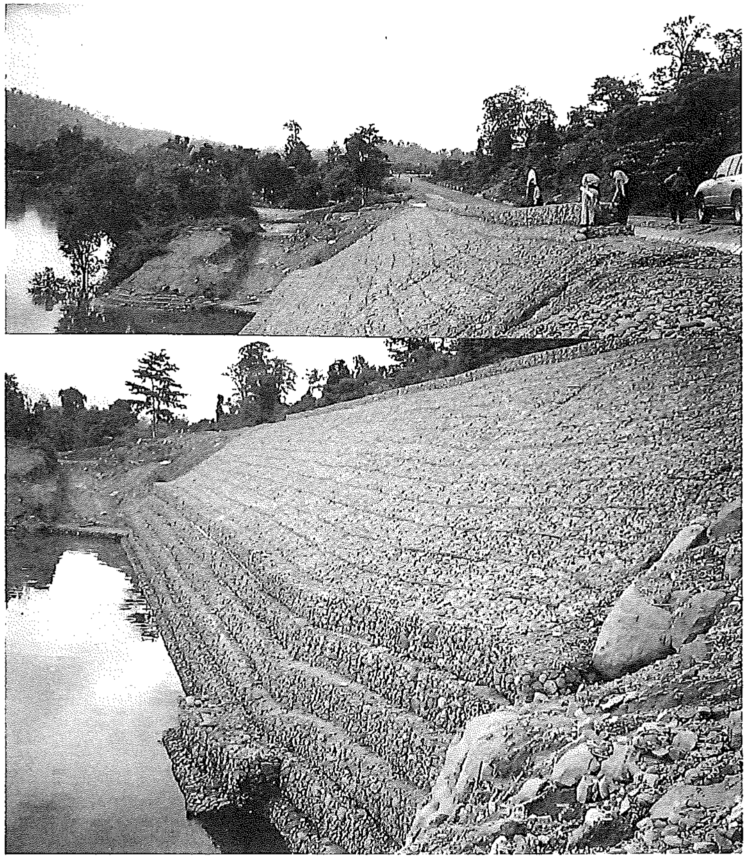
PHOTOGRAPHIC FEATURE

Erosion Control and Preservation of Environment
by D.T. Bergado[1], S. Pholsena[2], S. Kattignasak[3], and J. Kosonen[4]

Severe slope failure and soil erosion occurred adjacent to the banks of Namkading River in the vicinity of km 190+215 in Namkading to Savannakhet Road which is part of Route 13, the main north-south road artery of Laos. The site is located near the junction of Namkading River and the Mekong River. The remedial measure includes a combination of gabions, mattresses and geotextiles. The nonwoven and needle-punched geotextiles served as filter, drainage, separation, and reinforcement. The results of slope stability analyses indicated quite stable slope even during the critical condition of sudden drawdown. At present, the erosion control remedial scheme is functioning very well.



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EFFECTS OF USING ELECTRO-CONDUCTIVE PVD IN THE CONSOLIDATION OF RECONSTITUTED ARIAKE CLAY

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ABSTRACT

Induced consolidation of reconstituted Ariake clay using electro-conductive PVD as electrodes was studied. Rate of settlement using electro-conductive drain was compared with an ordinary PVD. Test results indicated that the time to achieve 90% degree of consolidation induced by electro-osmosis ranges from 5 to 10 times the normal consolidation through applied surcharge and 2 to 3 times faster than that when using non-electro-conductive drains. Electro-osmotic permeability was 200 to 1000 times greater than the hydraulic permeability. Thus, less time was required to achieve the same settlement when compared with conventional surcharge only. Settlement generated using electro-conductive drains was in the order of 1.4 to 2 times higher (40% to 100% increase) than that of non-electro-conductive drains. The result of induced consolidation using electro-conductive drain was dependent on several factors such as electric potential, electrode configuration and soil-water chemistry. The whole drain width should be electro-conductive to maximize the size of the electrical resistive block. Carbon electrodes achieved faster rate of consolidation than copper. Polarity reversal generated symmetrical strength distribution between electrodes which resolved problems associated with differential settlement.

INTRODUCTION

Thick deposits of clay will consolidate and generate significant settlement when loaded. This consolidation settlement of soft clay subsoil poses several problems in foundation engineering. Owing to the low permeability of clay, the consolidation takes longer duration to achieve primary consolidation. To shorten the consolidation time, vertical drains are installed together with preloading or vacuum pressure to shorten the drainage path. Consequently, consolidation time is reduced. With the drain installed, pore water is pushed out during consolidation of the clay due to gradients created by preloading or vacuum. Water can be discharged a lot faster through the drain towards the drainage layers. The vital purpose of vertical drain is to provide a quick drainage path for the pore water to be discharged. Consequently, consolidation process is accelerated thereby achieving rapid strength increase and improving the stability of embankments.

Recently, geosynthetic drains have gained most of the market because they are cheaper and faster to install. In order to expand the horizon of prefabricated drain application, a new generation of geosynthetic drain can be produced by making it an electro-conductive drain. Consolidation can further be induced through the application of electric current using electro-conductive drains as electrodes.

The purpose of this paper is to investigate the electro-osmotic dewatering effect of electro-conductive drain in the induced consolidation of Ariake clay and to compare the rate of consolidation using electro-conductive PVD with a non-electro-conductive one.

FLOW OF WATER BY ELECTRO-OSMOSIS

It is inherent that fine-grained clay particles with large interfacial surface area (5 m^2/g to 800 m^2/g) cause surface forces to dominate their behavior. The clay particles have a negative surface charge resulting from exposed hydroxyl groups and/or amorphous substitution where metal ions of aluminum, iron, or magnesium are substituted for

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silicon or aluminum within the sheets of silica tetrahedron that form the building block of clay particles (Lambe and Whitman, 1969). These negative surface charges on clay particles produce an electrostatic surface property known as the double layer. Cations from the electrolyte contained in the pore space orient themselves next to particle surface to balance the negative surface charge. Likewise, anions are repelled from the near surface. The resulting concentration gradient of ions next to the surface is known as the double layer. In a clay mass, the diffused double layers create a net abundance of cations in the pore space. When electrodes are placed across a clay mass and a direct current is applied, water in the clay pore space is transported to the cathodically charged electrode by electro-osmosis (Fig. 1). An applied electric field causes a change in the electric equilibrium within the clay double layer, displacing cations towards a more negative potential. Electro-osmotic transport of water through a clay is a result of diffuse double layer cations in the clay pores being attracted to a negatively charged electrode or cathode. Water molecules orient themselves around ions in the pore space as water of hydration. As these cations move through the pore space towards a negative potential (cathode), they bring with them associated hydration water or water molecules that clump around the cations as a consequence of their dipolar nature. In addition, frictional drag is created by the motion of the ions, as they move through the clay pores helping to transport additional water towards the negatively charged electrode. The water transport by this frictional drag is important as the total observed water transport is significantly greater than can be explained by hydration water alone. The macroscopic effects are seen as a flux of water toward the negative electrode. A net flow in one direction occurs when momentum transfer or frictional drag between migrating ions of one sign and the surrounding water molecules exceeds that of the ions of the opposite sign. Therefore, cation-anion distribution and water-ion distribution in the soil are of fundamental in the electro-osmotic phenomena (Gray and Mitchell, 1967).

Several cases had been reported using electro-osmosis as a technique for dewatering and stabilizing soft soil. Generally, results using this method ranged from poor to excellent. Direct current has been applied to soils to improve the stability of excavations, slopes, and embankments (Chappel and Burton, 1975; and Fetzer, 1967), to increase the capacity of piles (Soderman and Milligan, 1961), and to increase the strength of clays (Bjerrum, et al., 1967; Lo, et. al., 1991, 1992; and Shang and Dunlap, 1996). The same technique has also been used to remove/separate contaminants in the soil for remediation (Acar and Alshawabkeh, 1993, 1996; Acar, et al., 1994; Shapiro and Probstein, 1993; Fleureau and Saoud, 1996; and Mizoguchi and Matsukawa, 1996). Other applications are outlined in the work of Mitchell (1991). Esrig (1968) formulated the governing differential equation of electro-osmotic flow due to the application of direct current in both compressible and incompressible soils. He showed that pore pressures exhibited linear variations between a sealed (no drainage) and an open (free draining) electrode for an incompressible soil. He demonstrated that transient solution for a compressible soil under the same boundary conditions was analogous to usual expression for excess pore pressure found in a singly-drained consolidation test. Esrig (1968) also presented numerical solutions for cylindrical flow where water flowed radially towards a drainage well. Wan and Mitchell (1975, 1976) extended the theory to include combined effects of electro-osmotic treatment and direct load consolidation.

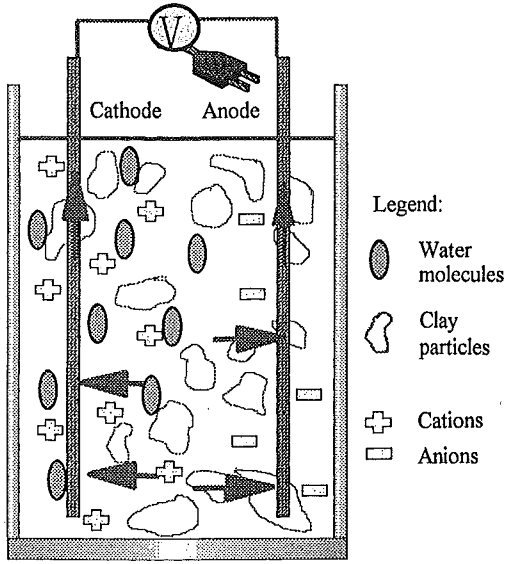

Fig. 1 Flow of Water by Electro-osmosis

Several theories have been proposed to explain electro-osmosis and to provide a basis for quantitative prediction of flow rates. According to Casagrande (1983), no one particular theory has been proven to be more accurate over the other. However, the most widely used one is Helmholtz-Smoluchowski Theory (Fig. 2). A liquid-filled capillary is treated as an electrical condenser with charges of one sign on or near the surface of the wall and counter charges concentrated in a layer in the liquid a small distance from the wall. The mobile shell of counter-ions is assumed to drag water through the capillary to plug flow. There is a high-velocity gradient between the two plates of the condenser.

According to the model, the electro-osmotic flow produced by an applied electric field is given by the expression:

$$v_e = \frac{D\varsigma\Delta E}{4\pi\eta\Delta L} \tag{1}$$

$$\varsigma = \frac{\sigma\delta}{D} \tag{2}$$

where, v_e = electro-osmotic flow velocity (cm/sec)
ΔE = applied voltage (volts)
ΔL = electrode spacing (cm)
η = viscosity (centipose)
D = dielectric constant of the soil water
ς = zeta potential (volts)
σ = surface charge density
δ = distance between the wall and the center of the plane of the mobile charge

This theory is reasonably valid for soils with large pores saturated with fresh water or dilute electrolyte solutions, because it assumed that the pore radii are large in relation to the thickness of the diffuse double layer surrounding the clay particles.

Electrolysis reactions dominates the chemistry at the boundaries, thereby developing pH difference between electrodes due to electrolysis reactions when there is no polarity reversal.

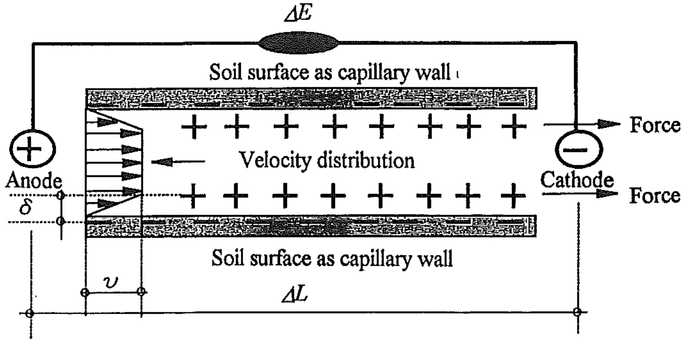

Fig. 2 Helmholtz-Smoluchowski Model for Electro-osmosis

Primary Reactions:

at the anode: $$2H_2O - 4e^- \rightarrow O_2\uparrow + 4H^+ \; (E_o = -1.229) \tag{3}$$

at the cathode: $$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^- \; (E_o = -0.828) \tag{4}$$

where E_o is the standard reduction electrochemical potential which is a measure of the tendency of the reactants in their standard states to proceed to products in their standard states.

Secondary Reactions: Depends upon the concentration of available species.

$$H^+ + e^- \rightarrow \frac{1}{2}H_2\uparrow \tag{5}$$

$$M_e^{n+} + ne^- \rightarrow M_e \; (M_e \text{ refers to metals}) \tag{6}$$

$$M_e(OH)(s) + ne^- \rightarrow M_e + nOH^- \tag{7}$$

EXPERIMENTAL INVESTIGATION

Soil Sample

The soil sample used in this experiment was leached marine Ariake clay collected at Saga plain in Saga, Japan. The sample excavated at about 2 m depth was generally a very soft gray silty clay (about 66% clay, 26% silt and 8% fine sand). The clay was highly plastic (CH) with natural water content of about 110% - 120%.

The clay sample was predominantly low-swelling smectite accompanied by illite, kaolinite and vermiculite and changed in their relative proportions with depth (Egashira and Ohtsubo, 1982). The low-swelling characteristics of this smectite were attributed to the considerable substitution of Fe^{+2} for Al^{+3} in the octahedral layer which depressed the dissociation of smectite unit layers (Egashira and Ohtsubo, 1983).

Electrode

Both electro-conductive and non electro-conductive drains were used as electrodes to compare the results. The size of the electrode was 30 mm wide and 300 mm long. Non-electro-conductive drain was one of the commercially available prefabricated vertical drains. It consisted of porous geotextile filter wrapped around a plastic drainage core. On the other hand, electro-conductive drain was made of common prefabricated geosynthetic drain with electro-conductive copper rods 2 mm in diameter inside the drain core. Some were wrapped with carbon fibers and others were coated with electro-conductive paste to make the common drains electro-conductive. Several types (Table 1) of electro-conductive drains were produced to study the effect of its electro-conductive material in accelerating the consolidation process.

Table 1 Summary of Electrode Types

Type	Description
1	12 copper rods have been inserted to the grooves, 6 on each sides
2	4 copper rods 2 on each sides
3	Coated with elector-conductive paste
4	Wrapped with carbon fibers

Apparatus Set-up

The test was conducted using an electro-osmotic cell (Fig. 3). The cell can accommodate a disturbed sample up to 300 mm in diameter and 300 mm in height. (Soil was mixed homogeneously using an electrically-operated mixer and then placed into the cell). The cell consisted of caps at both ends to contain the soil in place. Both caps have openings to accommodate the drain in place and to allow water to be discharged and collected. Both the upper and lower caps were connected by transparent 6-mm ∅ tubes, *"T"* and *"L"* connectors equipped with lock valves to fluid supply source (i.e., burettes to supply special solution for enhancement) and to sample collection, respectively. The upper cap openings were enclosed with transparent plastic box. This box allowed the upper cap to collect gas generated in both electrodes when gas volume measurement was required. It also permitted convenient supply of both electric power and enhancement solution to be supplied into the system through special connectors provided. On the other hand, the bottom cap has two discharge holes coincident with the drain locations. The volume of the discharged and collected water was measured accordingly during any desired time to determine the permeability of the soil. (Water discharged from both electrodes was collected separately). From the collected water discharge, chemical analysis was carried out to analyze the chemistry of the sample. The voltage gradient was supplied through direct current source at different levels. Constant voltage gradient across the soil sample was monitored through a voltmeter. Vertical load was applied on the steel plate of the top cap through the loading piston located on top of the frame. Load intensity requirement was adjusted properly through pressure meter system. Electrode polarity reversal was carried out manually at desired time duration using a manual switch.

Testing Program

To investigate the electro-osmotic dewatering effect through electro-conductive drains, several tests (Table 2 and Table 3) were carried out using three variable parameters namely voltage gradient, water content and vertical stress. Electrodes were spaced 200 mm apart. Polarity reversal was carried out once every 24 hours. All tests were stopped once the 90% degree of consolidation was achieved.

RESULTS

Electro-osmosis and Ariake clay

Ariake clay showed favorable response to electro-osmotic phenomenon having electro-conductive drains as electrodes. Soil properties measured before and after testing are summarized in Table 2. These properties are discussed in succeeding sections.

Electro-osmotic discharge of water and the consequent induced consolidation of clay depend on several factors namely: soil-water chemistry (i.e., cation-anion distribution and water-ion distribution), applied electrical gradient, electrode configuration and boundary conditions, frequency of polarity reversal, electro-osmotic permeability, (Shang, et al., 1996), the size and shape of pores and on the relationship between the intergranular stress and the pore water tension, and availability of free water at the anode (Casagrande, 1983), flow resistance of soil, and the frictional drag exerted by the migrating ions on the water molecules (Gray and Mitchell, 1967).

Time vs. Settlement Curves

Three different consolidation curves are shown in Fig. 4, namely: Group 1 - without drain, Group 2 - with non electro-conductive drain, and Group 3 - copper electro-conductive drain. Three distinct trends are manifested with the electro-conductive drain achieving the maximum rate of settlement and the no-drain curve yielding the least. Consequently, it took the longest time for no-drain curve to achieve the same settlement. This observation simply showed the remarkable effect of induced consolidation as a consequent of electro-osmotic phenomenon was evident which resulted from using electro-conductive drains. For the same initial conditions (i.e., overburden load, water content, void ratio, etc.) faster rate of settlement was achieved using electro-conductive drains than when using a non-electro-conductive drain with the same features. Consequently, it took shorter time for the former to achieve 90% degree of consolidation. It took 6.3 days and 7.0 days having 4kPa vertical stress and 120V/m and 60V/m electrical potential to reach 90% degree of consolidation, respectively (Table 3).

On the other hand, it took 12 days for the sample with non-electro-conducive drain to reach 90% degree of consolidation. The time to achieve 90% degree of consolidation induced by electro-osmosis ranges from 5 to 10 times

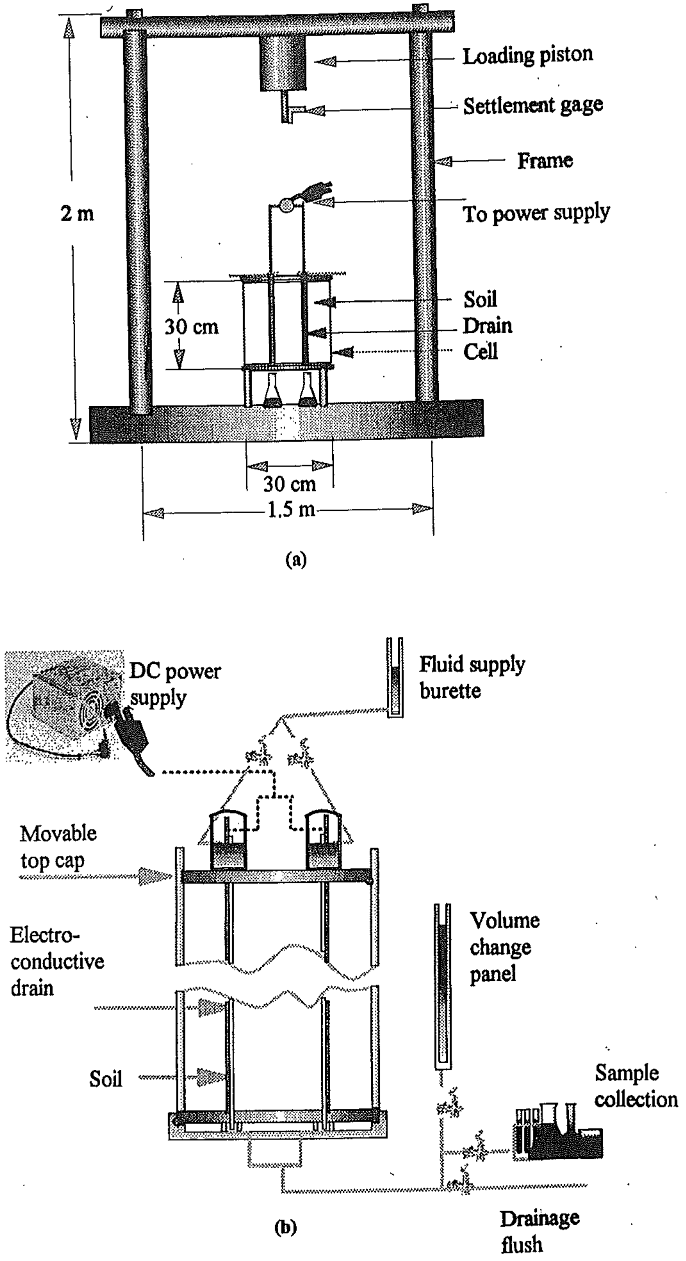

Fig. 3 (a) Experimental Set-up, (b) Electro-osmotic Cell Diagram

Table 2 Summary of Ariake Clay Properties Before and After Testing

Parameter	Before testing	After testing
Water content (%)	125 – 127	depends on location (Fig.8)
Liquid limit (%)	65 – 75	94 – 98 (Fig. 9)
Plastic limit (%)	33 – 40	39 – 43 (Fig. 9)
Shear strength (kPa)	2.8 – 3.5	depends on location (Fig. 13)
Pore water pH	6.8 – 7.4	11 – 12
Salinity (g/L)	1.5 – 2.1	2.4 – 4.9
Electro-conductivity (mS/cm)	100 – 150	250 – 300

Table 3 Summary of Consolidation Test Results

Test	Vertical load (kPa)	Initial water content (%)	Electric gradient (V/m)	Time at 90% U, (t_{90}) (days)	C_v (cm^2/hr)
A	4	90	None	60.0	11.08
B	2	128	None	18.4	36.17
C	2	128	60 (WPR)	9.4	70.73
E	2	128	120 (WPR)	6.5	102.28
G	4	90	None	12.0	55.22
H	4	90	60 (WPR)	7.0	94.44
I	4	90	60 (NPR)	7.0	94.44
J	4	90	120 (WPR)	6.3	105.53
K	4	90	120 (NPR)	5.8	116.60

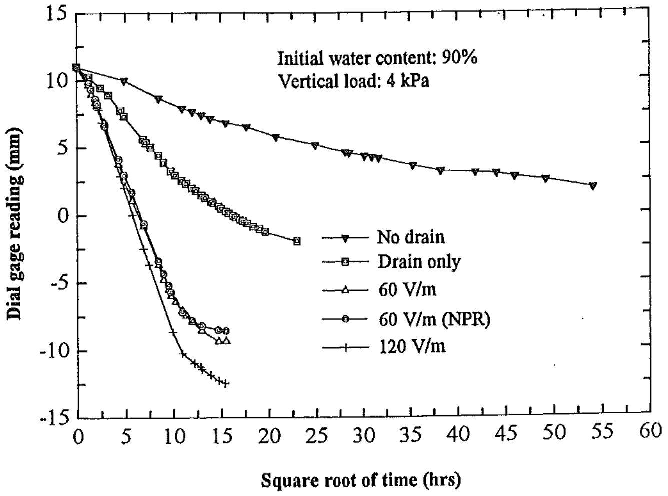

Fig. 4 Settlement versus Time Graph with 4 kPa of Vertical Load

the normal consolidation through applied surcharge and 2 to 3 times faster than when using non-electro-conductive drains. More settlement and shorter time were achieved as the electric potential increased due to a greater force generated to induce consolidation. The computed coefficient of consolidation, C_v, using electro-conductive drains was twice to three times (100% to 200% increase) that when using non electro-conductive drains, with higher increase corresponding to higher electrical potential. Likewise, a decrease in void ratio ranging from 3% to 5% was achieved (Fig. 5). Consequently, a corresponding increase in compressibility index was observed.

The induced consolidation effect of electro-osmotic phenomenon to accelerate settlement with ensured slope stability and greater gain in strength of clay by using electro-conductive drain is an outstanding manifestation of the fact that less surcharge could be used thereby reducing material cost in achieving such effects. Even with more surcharge, the magnitude of achieved settlement can be duplicated by the application of greater load but due to very low hydraulic permeability of clay, the rate of settlement with time could be an important factor that should be considered in increasing the surcharge load in order to accelerate consolidation rate especially when slope stability is concerned.

The range of settlement rate and magnitude of consolidation when using electro-conductive drains (i.e., Group 3 curves) were in close proximity with each other (Fig. 4) regardless of the difference in vertical load, and electrical gradient. A very light overburden load was applied in order to observe the effect of induced dewatering by electro-osmosis. At the end of the test, settlement generated using electro-conductive drains was in the order of 1.4 to 2 times higher (40% to 100% increase) than that of non-electro-conductive drains. This tremendous difference in achieved settlement was due to the fact that hydraulic and electro-osmotic consolidations are the results of different forces and mechanisms. Ordinary consolidation is caused by a vertical pressure gradient such as surcharge load in unconsolidated soils. However, consolidation under the influence of an electric potential is a result of pore water being "pulled" along by the movement of ions toward one of the electrodes (usually but not always toward the cathode). The dewatering process leads to consolidation and consequent strength increase. During normal consolidation, water is squeezed out of the voids in the soil. On the other hand, electro-osmotic consolidation is the result of water being removed/pulled from the soil. The cause and effect of the process is the reverse of the normal consolidation process (Casagrande, 1983). In this case, greater surcharge load should have been required using non electro-conductive drain to achieve the same settlement to duplicate that which can be achieved by electro-osmotic consolidation. Significant increase in strength more than what was expected just from dewatering has also been observed. Details are discussed in succeeding sections.

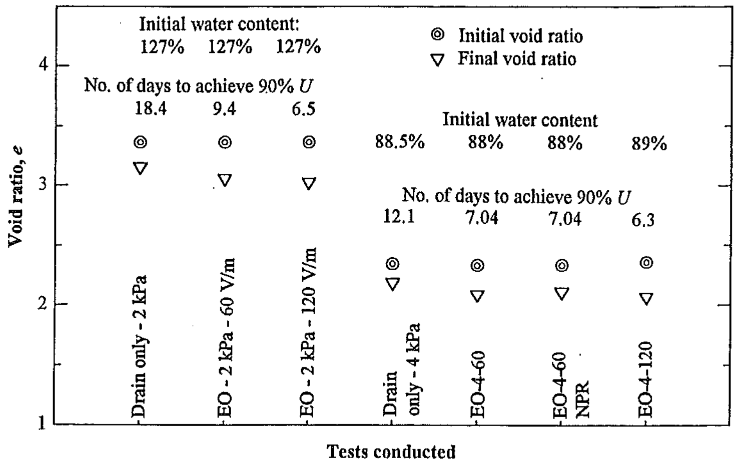

Fig. 5 Void Ratio Before and After Testing

Electrode Type

Similar tests were conducted using several types of electro-conductive drains to study its effects in accelerating the consolidation process. Three distinct set of curves, Group 1 to Group 3 are shown in Fig. 6. These curves are plotted together with the original set of curves shown in Fig. 4. The details of electrode type and test parameters were given in Table 1, Table 3 and Table 4.

Among the Group 2 curves were the plot of tests *B*, *G*, *L*, *M* and *N* (Table 3 and Table 4). Tests *B* and *G* were the consolidation tests using non-electro-conductive drains. Type 3 electrode (Table 1) used in test *L*, although coated with electro-conductive material, did not produce an electro-conductive drain because the coating material did not produce a compatible electro-conductive material. Thus, its curve was similar to that of the common drain. Likewise, Type 2 electrode used in tests *M* and *N* produced a plot similar to that of tests *B* and *G*. Type 2 electrode , although having copper as the electrode, have a limited resistive area block to be able to produce a strong electro-osmotic flow of water. Therefore, the settlement versus time plot of these drains plotted similar trend to those non-electro-conductive drains. The main reasons why the drains whose settlement versus time curve were plotted similar to the non-electro-conductive drains are a).the area of the resistive electrical block was limited; b). the resistance of the coating material to conduct electricity was ineffective (i.e., Ohms law).

Considering the electrode configuration, the area of the electrical resistive block and electrode resistance are very important. The area, *A* of the resistive block is illustrated in Fig. 7. It is the product of the length of the electrode, *L*, and the electrode width, *W*. The resistive block is the product of the area, *A* and the distance between electrodes, *D*. Therefore, in order that the drain would effectively serve its purpose of being electro-conductive and to optimize the drain width, the area at which the electrical gradient be supplied through should be equal to the area of the resistive block, *A*.

Carbon electrode achieved more settlement and faster rate of consolidation (Tests *P* and *Q* in Fig. 6). Since carbon was an inert material to electrolysis reactions, it prevented introduction of additional chemical species that would have complicated the electro-chemistry of the process. On the other hand, copper was oxidized which caused corrosion of the electrode especially at the anode. Corrosion highly affected the performance of copper electrodes. The only deficiency of the carbon fiber electrodes is that it would decompose with time. The time-dependent disintegration of the material used depended on several factors such as combined effect of electrical and pH gradients.

Table 4 Additional Tests Conducted with Other Types of Electrodes

Test	Elect. Gradient V/m	Stress kPa	Water content (%)	Polarity status	Electrode type
L	120	4	90	WPR	3
M	120	4	90	NPR	2
N	120	4	90	WPR	2
O	120	2	126	NPR	1
P	120	2	126	NPR	4
Q	60	4	90	NPR	4

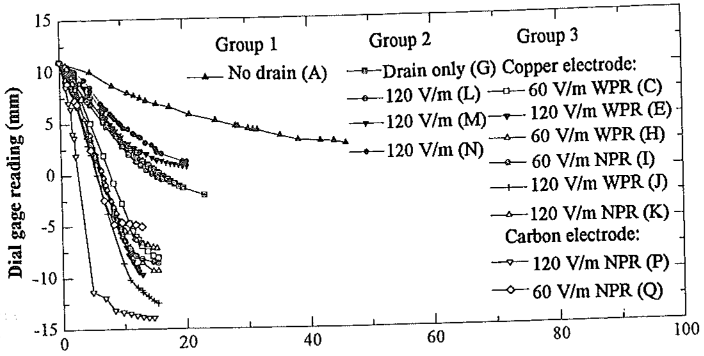

Fig. 6 Settlement versus Time Graphs from Different Tests

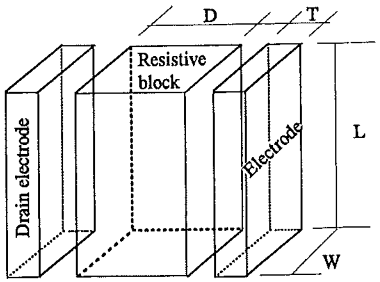

Fig. 7 Electrical Resistive Block

Polarity Reversal

Electro-osmotic testing with both normal polarity only and with polarity reversal were conducted. In the case of no polarity reversal tests, since water was not replenished, as the water was discharged towards the cathode, excessive desiccation was evident at the vicinity of the anode fissures up to about 2 mm in opening originating from the anode running on both sides along the perimeter almost halfway between electrodes were observed. These cracks hindered the continuity of electrical flow thereby affecting the full development of increase in strength since water was not discharged properly. Other effects like soil hardening and other electro-chemical effects which could have been achieved had there been no discontinuities of current flow had been minimized. Furthermore, water content at the cathode was 10% higher than that at the anode. Consequently, higher strength was measured around the vicinity of the latter. Due to extreme pH gradients generated even after an hour of testing, the oxidation of copper electrode especially at the anode further enhanced soil strength improvement at the anode. But due to corrosion with time, copper electrode became inefficient in conducting electric current. Another set of experiment employing polarity reversal was conducted. Employing polarity reversal prevented excessive desiccation at the anode, thereby limiting thermal energy loses cause by resistive heating. It also enhanced more symmetrical increase in effective stresses. Consequently, more symmetrical water content and strength increase were developed. Likewise, differential settlement was further avoided. Polarity reversal prevented development of pH gradients and non-uniform electro-chemical changes at both electrodes (Shang, et al., 1996). When polarity was reversed regularly, pH at both electrodes were almost identical. Had polarity reversal not been employed, physical and electro-chemical changes should have been predominant especially when the voltage gradient was increased indiscriminately which would hinder generation of electro-osmotic pore pressure, reduce electro-osmotic permeability of the soil, and increase power consumption. With polarity reversal, electrode corrosion can also be reduced.

Water Content

Having an open boundary conditions at both electrodes, under normal circumstances, water was not available at the anode to replenish the pore water. Thus, as the water flowed towards the cathode, the water content near the anode gradually decreased increasing towards the cathode. With non-electro-conductive drain, water content was reduced by 10% at the time when 90% degree of consolidation was achieved. The same order of magnitude was observed in the case of electro-osmotically treated samples though equilibrium (i.e., 90% degree of consolidation) was achieved in shorter time. Thus, dewatering at the anode can be achieved quickly and effectively using electro-conductive drains.

Figure 8 shows the variation of water content after testing across the two drains. A more uniform reduction was observed across the non electro-conductive drains. This was achieved because it took longer time for pore water to dissipate and no changes in clay properties were generated. Greater reduction of water content around the vicinity

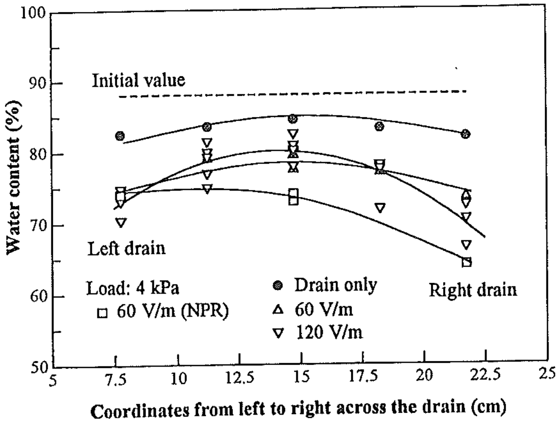

Fig. 8 Variation of Water Content Across the Electrode

of the electro-conductive drain was observed. This was the effect of complex electro-chemical changes which have been generated due to the application of electric current in addition to soil desiccation. These changes will be discussed in succeeding sections. A larger water content difference across the drains became more predominant as the electrical potential was increased. Generally, water content of treated soil was lower compared to the untreated one.

Atterberg Limits

The use of electro-conductive drain did not only reduce the water content more than what can be achieved by using the normal drain but also increased the liquid limit as well as the plastic limit. This increase in Atterberg limits was more pronounced in the vicinity of the anode and decreased at the vicinity of the cathode. The increase in magnitude of Atterberg limits depends on the length of treatment (Casagrande, 1983). The increase in Atterberg limits was due to increased salt concentration of the soil after treatment as shown in Fig. 9 (Lo, Ho and Inculet, 1991; and Bjerrum, 1954). The increase in salt concentration consequently increased the water-holding capacity of clay thereby increasing its liquid limit. In contrast to most high-swelling smectites, liquid limit of Ariake clay which was predominantly low-swelling smectite, increased as the salinity increased or as the cation saturation changed from lower valence to higher valence cations. Liquid limit of high-swelling smectites will decrease for a corresponding increase in salt concentration (Torrance and Ohtsubo, 1995; and Ohtsubo, et al., 1998).

Permeability

The volume of water discharged at a certain time was measured in order to evaluate the electro-osmotic permeability of the sample. The coefficient of electro-osmotic permeability was computed as follows:

$$k_e = \frac{Q_e L}{A t_e E} \left(cm^2 / V - \mathrm{sec} \right) \qquad (8)$$

where: Q_e = water volume discharged in time, t_e (cm^3)
L = distance between electrodes, (cm)
A = cross-sectional area between electrodes, (cm^2)
t_e = elapsed time during which Q_e is measured (sec)
E = voltage between electrodes, (Volts)

The measured permeabilities of Ariake clay are shown in Fig. 10. As the void ratio decreased, permeability decreased. Hydraulic permeability of both remolded and undisturbed samples were plotted close to each other. These values were determined using the standard procedure in Japanese Geotechnical Standard Testing Methods. The plot of electro-osmotic permeability was much greater than the hydraulic permeability. This simply shows that electro-conductive drains were very useful in accelerating the water discharge from fine-grained soils. Consequently, consolidation time is reduced and gain in strength can be achieved in shorter time. Electro-osmotic permeability ranged from 10^{-4} to 10^{-6} cm/sec per volt/cm while the hydraulic permeability ranged from 10^{-7} to 10^{-8} cm/sec. This means that electro-osmotic permeability can be up 200 to 1000 times greater than the hydraulic permeability. With this values, it would take 200 to 1000 times as long for the vertical load to reduce the same amount of water as the electro-conductive drain would.

Measured electro-osmotic permeability was maximum during the first 24 hours for both copper and carbon electrodes. During the first hour, the electro-osmotic test with copper electrode had more water volume discharged than the one with carbon electrode since the electro-chemical changes were not predominant yet. Furthermore, since copper electrode has lower resistance than carbon electrode, with the same voltage gradient, greater current intensity flowed through the former than the latter. Consequently, stronger pulling force was available to induce water discharge. But an hour later after testing started, electro-chemical effects became predominant at the vicinity of the electrodes. This was substantiated by the sudden increase in pH of water being discharged increasing from pH 7 to pH 11. As electro-chemical changes dominated the vicinity of the electrodes, copper electrode being highly reactive was oxidized reacting with the adjacent soil producing chemical complexes which gradually hindered the water flow. Corrosion and the subsequent copper rod size reduction was another factor decreasing its efficiency. On the other hand, carbon electrode was a very chemically stable electrode. It did not produce similar reactions as the copper electrode had. Thus, its efficiency in inducing water discharge was almost consistent for 24 hours.

In the case of hydraulic permeability test, each point on the plot corresponds to a different vertical consolidation load. The plot shows that void ratio decreases linearly with hydraulic permeability. Whereas in the case of electro-osmotic permeability, all of the points plotted has uniform vertical load and electrical gradient. From Fig. 10, it can be observed that electro-osmotic permeability decreased with very negligible change in void ratio after 24 to 48 hours of electro-osmotic treatment since in addition to electro-chemical effects generated, there was no water being replenished at the electrodes. On the other hand, hydraulic permeability decreased with a corresponding decrease in void ratio. This simply proves that electro-osmotic permeability was not dependent on pore size and void ratio as the hydraulic permeability was.

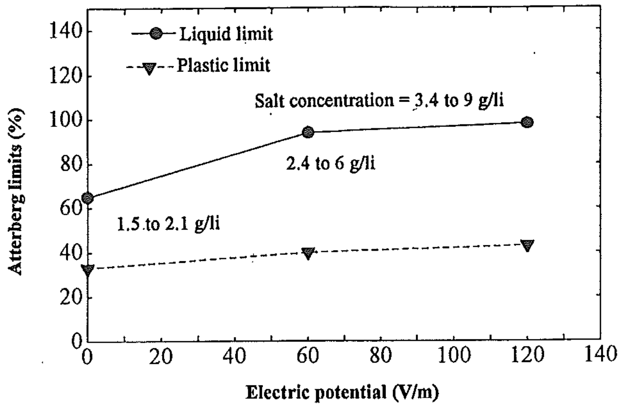

Fig. 9 Effect of Salt Concentration on Atterberg Limits

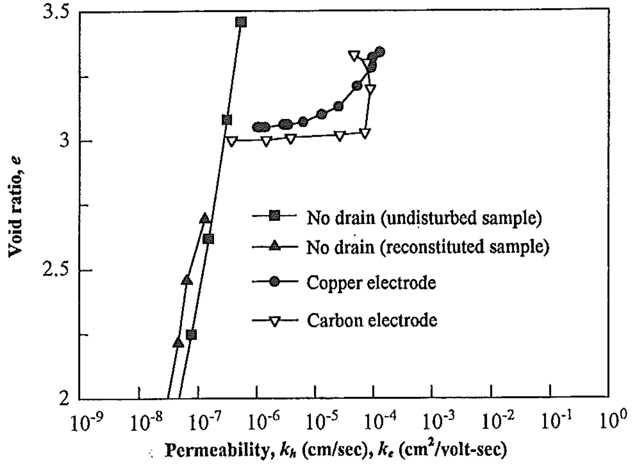

Fig. 10 Hydraulic (k_h) and Electro-osmotic (k_e) Permeabilities

Increase in Shear Strength

Prior to testing, vane shear strength of the sample was taken using the customized vane shear apparatus at predetermined points (Fig. 11). Another set of readings was taken after testing at the same points. The relation between water content and shear strength both before and after treatment is shown in Fig. 12.

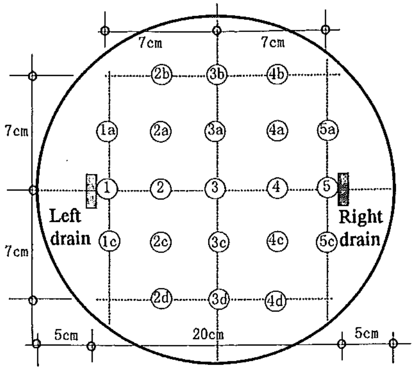

Fig. 11 Location of Sampling Points

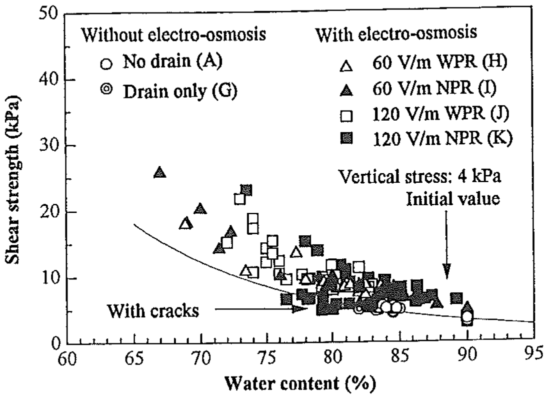

Fig. 12 Shear Strength versus Water Content

After electro-osmotic treatment, there was subsequent decrease in water content. Corresponding to a water content decrease, an increase in shear strength has been observed partly due to the tensile stresses developed in the pore water which consequently resulted in consolidation and strength increase. In the case of non-electro-conductive drain consolidation, the location of points on the shear strength-water content plot is close to each other. Although the location of some of these points was adjacent to the drain, the reduction in water content was not much different from those located at the center. Consequently, there was not much difference in the improved shear strength (i.e., 4.4 kPa to 5.6 kPa.). On the other hand, consolidation using electro-conductive drain yielded much lower water content and consequently higher shear strength especially near the electrode vicinity. Significant increase in strength was more than what was expected just from dewatering. Strength increase was evident between the electrodes even the sample had been treated only for a short period of time. In some instances, excessive drying and consequent excessive tensile stresses occurred in the vicinity of the anode. This produced 2 mm to 3 mm cracks at different fashions from the anode towards the cathode and around the anode extending from top of the sample down to the bottom if not to the middle portion. The cracks interrupted the continuity of electric current transfer thereby unyielding the necessary electro-osmotic effects in inducing water discharge. Consequently, there was no significant improvement in the shear strength of the soil.

Dramatic changes in the soil-water electro-chemistry caused by electrolysis reaction brought about complex chemical reactions which resulted in the formation of compounds which reacted with soil and subsequently increased strength which was more than what can be explained by water reduction. Significant rate of increase in strength of electro-osmotically-treated soils was achieved due to (a) rapid decrease in water content due to a different mechanism of electro-osmotic consolidation resulting to faster rate of settlement; (b) formation of menisci in the soil voids which yielded undefined structural change in clay due to stress adjustment; (c) bonding and/or cementation of soils particles by insoluble chemical precipitates as a result of the complex chemical reactions generated; (d) ion exchange which altered the plasticity of clay specimen. High negative pore pressure generated especially at the vicinity of the anode might have been responsible for the structural change. All these effects combined with the predominant electrolysis effects increased undrained shear strength of the soil at a particular water content and reduced compressibility.

The variation of shear strength across the electrodes are shown in Fig 13. Extremely high increase in strength was observed around the vicinity of the electrodes with decreasing intensity with distance from the anode. Without polarity reversal (indicated as NPR in Fig 13), there was uneven increase in strength. Higher increase was observed at the anode with decreasing intensity at the cathode. The increase at the cathode was due to the oxidation of the copper electrode and the pertinent electro-chemical effects such as ion exchange, desiccation from heat generated, mineral decomposition and precipitation of secondary minerals, fabric change and oxidation-reduction. With polarity reversal, a more symmetrical increase in strength was observed. At points closer to the electrodes, shear strength was higher as predicted by electro-osmotic theory. Thus, the efficiency of electro-osmotic dewatering effect diminishes with distance from the electrodes specifically from the anode.

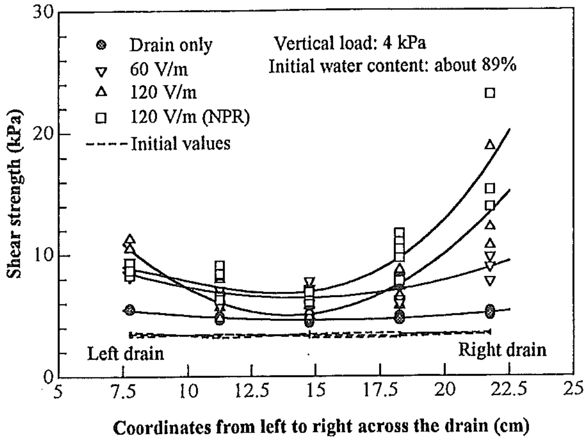

Fig. 13 Variation of Shear Strength Across the Electrodes

CONCLUSION

1. Incorporating electrokinetic item in the properties of PVD is very useful in dewatering highly compressible and low permeability clay since electro-osmotic permeability is 200 to 1000 times higher than hydraulic permeability.
2. Due to a different consolidation mechanism, faster rate of settlement was achieved using electro-conductive drains. The rate of induced consolidation through electro-conductive drains ranged from 2 to 3 times faster than that of the non-electro-conductive drains. The rate is dependent on several factors such as current density, electrode configuration in addition to water-soil chemistry.
3. Electrode type is a very important factor in achieving efficient dewatering of low permeability clays. Carbon electrode, being an inert material, achieved faster consolidation rate than copper electrodes.

4. Significant rate of increase in strength of EO-treated soils was achieved as a consequence of (a) rapid decrease in water content due to a different mechanism of EO consolidation resulting to faster rate of settlement; (b) formation of menisci in the soil voids; (c) bonding and/or cementation of soils particles by insoluble chemical precipitates as a result of the complex chemical reactions generated; (d) ion exchange which altered the plasticity of clay.
5. In geotechnical point of view, polarity reversal technique produced more favorable effects than those with employing normal polarity only. More symmetrical water content, shear strength increase and increase in effective stresses were developed due to similar changes generated at both electrodes. Consequently, it prevented excessive desiccation at the anode, thereby limiting thermal energy loses caused by resistive heating.
6. Carbon electrodes are more suitable material for electrodes than copper since it is an inert material.
7. The increase in liquid limit of predominantly low-swelling smectite Ariake clay was due to the increase in salt concentration after treatment.

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