cracks and joints. When infiltration exceeds sump pump capabilities, standing water and residual dampness can corrode or ruin fixtures, equipment, and stored supplies, also promoting mold growth that can make workers ill. The conventional solution—trenching and installing drainage tiles—is expensive, disruptive, and often ineffective. This report documents the development and demonstration of a patented electro-osmotic dewatering technology that works with outdoor wells and pumps to lower the water table around subgrade structures, thereby reducing or eliminating damage to building contents and the subgrade structure.

After a pilot test at an installation in Japan and a site-selection procedure, an optimized prototype system was installed for an administrative building at Blue Grass Army Depot, KY. The system was able to nominally lower the water table, and electro-osmotic flow was confirmed to positively impact pumping rates. However, site-specific drainage issues allowed rainwater to bypass the system and infiltrate the basement. Given less problematic site conditions, the projected return on investment for the technology was 9.97. Recommendations are offered for further development that could significantly increase technology effectiveness.

15. SUBJECT TERMS
Corrosion; Electro-osmotic dewatering; Groundwater; Water table; Dampness in buildings; Dampness in basements; Military bases–Buildings

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