Electrokinetic dewatering of Orr Dam Sediment

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Abstract: This study addresses the application of electroosmosis for dewatering sediment collected from the RT Orr dam in Stratford, Ontario, Canada. Sediment buildup in the Orr Dam is affecting reservoir capacity and normal operations, thus dewatering and disposal are necessary. This study is carried out to evaluate the effects of electrokinetic (EK) treatment on river sediments as well as to assess the feasibility of EK dewatering of this specific sediment. This is accomplished by a series of laboratory tests to characterize the sediment, to measure the coefficient of electroosmotic permeability, k_e, and to measure the sediment's response to electrokinetic dewatering. An analytical model of one-dimensional consolidation generated by the combined effect of EK and surcharge is developed to evaluate the results obtained in the dewatering tests. The results of this study show that EK dewatering is very effective on the Orr Sediment, generating high EK flows and significant reduction in sediment moisture contents. Overall the EK dewatering is two to three times more effective than dewatering by surcharge alone.

Keywords: electrokinetics, electroosmosis, consolidation, surcharge, river sediment, dam, dewatering.

1. Introduction

Sediment build-up is a problem facing many small dams operated by the Upper Thames River Conservation Authority (UTRCA) in Ontario, Canada. The deposits in the fore bay of the R. Thomas Orr dam in particular have resulted in numerous problems. In addition there are concerns about the disposal of the sediment that has been contaminated by metals and Polyaromatic Hydrocarbons (PAH) from the runoff of local parking lots, roads and residential and commercial lots. The total amount of sediment that needs to be removed is 800 m^3. The handling of dredged sediment under consideration includes reuse on the site as fill on park lands, disposal at a landfill cover soil, or use as a fill at a Brownfield site. All of these possible solutions require the sediment being dewatered to a consistency so that it can be handled as solids. After dewatering the sediment must (1) meet the waste slum requirements of the landfill; and (2) allow for safe transport of the materials (Talsma and Mark 2007). The methods of dewatering considered for the sediment include in-situ drainage, spreading and drying, dewatering by a filter press, etc. However, the predominant fines in the sediment make the conventional dewatering techniques mentioned above either time consuming or costly.

The objective of this study is to investigate the feasibility of electrokinetic (EK) dewatering on sediments from the fore bay of the Orr Dam. An experimental study was designed and performed to characterize the sediment and to measure the coefficient of electroosmotic (EO) permeability, k_e, as well as the effectiveness of EO dewatering.

2. Background

Electroosmotic consolidation as a soil improvement technology was patented in 1939 in Germany (Casagrande 1952, Adamson et al. 1966). Since then, electroosmosis has been applied to various geotechnical applications such as: Electrokinetic consolidation of soils (Adamson et al. 1966, Bjerrum et

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al. 1967, Lo et al. 1990), Electrokinetic remediation of contaminated soils (Hamad et al. 1991, Acar and Alshawabkeh 1993, 1996, Acar et al. 1995, Alshawabkeh and Acar 1996), Electrokinetic barriers to control seepage of contaminants (Mitchell and Yeung 1990, Narsasimhan and Ranjan 2000), and Electrokinetic treatment of waste sludge (Laursen and Jensen 1993, Yuan and Weng 2003).

Electrokinetics encompasses three specific concepts: electroosmosis, electrophoresis, and electromigration, all induced by an applied electric current. Electroosmosis refers to the motion of particles suspended in a fluid. Electromigration refers to the transport of ions. Electroosmosis refers to the motion of fluids in a porous medium (Mitchell and Soga 2005). The focus of this study is electroosmosis. Electroosmosis is a phenomenon involving the flow of fluid through a channel under an applied electric field; in most cases walls in these channels are characterized by the presence of surface charges (Deshpande et al. 1998). In the case of soil, the microchannels in question are represented by the surface of the soil particles, which carry a negative charge. The application of the electric field exerts a force on the fluid due to the surface charge of soil particles. The quantity of liquid moved per unit time by electroosmosis is given by:

$$Q = k_e EA \qquad [1]$$

Where the parameter that governs flow induced by electroosmotic (EO) permeability, k_e (m^2/sV), E (V/m) is the electric field intensity, and A (m^2) is the cross-sectional area perpendicular to water flow. The electric field intensity is calculated using the voltage drop across the length of the porous medium (Casagrande 1952). Theoretically the coefficient of EO permeability is expressed as (Mitchell and Soga 2005):

$$k_e = \frac{\zeta \varepsilon n}{\mu} \qquad [2]$$

Where ζ (mV) is the zeta potential of solids, ε (F/m) is the permittivity of the pore fluid, n is the porosity of solid skeleton, and μ (Ns/m^2) is the viscosity of the pore fluid. Since the permittivity and viscosity are constants, k_e is largely governed by the porosity and zeta potential (Mitchell and Soga 2005). The coefficient is the volumetric flow rate per unit cross-sectional area per unit electric field intensity. It is the defining parameter for the efficiency and effectiveness of electroosmosis. Along with the hydraulic conductivity of the soil, k_h, it governs the generation of negative pore-water pressure and thus consolidation due to electroosmosis through the EO permeability ratio (k_e/k_h). For an EK project to have engineering significance, the k_e/k_h ratios have been reported of greater than 0.1 (Mohamedelhassan and Shang 2001).

The application of an electric field results in electrolysis reactions at the anode and cathode. At the anode, hydrogen (H+) ions and oxygen gas (O_2) are produced lowering the pH in the vicinity of anode. At the cathode, hydroxide ions (OH-) and hydrogen gas (H_2) are produced, leading to the increase in pH at the vicinity of the cathode.

The protons generated at the anode migrate towards the cathode and expand an acidic zone, which may eventually dominate the soil (Hamad et al. 1991). Conversely, hydroxides generated at the cathode expand outwards as well, creating an alkaline zone. In a soil with a high buffering capacity, the increase in soil acidity is inhibited and the base zone gradually dominates. Soils with high carbonate contents usually have a high buffering capacity due to the dissolution of calcite:

$$CaCO_3 + H^+_{(aq)} \text{ --> } Ca^{2+}_{(aq)} + HCO_3^+_{(aq)} \qquad [3]$$

Free protons (H+) are consumed in this reaction, inhibiting the generation of an acidic condition. At the cathode, the increased pH induces precipitation of filmy cements of calcium carbonate. In addition, certain materials used as anodes, such as steel, release dissolved iron, resulting in iron rich cements, which are stable in a wide range of pH (Rittirong et al. 2008).

The acidification of the vicinity of anode can lead to changes in the flow rate and corrosion of consumable anodes. The coefficient k_e is dependent on the zeta potential, which is dependent on the zero point charge (ZPC) that is the pH at which the net charge on the sediment particle surface is zero. When the pH is above the ZPC, the sediment particles have a negative zeta potential and the resulting EO flow is towards the cathode, conversely when the pH is below the ZPC, the flow is towards the anode (Reddy et al. 2006). Advances in the anode technology have led to major breakthrough in EK applications. Anodes made of mixed metal oxide (MMO) coated titanium, which is in the category of Dimensionally Stable Anodes (DSA), are available commercially and have service lives comparable to precious metals such as platinum. In this study, a mesh anode made of MMO coated Ti was used in all EK tests.

3. Experimental Study

The Orr Dam sediment was collected from the fore bay of the Orr Dam in Stratford, Ontario in the spring when the water level was lowered, at the location adjacent to the dam. The sediment was placed in twenty-gallon containers with the water level at the top to keep the sample saturated. The sediment characteristics were measured in lab, including: the grain size distribution, specific gravity, Atterberg limits, Carbonate content, organic matter content, compressibility (consolidation tests), and hydraulic conductivity. The coefficient of EO permeability was measured in the cell shown in Fig. 1, following the procedure developed in Mohamedelhassan (1998).

A schematic of the dewatering cell setup is shown in Fig. 2. The general design considerations of the apparatus include:

- Horizontal electrodes, with the anode at the top and cathode at the bottom. This was designed as to allow the combined effect of downward flow due to electroosmosis and gravity; and
- Application of a surcharge pressure on the top of anode. This was designed to test the effectiveness of dewatering under various consolidation pressure and void ratio conditions. In addition an applied surcharge pressure would ensure contact between the anode and sediment, allowing for a continuous electric field.

The dewatering cell consists of a tank with 1cm thick Plexiglas walls, with dimensions of 35x10x25 cm (length x width x depth). On the bottom of the tank a stainless steel (SS316) mesh is placed to act as a drainage channel. On top of the steel mesh a layer of geotextile is placed upon which the cathode is placed. The sediment sample, is first agitated until it has the consistency of a slurry and then is then poured into the cell, overlain by a layer of geotextile, which acts as a separator and support to prevent the anode from sinking into the sediment slurry.

The electrodes used in the EK dewatering tests included a Siemens MMO coated Ti anode, and a Stainless Steel (SS316) mesh cathode. The water collected at the bottom of the cell via two drainage valves is connected to a graduated cylinder. The water that seeped above the anode at the top of the cell was collected by a syringe.

The dewatering tests were carried out in three series. The common procedure for all dewatering tests involved placing the sediment sample between two horizontally placed electrodes, applying an electric current, monitoring the outflow of water, the settlement of the sample, and measuring the moisture contents of the sediment sample at the beginning and end of each test.

In the first test series, preliminary tests were carried out to find the optimal cell configuration for all subsequent tests. Three configurations of cathode-geotextile placement at the bottom of the cell were tested: (1) cathode at the bottom, overlain by a layer of geotextile, (2) geotextile at the bottom, cathode on top overlain by another layer of geotextile, and (3) Steel wire mesh at the bottom to create a drainage channel, a layer of geotextile, and the cathode. The effectiveness of each configuration was then evaluated through the quantity of water outflow, the final and initial solids contents, and general observations.

In the second test series, four one-hour dewatering tests were carried out to find the optimum combination of the current density and surcharge pressure. A constant voltage was applied on the sediment sample for one hour. The water outflow, settlement, water pH, electrical conductivity, and

sediment temperature were monitored during each test. The sediment moisture content was measured before and after the tests, and the results were used to determine the operating parameters for the third test series.

In the third test series, the optimum applied current density and surcharge pressure as identified from the second test series were applied on the sediment samples for longer durations in order to investigate the maximum reduction in the water content achievable by the EK treatment, duration of dewatering, and power consumption. The electric current was applied on the sediment sample until the water flow reached a complete stop. During the second and third test series the water outflow, sample settlement and temperature, and water pH were measured in real time. For comparison of results, a control test was carried out in parallel with every EK test under which the dc current was not applied.

4. Sediment Properties

The geotechnical properties of the sediment are summarized in Table 1. The solids are 100% finer than a #200 sieve (74 µm), with a clay fraction of 10% and a silt fraction of 90%. The particle size distribution curve for the sediment is shown in Fig. 3. The sediment contains 28% carbonates, and 14.8% organic matter. The high carbonate content is a positive indicator for the effectiveness of EK dewatering, as discussed in the previous section. The sediment has a specific gravity 2.59; liquid limit 63.15% and plastic limit 36.2%. The zeta potential of solids ranged from -15 mV to -29 mV in the pH range of 3 to 10.5, as seen in Fig. 4. The hydraulic conductivity was measured in the range of $\sim 10^{-8}$ m/s, from both seepage analysis (Seep/W, Geostudio 2007) in the testing cell and from oedometer tests (ASTM D2435-04). The coefficient of consolidation ranged from 0.5×10^{-7} m^2/s to 1.19×10^{-7} m^2/s, depending on the sediment void ratio. The average coefficient of EO consolidation is measured as 3.9×10^{-9} m^2/sV, thus the k_e/k_h ratio is about 0.4. The results indicate that from factors such as high carbonate content, negative zeta potential, fine grain size distribution and EO permeability, the Orr Dam sediment would be a good candidate for EK dewatering.

5. Electrokinetic Dewatering Tests

The first series of tests (preliminary tests) show that placing the cathode over the geotextile and a steel mesh drainage channel gave the best overall results, because it allowed better drainage, and prevented water pool at the cathode. Furthermore, direct contact between the cathode and sediment enhanced dewatering. Thus, this configuration was chosen for all dewatering tests in this study.

The second test series (D-Series) consisted of one hour tests designed to find the optimum applied current density and surcharge pressure. A constant current density was applied to the sediment sample for one hour under the surcharge pressure of 5 kPa. A control test (D1) was also performed under the same surcharge pressure. The results of the D-Series of tests are summarized in Table 3. The water flow increased linearly with the current density, as shown in Fig. 5. The most effective current density was 24 A/m^2 , under which 217 mL water was collected within 60 minutes, approximately three times more than the control test D1, which collected 72 mL water. The sediment moisture content was reduced from the initial 146.8% to a range from 117% to 127%, with the degree of saturation reduced to a range of 92% to 98%. Fig. 6 shows the average sediment temperature for each test, in comparison to the room temperature. Temperature fluctuations in the sediment samples were minimal during testing, with the highest temperature increase occurring in test D4 under a current density of 24 A/m^2, where a change of 4.3 degrees was noted within 60 minutes. Based on these results, an applied current density between 15 and 24 A/m^2 was chosen for the 3rd test series (Test Series-DW).

In the third series of tests (DW-Series), the optimum electrical current densities obtained in the Test D-Series was applied on two sediment samples until the flow stopped. The surcharge pressures on the sediment samples were 5 and 10 kPa, respectively, applied gradually over one hour to prevent shear failure. The dc current was applied after loading and maintained constant. The conditions of the DW-

series of tests are summarized in Table 4(a). The evaluation of the dewatering effectiveness was carried out through comparison between EK dewatering tests and control tests. The Orr Dam sediment, as placed in the EK cell, was 10 cm high, had an initial average solids moisture content of 110.5%, and zero shear strength.

Fig. 6 describes the discharge of water in all DW-Series tests as a function of time, and Table 4(b) summarizes the results. Test DW1 was carried out under a surcharge pressure of 10 kPa and an initial current density of 15 A/m^2. The moisture content was 54.2% after approximately 48 hours, compared to 87.4% after approximately 24 hours in the control test, DW1C. The total water collected in test DW1 was 1351 mL, over 48 hours of treatment, 1.4 times more than the control test DW1-C (558 mL). Fig. 7 depicts the sample settlement vs. time. The sediment settlement in test DW1 was 3.7cm, approximately 1.2cm higher than that of the control DW1C, where ~2.5 cm of settlement was measured.

Fig. 8 shows the pH of the discharged water and sediment temperature versus time during treatment. Test DW1 generated significant changes in water pH over 48 hours of electric current application. The pH of the expelled water, collected from the bottom cathode and above the top anode peaked at 12.1 after 1610 minutes. The water pH remained fairly stable and never dropped below 11, which is attributed to the high carbonate content of the sediment. A temperature increase of 2.5 C was registered after 120 minutes, after which the temperature began to drop then rose again after 330 minutes. Temperature data collection was interrupted after 510 minutes due to a malfunction of the thermocouple. Fig. 9 depicts the change in the electrical current over treatment time and shows for test DW1, a constant current was maintained for approximately 500 minutes.

Test DW2 was carried out under a surcharge pressure of 5 kPa and an initial current density of 20 A/m^2. The final moisture content of the sediment was 70.5% for test DW2 after approximately 24 hours, compared to 87.3% after approximately 24 hours for the control, DW2C. The total water collected in test DW2 under the combined EK dewatering and surcharge pressure was 831 mL, double the quantity from the control test (415 mL). Only 1 cm settlement was registered at the end of Test DW2, compared to 1.4 cm by the end of test DW2C (Fig. 7), which is attributed to electrochemical reactions, such as precipitation of calcium carbonate and cementation associated with higher current density in this test.

During test DW2 a malfunction of the thermal couple occurred at the start of the test. The highest pH was 11.6 after 24 hours and remained relatively constant, as shown in Fig. 8.   The applied current in test DW2 was constant for a shorter period than in test DW1 (Fig. 9).

The results of DW test series show that the combined surcharge and electrokinetic dewatering is more effective than the surcharge alone. The moisture contents with respect to the sampling location (normalized to the distance from the cathode) are shown in Fig. 10. The decrease in the sediment moisture content was fairly uniform throughout the sediment after test DW1, with insignificant differences at the anode, cathode and middle (53.9-55.75%). The sediment was found to be fairly brittle with noticeable cracks formed during treatment. On the other hand, there were noticeable differences in the sediment moisture contents measured at the top (60.1%), bottom (77.9%) and middle (73.4%) of the test cell. At the anode the degree of saturation of the sediment reduced to 86% for test DW1, and to 63% for test DW2.

Overall the results of test DW1 (10 kPa, 15 A/m^2) were better in terms of the final moisture content, water discharge and duration of treatment. Throughout all tests, a single MMO coated Ti anode was used, which performed well with no noticeable degradation.

6.0 Theoretical Modeling of Electrokinetic Consolidation

An analytical model is developed for one dimensional (1D) consolidation of combined surcharge and EK to provide insight of the process and comparison between the experimental and theoretical results. The model is based on Terzaghi's 1D consolidation theory, as well as the analytical model of EK consolidation (Esrig 1968, 1971). The general approach in the derivation is also based on a study for 1D

combined vacuum and surcharge consolidation (Mohamedelhassan and Shang 2002). The general differential equation for the excess pore water pressure, u, is:

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t}, \qquad (0<z<H, \ t>0)$$ [4]

Where t [s] is time, z (m) is depth, H (m) is the drainage path, and c_v (m²/sV) is the coefficient of consolidation. The initial and boundary conditions for Eq. [4] for the surcharge preloading are:

u(0,t) = 0   (t>0), free drainage at the bottom of the soil layer [4a]
u(2H,t) = 0   (t>0), free drainage at the top of the soil layer [4b]
u(z,0) = q   (0<z<2H) [4c]

In the case of surcharge preloading the initial excess pore water pressure is equal to the applied surcharge pressure, and it dissipates to zero with time. The initial boundary conditions for Eq. [4] for the case of electrokinetic consolidation are:

u(0,t) = 0   (t>0), free drainage at the open cathode (bottom of the cell) [4d]
$\frac{\partial u}{\partial z}(H,t) = 0$ (t>0), impervious boundary at the anode (top of the cell) [4e]
u(z,0) = 0   (0<z<H) [4f]

In the case of electrokinetic consolidation the initial excess pore water pressure, u_{ek} , is equal to zero and becomes negative once the current is applied. It should be noted that negative pore water pressure in the sediment is unlikely to exceed -100 kPa (or -1 atm) due to cavitation of soil pore water (Holtz and Kovacs 1981).

The assumptions used in this analytical model are the same as those in Terzaghi's 1D consolidation theory. The solution to Equation [4] for electrokinetic consolidation was developed by Esrig (1968), for an open cathode, closed anode configuration:

$$u_e(x,t) = \eta \frac{k_e}{k_h}\left[-\gamma_w U \frac{x}{L} + \frac{2}{\pi^2}\gamma_w \sum_{n=0}^{\infty} \frac{(-1)^2}{\left(n+\frac{1}{2}\right)^2} \sin\frac{\left(n+\frac{1}{2}\right)\pi x}{L} e^{-\left(n+\frac{1}{2}\right)^2 \pi^2 T_v}\right]$$ [5]

Where u_e (kPa) is the excess pore water pressure, η is an empirical factor for efficiency of electrodes, k_e (m²/sV) is the EO permeability coefficient, k_h (m/s) is the hydraulic conductivity, γ_w (kN/m³) is the unit weight of water, x (m) is the distance from the cathode, L (m) is the spacing of the electrodes, U (V) is the voltage across the cell, T_v, the time factor for consolidation is:

$$T_v = \frac{c_v t}{H^2}$$ [6]

Where c_v (m²/s) is the coefficient of consolidation, and H is the length of the drainage path. In the case of surcharge preloading, the solution to Eq. [4] is based on Terzaghi's theory (Holtz and Kovacs 1981):

$$u_q = q \sum_{n=0}^{\infty} \frac{4}{(2n+1)\pi} \sin\frac{\left(n+\frac{1}{2}\right)\pi z}{H} e^{-\left(n+\frac{1}{2}\right)^2 \pi^2 T_v}$$ [7]

Where u_q (kPa) is the excess pore water pressure generated by the surcharge, q (kPa). In the case of combined surcharge preloading and electrokinetic consolidation, the excess pore water pressure is expressed as the sum of Eq. [5] and Eq. [7]:

$$u(z,t) = u_e(z,t) + u_q(z,t)$$ [8]

To analyze the consolidation under combined electrokinetic and surcharge pressure the average degree of consolidation, $U(\%)$, needs to be evaluated:

$$U(\%) = \frac{total\ volume\ change\ at\ time\ t}{ultimate\ volume\ change} x100\%$$ [9]

The same approach for obtaining the average degree of consolidation in Holtz and Kovacs (1981) is taken i.e.:

$$U(\%) = \frac{\int_0^{2H} q\,dz - \int_0^{2H} u_q\,dz - \int_0^H u_{ek}\,dz}{\int_0^{2H} q\,dz + \int_0^H \eta \frac{k_e}{k_h} \gamma_w U \frac{z}{H}\,dz}$$ [10]

For the purposes of expediency, the constants in the pore-water pressure due to EK equation will be referred to as c_1, i.e.,

$$c_1 = \eta \frac{k_e}{k_h} \gamma_w U$$ [11]

Therefore, the solution for Equation [10] gives the average degree of consolidation for the combined surcharge and EK,

$$U(\%) = \frac{100}{\left[2qH + \frac{c_1 H}{2}\right]} \left[2qH\left(1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{\left[-\left(n+\frac{1}{2}\right)^2 \pi^2 T_v\right]}\right) + \frac{c_1 H}{2}\left(1 - \frac{4}{\pi^3}\sum_{n=0}^{\infty} \frac{(-1)^n}{\left(n+\frac{1}{2}\right)^3} e^{-\left(n+\frac{1}{2}\right)^2 \pi^2 T_v}\right) \right]$$ [12]

Thus it is possible to model the excess pore water pressure and consolidation through Eq. [8] and Eq. [12], and a schematic of this analytical model is presented in Fig. 11. It should also be noted that the rate of consolidation due to electroosmosis depends on the coefficient of consolidation, which varies with the hydraulic conductivity of soil, k_h, but is independent from k_e (Mitchell and Soga 2005). Therefore, in this analytical model, the coefficient of consolidation and hydraulic conductivity obtained from the oedometer tests will be used.

Finally, the settlement as a function of time is given by:

$$s(t) = U(\%) * s_{ult}$$ [13]

Where the ultimate settlement due to ek and surcharge, s_{ult}, is:

$$s_{ult} = \sum_{i=1}^n \Delta H \frac{C_c}{1+e_o} \log \frac{\sigma'_o - \Delta\sigma}{\sigma_o} = \sum_{i=1}^n \Delta H \frac{C_c}{1+e_o} \log \frac{\sigma'_o + q - u_f}{\sigma'_o + q}$$ [14]

Where C_c is the compression index, e_o is the initial void ratio, ΔH is the height of the soil layer, and u_f is final excess pore water pressure.

The development of the analytical model is based on several assumptions, including the constant coefficient of EO permeability, k_e, the hydraulic conductivity, k_h and the electric field intensity E. Table 6 summarizes the input parameters used in the analytical model.

Fig. 12 shows the results of the settlement during Tests DW1 and DW2 against theoretical settlements obtained from the model. For test DW1 (10 kPa, 15 A/m^2) the theoretical results are in general agreement with the actual settlement, with a ~0.3cm difference between ultimate theoretical and

ultimate actual settlement. These differences may be attributed to the assumptions made in the 1D Consolidation model. On the other hand at the start of Test DW2 (5 kPa, 20 A/m^2) the experimental results are in agreement with the theoretical curve initially, however, after 200 minutes into the test the settlement slowed significantly. At the end of the test the sample settled approximately 1.05 cm, less than the theoretical value of 2.5 cm and the control test DW2C value of 1.5 cm. Loss of contact between the electrode and the sediment and rapid desaturation of sediment at the anode are the most plausible explanation for the early end of the water flow in test DW2. This is supported by the fact that the sediment moisture content was the lowest at the anode (60.1%), compared to the rest of the sample (~75%). It should be noted that from the zeta potential profile shown in Fig. 4 that the solids zeta potential would remain negative at the water pH measured at the end of test, hence the early stop of flow could not be attributed to the pore fluid acidity.

The degree of saturation of the sediment at the anode was approximately 63% in test DW2 at the end of test, and the electric current density was 1.74 A/m^2. In comparison the degree of saturation was approximately 86% at the end test DW1, with a current density of 3.8 A/m^2. It was also observed that the sediment had more uniform moisture content throughout the sample mass after test DW1, as shown in Fig. 10. Assuming the limiting negative excess pore water pressure -100 kPa (Holtz and Kovacs 1981), one can calculate the current density, j (A/m^2), required to maintain flow in both tests DW1 and DW2 using the equation:

$$j = \frac{100 k_h \lambda}{\eta \gamma_w k_e z}$$
[15]

Where k_h (m/s) is the hydraulic conductivity, λ (S/m) is the soil electrical conductivity, η is an empirical factor for electrode efficiency, γ_w (kN/m^3) is the unit weight of water, k_e (m^2/sV), and z is the distance from the cathode. Based on Eq. [15] the current density required to maintain the flow at the anode can be estimated. For the conditions of Test DW1, the current density required to maintain an electrokinetic flow is 8.41 A/m^2. For test DW2 the current density that must be maintained is 2.09 A/m^2. In both tests the current density (3.8 A/m^2 for DW1 and 1.7 A/m^2 for DW2) fell below what is required for the continuation of flow at the end of testing. This suggests that drying at the anode was the main cause for the stop of flow. The drying effect happened faster in test DW2 than in test DW1 based on the moisture content profiles shown in Fig. 10. Furthermore, the results indicate that the degree of saturation at which the loss of contact between the anode and the Orr sediment occurs is in the range of 63% to 86%.

7.0 Conclusions

This study investigates dewatering of the Orr Dam Sediment by means of electrokinetic treatment. The sediment characteristics, such as fines content, carbonate content, zeta potential, hydraulic conductivity and the coefficient of EO permeability, indicated that the sediment would respond positively to EK dewatering. A testing cell was developed to investigate the response of the Orr Sediment to EK dewatering. The sediment was placed inside a Plexiglas tank between two horizontally placed electrodes. Sediment dewatering investigation was carried out in three test series. Overall the sediment responded positively to dewatering under combined surcharge and electroosmosis, with the moisture content reduction between 40% and 55% for the EK tests as opposed to ~23% for the controls with the surcharge pressure only, therefore the EK and surcharge combined dewatering was 1.7 to 2.5 times more effective than the surcharge alone. The IrO$_2$/Ti dimensionally stable anode was used for all tests with satisfactory performance. Furthermore, an analytical model of 1D consolidation generated by the combined effect of surcharge and electroosmosis was developed and used to evaluate the results of the tests (Series-DW). The results of the analysis indicate that desaturation of the sediment at the anode was the primary cause for the stop of flow. Therefore the performance of EK dewatering can be enhanced by a proper design of the applied current density for sustained water flow over a prolonged time.

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Material Property	Value
D_{10}	2 μm
D_{30}	5 μm
D_{60}	10 μm
Specific Gravity, G_s	2.59
Liquid Limit, LL	63.15%
Plastic Limit, PL	36.2%
Carbonate Content	28.4%
Organic Matter Content	14.8%
Coefficient of consolidation, c_v	$0.545 \sim 1.19 \times 10^{-7}$ m^2/s
Hydraulic Conductivity, k_h	$\sim 10^{-8}$ m/s
Average Coefficient of EO Permeability, k_e	3.86×10^{-9} $m^2/sV \pm 1.06 \times 10^{-9}$ m^2/sV
EO Consolidation Ratio (k_e/k_h)	~0.39

Table 1: Material Properties - Orr Dam Sediment

Test No.	$j_{applied}$ (Amp/m^2)	Void Ratio e	k_e (x10^{-9} m^2/sV)	k_e/k_h
EK1	23.14	3.21	4.77	0.34
EK2	17.47	3.21	3.59	0.26
EK3	10.97	3.21	2.50	0.18
EK4	24.23	3.21	5.25	0.38
EK5	11.36	3.21	3.67	0.26
EK6	11.09	2.58	2.635	0.35
EK7	23.14	2.58	5.22	0.70
EK8	19.97	2.58	3.24	0.43

Table 2: EK Cell Test Summary (Provisional)

w_o	146.8%
H_o	10 cm
e_o	3.81

Test No.	j (A/m^2)	Water Collected (mL)	Final w (%)	ΔH	e_f	Final S(%)
D1 (Control)	0	72	127.3%	0.7	3.4733	94.9%
D2	7	118	116.6%	1.1	3.2809	92.0%
D3	15	155	122.6%	1.2	3.2328	98.2%
D4	24	217	126.1%	0.8	3.4252	95.3%

e_f and S(%) based on assumption that initial S(%) = 100%

Table 3: Series-D Dewatering Tests Summary

w_o	110.5%
e_o	2.86

Test No.	Surcharge (kPa)	Applied Voltage (V)	Voltage Gradient (V/m)	Current (Amp)	j (A/m^2)	H_o (cm)
DW1	10	20-30	200-300	0.43-0.28	15	11.5
DW1C	10	0	0	0	0	11
DW2	5	28-30	280-300	0.56-0.05	20	10.4
DW2C	5	0	0	0	0	10.2

Table 4(a): Series-DW Dewatering Test Initial Conditions

Test No.	w_f (%)	Δw (%)	Final/Control	ΔH (cm)	e_f	S (%) - Anode
DW1	54.61	55.89	2.46	3.7	1.62	86.5%
DW1C	87.8	22.7		2.3	2.05	100%
DW2	70.47	40.03	1.72	1.05	2.47	63%
DW2C	87.28	23.22		1.5	2.29	91.5%

Table 4(b): Series-DW Dewatering Test Results

Parameter	Unit	Value - DW1	Value - DW2
q	kPa	10	5
c_v	m^2/s	1.19×10^{-7}	5.48×10^{-8}
H	m	0.1	0.1
k_h	m/s	2.24×10^{-9}	6.54×10^{-10}
k_e	m^2/sV	3.01×10^{-9}	3.54×10^{-9}
η	-	0.9	0.9
γ_w	kN/m^3	9.8	
C_c	-	1.18	
U	Volt	15	20

Table 6: Input Parameters - 1D Consolidation EO + Surcharge Model
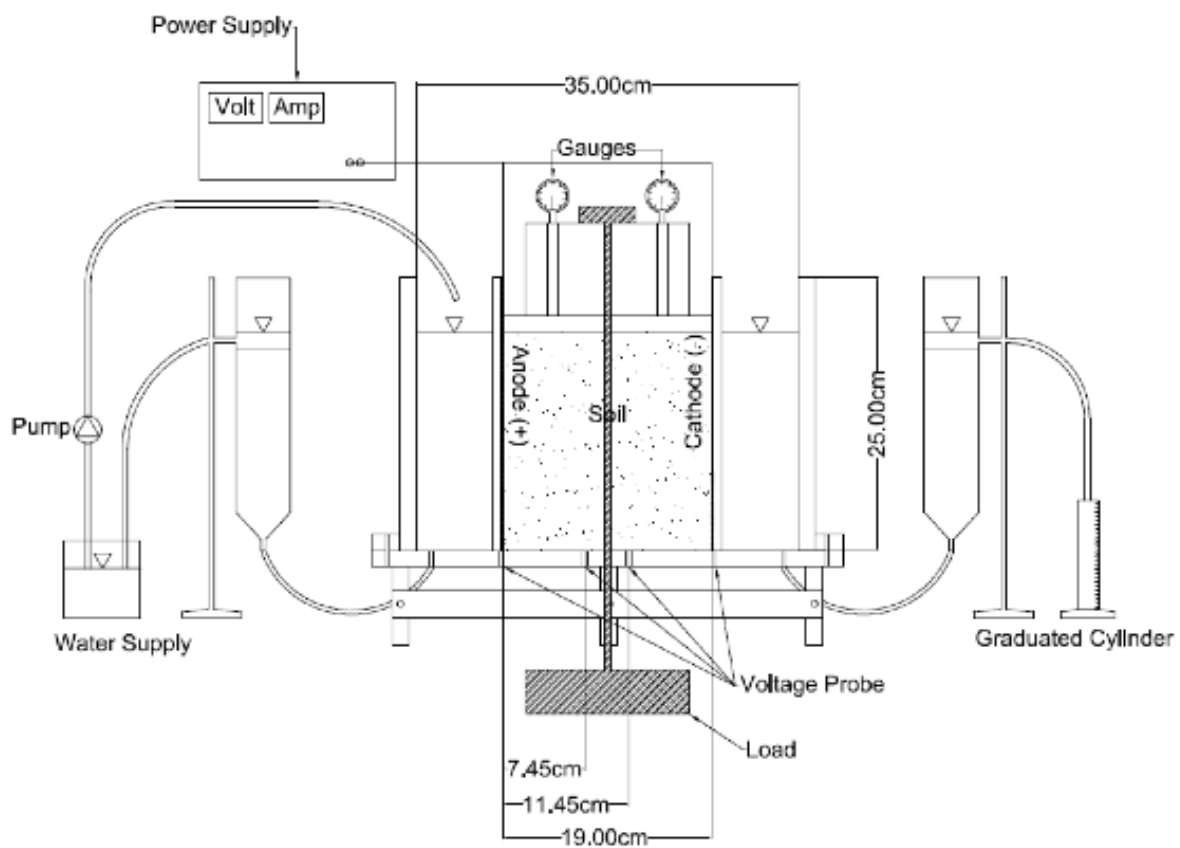
Fig. 1: EK Cell Test Schematic
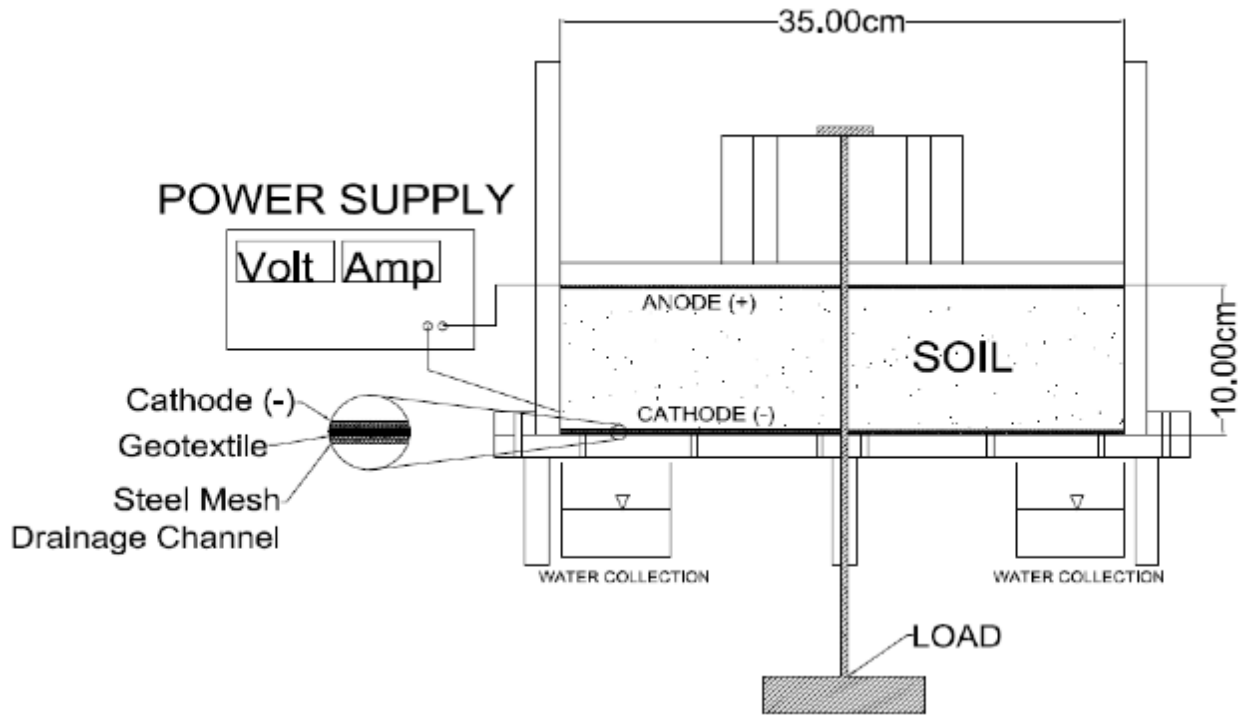
Fig. 2: EK Dewatering Test Schematic
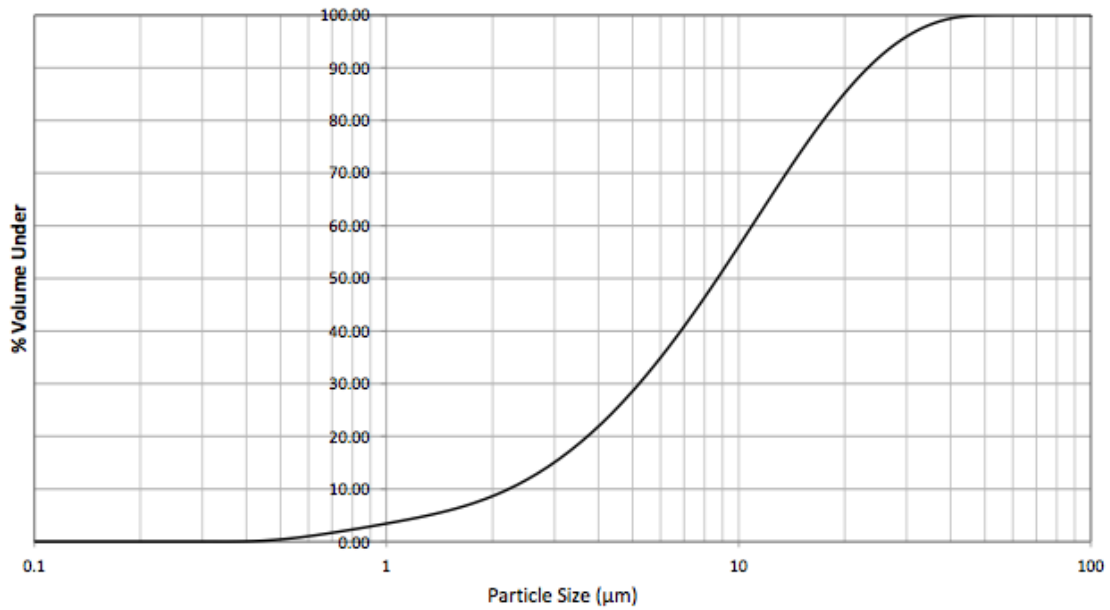
Fig. 3: Orr Dam Sediment - Particle Size Distribution
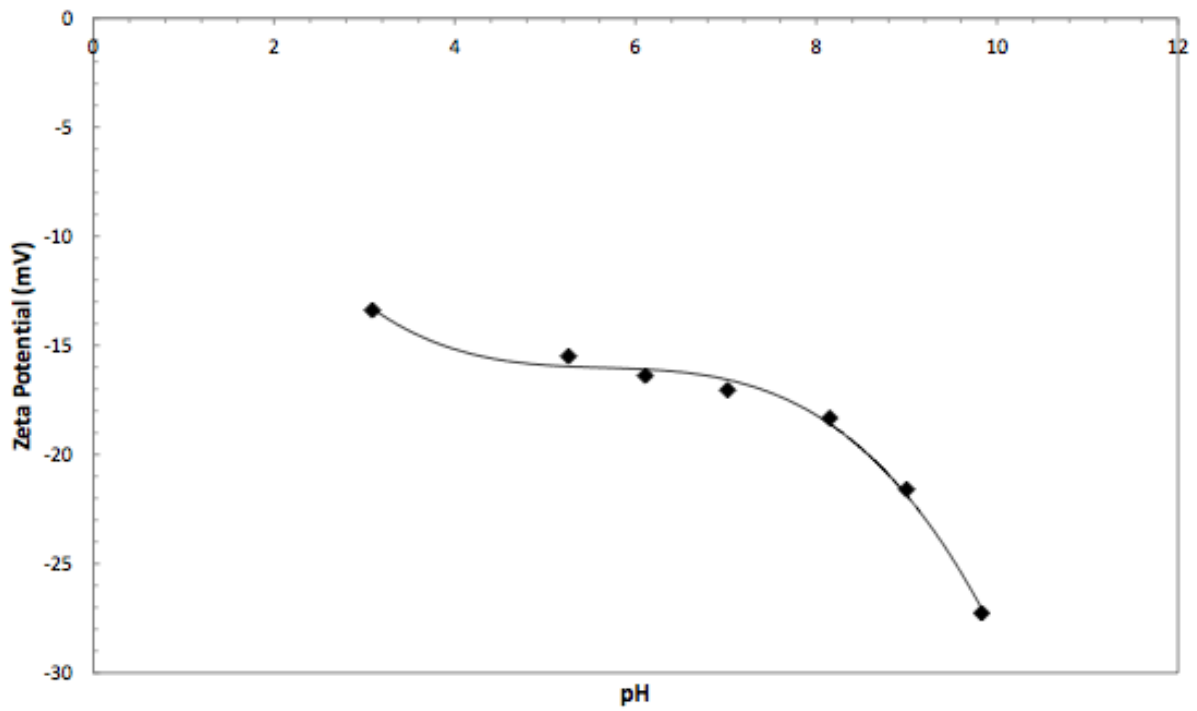
Fig. 4: Orr Dam Sediment - Zeta Potential vs. pH
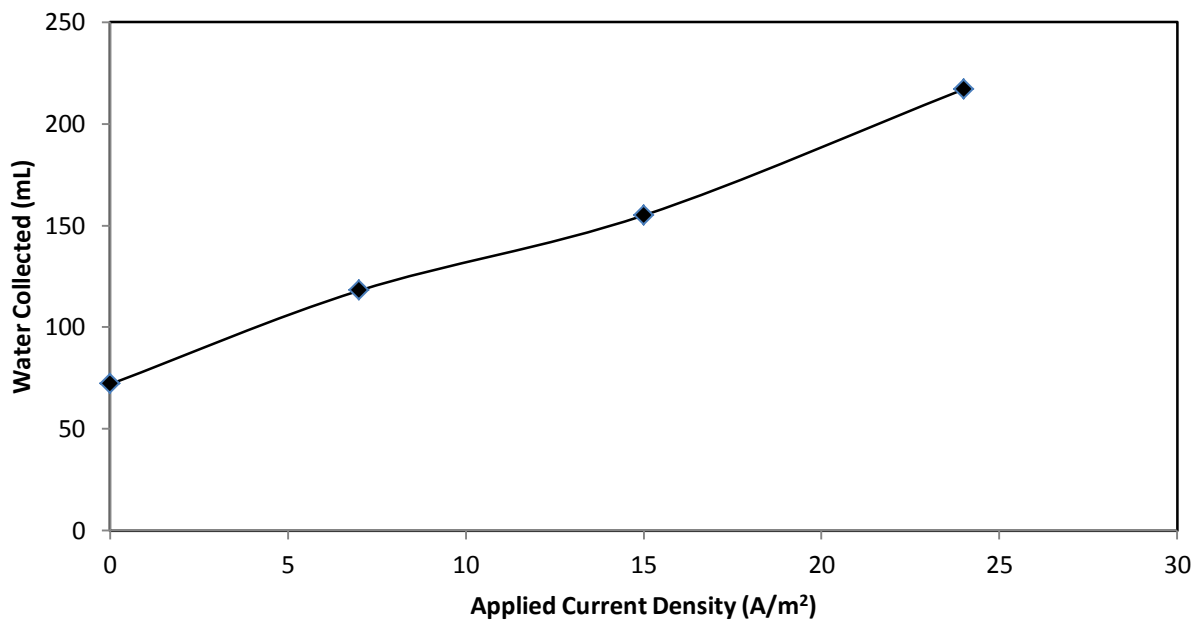
Fig. 5: Series D - Water Discharged vs. Applied Current Density (Provisional)
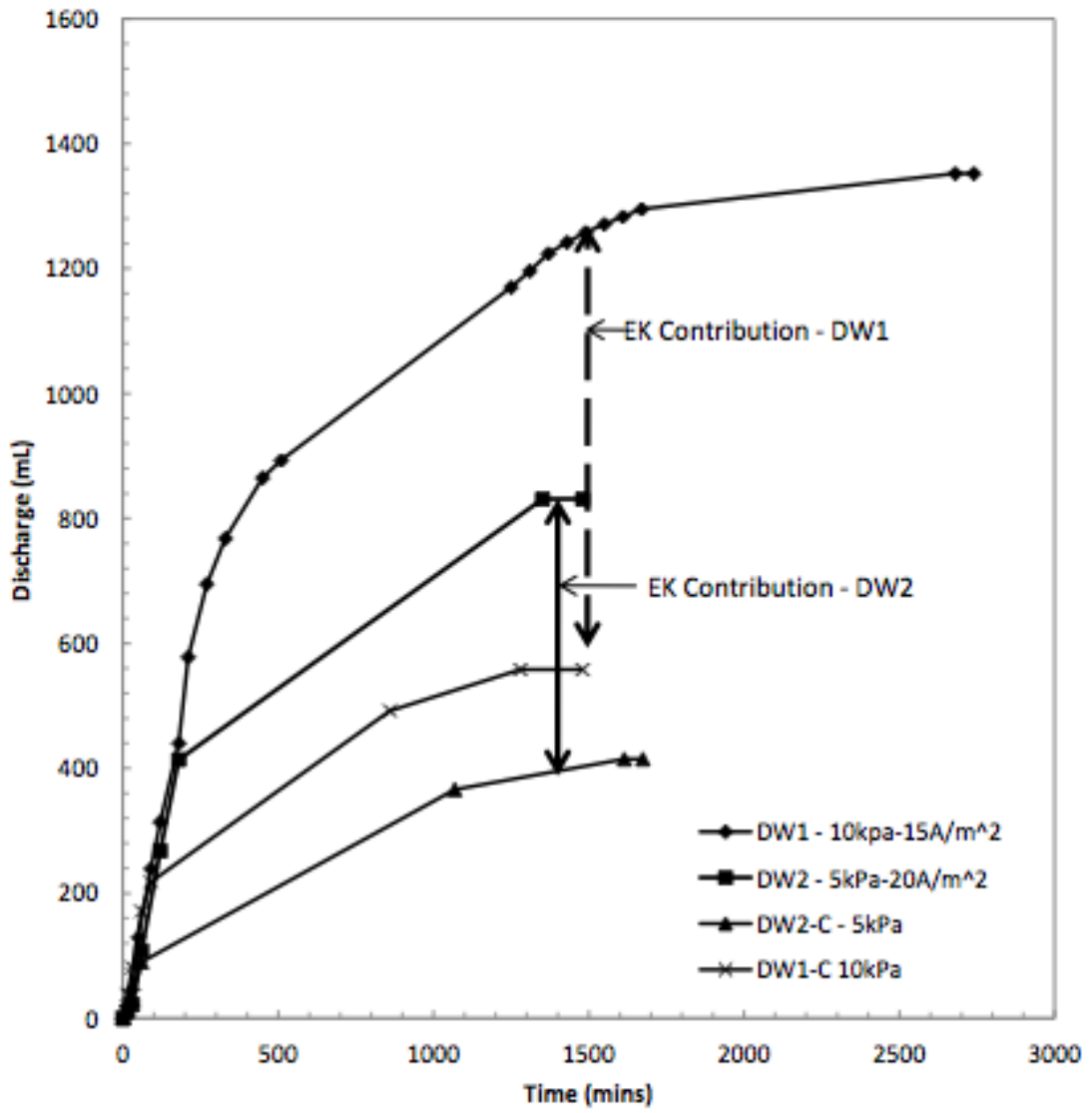
Fig. 6: Series DW - Discharge vs. Time
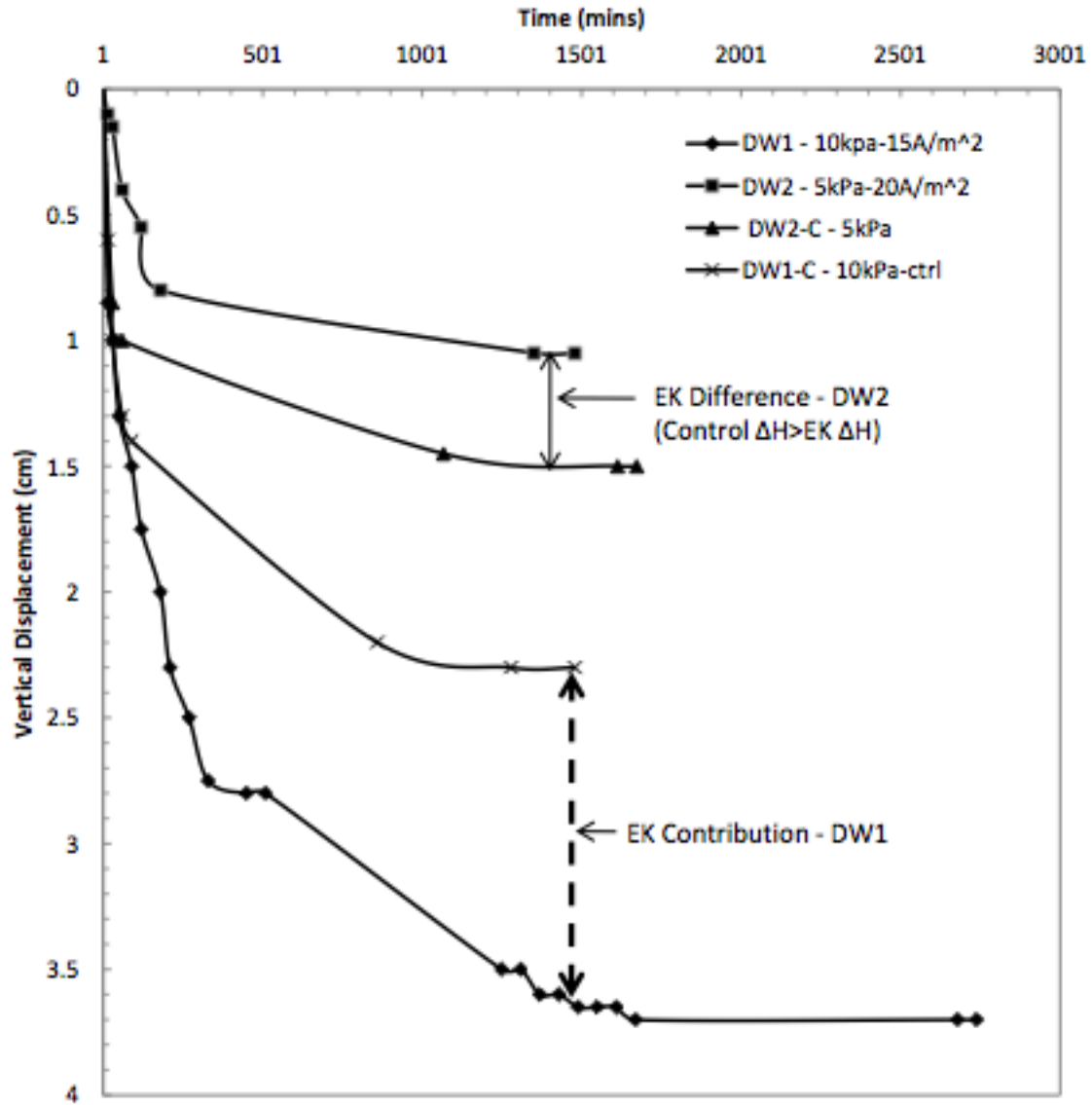
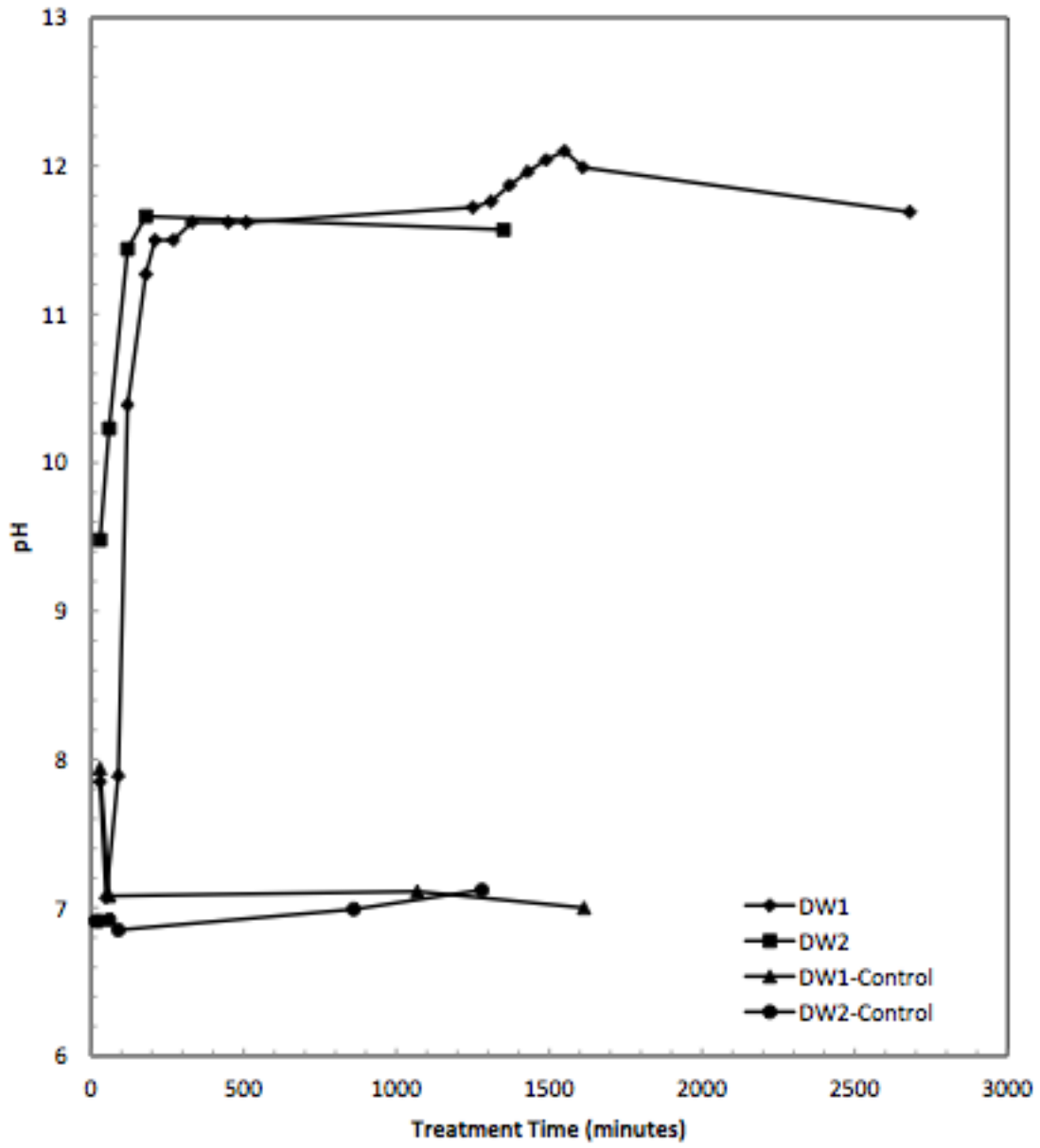**Fig. 7: Series DW - Soil Settlement vs. Time**

Fig. 8: Series DW - pH vs. Time
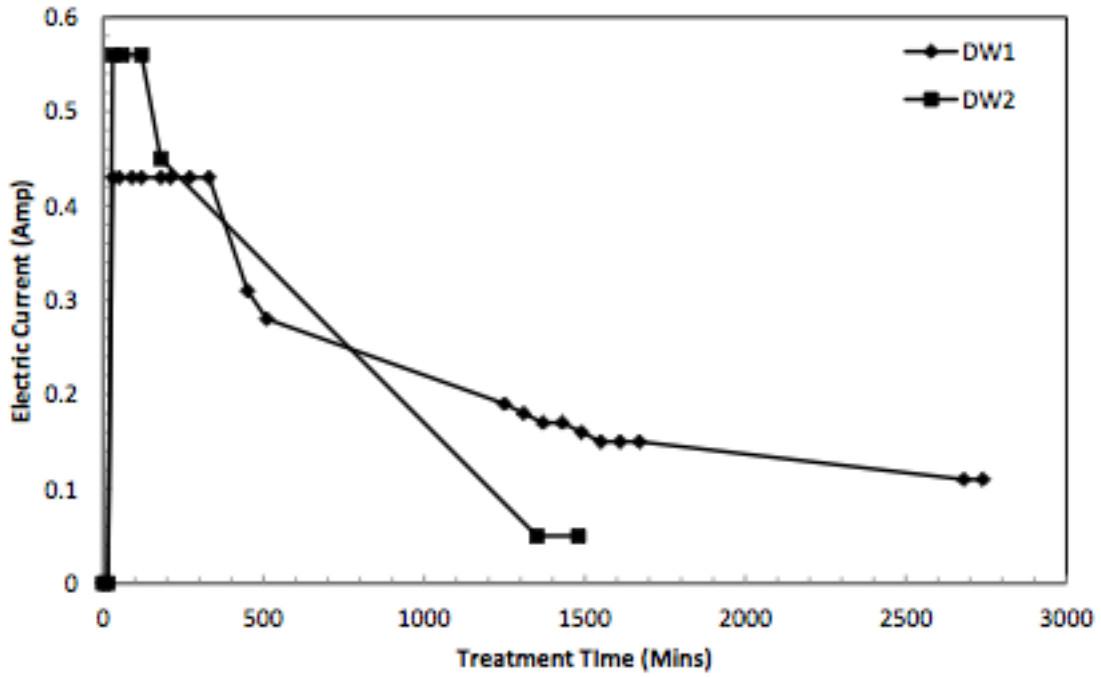
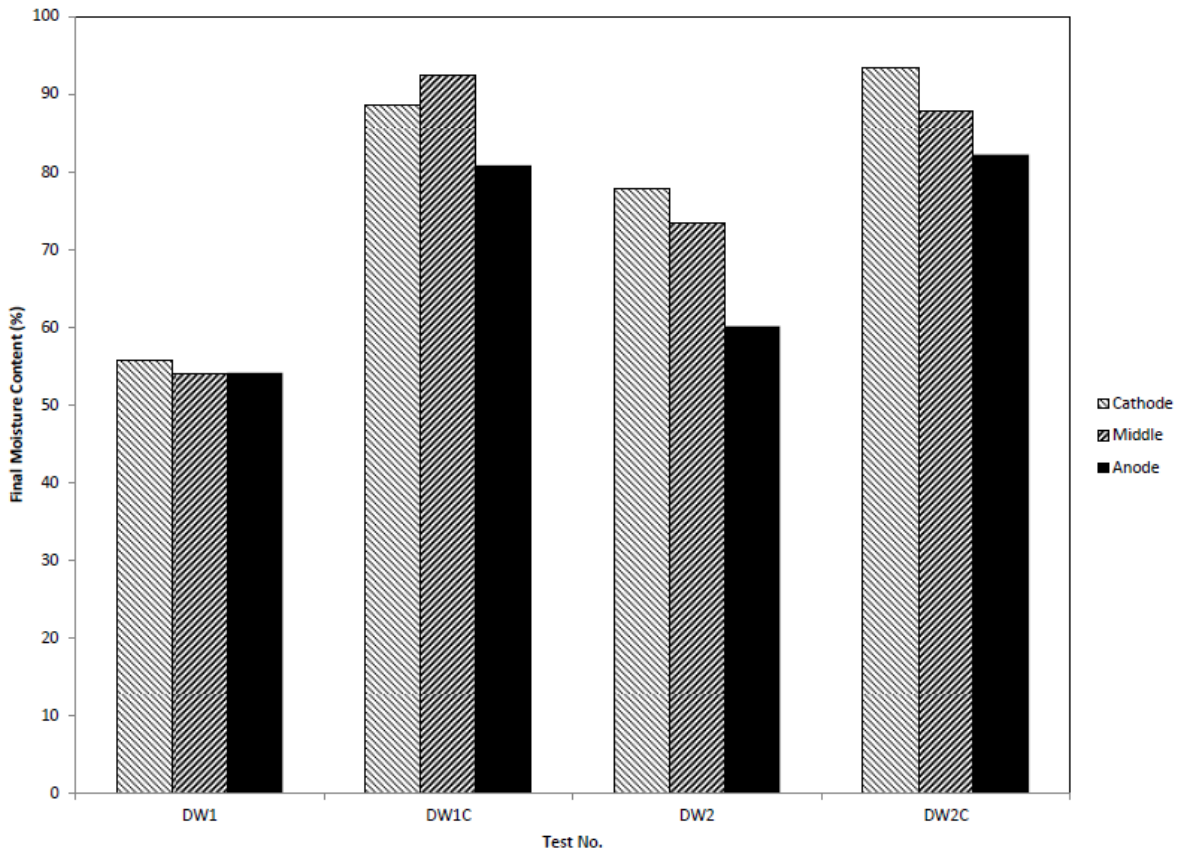**Fig. 9: Series DW - Electric Current vs. Time**

Fig. 10: Series DW – Final Moisture Content

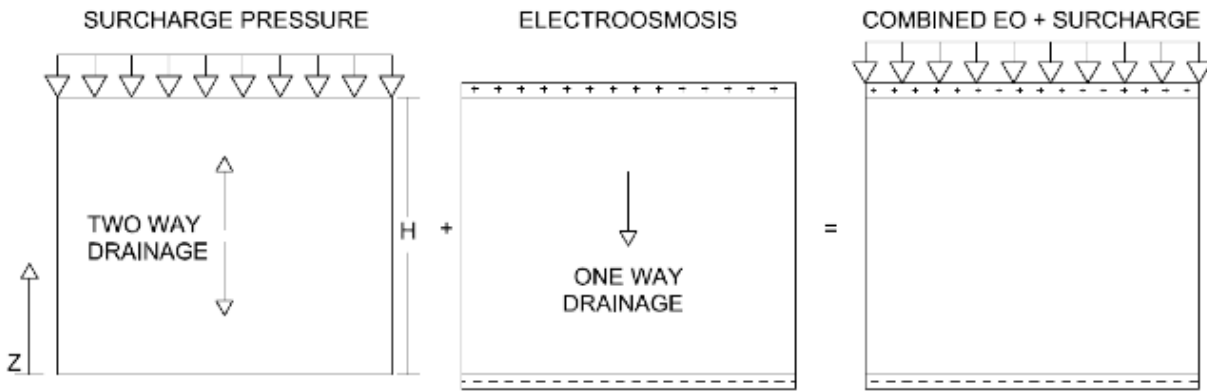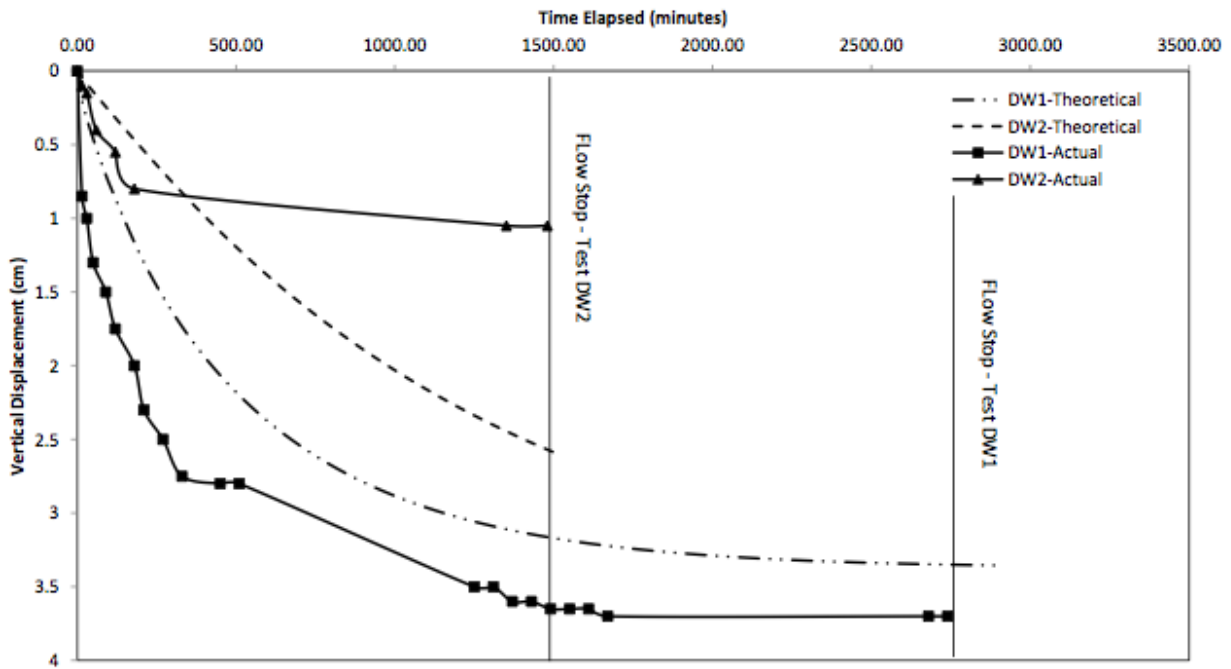**Fig. 11: Series DW - 1D EO + Surcharge Consolidation Model Schematic**

Fig. 12: Series DW - Actual vs. Theoretical Settlement