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Electrokinetic Strengthening of Marine Clay Adjacent to Offshore Foundations

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ABSTRACT

Skirted foundations have been used increasingly to provide uplift resistance and to carry structural loads in offshore structures. When soft clay soils are encountered in a site, the soil shear strength is one of the major concerns in the design of skirted foundations with respect to the bearing capacity. Originated from the problem facing offshore engineering practice, this study is focused on electrokinetic strengthening of soft marine clays adjacent to skirted foundations. A series of laboratory electrokinetic experiments was conducted in a natural marine clay. A steel plate was embedded in the soil during the electrokinetic treatment to simulate part of a skirted foundation. The design, execution and results of the electrokinetic tests are reported. The results show that the undrained shear strength of the soil around the embedded steel plate was increased considerably after the electrokinetic treatment. It is also evidenced that the soil shear strength was further increased with time after the electric field was withdrawn, attributable to electrokinetics induced soil particle cementation during post-treatment ionic diffusion. In order to obtain uniform strength increase between the electrodes, to reduce energy consumption and to prolong the service life of electrodes, the effects of polarity reversal and current intermittence under a constant applied voltage were also investigated.

KEY WORDS: electrokinetics, skirted foundations, soft marine clay, soil improvement, soil shear strength.

INTRODUCTION

Skirted foundations have now become competitive alternatives to other more traditional foundation solutions such as piles and drag anchors for many types of offshore structures. They have been used increasingly worldwide as an attractive and effective foundation solution in various types of soils, ranging from soft clays (Colliat et al., 1996) to dense sands (Tjelta, 1995). Skirted foundations have been used for floaters, tension leg platforms, gravity platform jackets, jack-up rings, subsea systems and other protection structures (Anderson and Jostad, 1999). Skirted structures also have the potential of being used for other purposes, such as pipeline pull-in anchors or stand-by moorings (Lacasse, 1999). Deep skirted foundations have actually been successfully used in water depths ranging from 70 m (e.g., two heavy jacket in the North Sea, Draupner E and Sleipner B) to about 1000 m (e.g., semi-submersible platform at Marlim field offshore Brazil). The primary advantages of skirted foundations compared to traditional piles and drag anchors are the relatively short on-site installation time required, high position accuracy and re-usability of the structures.

Skirted foundations are normally cylindrical units made by steel or concrete. The basic functions of the skirts are mainly to confine any soft surface layers and carry structural loads, to resist lateral loads effectively against sliding and to provide uplift resistance. The capacity to carry loads depends on factors such as depth of skirt penetration, cylinder diameter, soil strength and the combination of horizontal, vertical and moment loads. However, when soft soils are encountered in a site, the bearing capacity is governed by an undrained shear failure in the soil and, therefore, the soil undrained strength becomes one of the major concerns in the design of skirted foundations. Marine clay deposits in many offshore areas are often characterized by low shear strength and high compressibility. The poor engineering properties of these deposits pose foundation problems to offshore structures. There are two alternatives to overcome these problems, i.e., to increase the size of skirted foundations and to improve the soil. Electrokinetics may be used to strengthen the soil when the latter alternative is considered in the design and construction.

The application of direct or alternating electric fields in clayey soils generates electrokinetic processes including electroosmosis (transport of pore water toward the cathode), electrophoresis (transport of negatively charged particles toward the anode) and ionic migration (transport of ions toward electrodes). Upon application of an electric field to clays and silts, consolidation and strengthening occur if the method of application is properly designed and physical and chemical properties of the soil satisfy certain requirements. The earliest application of the electrokinetic method is electroosmosis used in silts and clays (Casagrande, 1949, 1983; Bjerrum et al., 1967; Lo et al., 1991a). Bjerrum et al. (1967) employed electroosmosis to stabilize an excavation in a very soft Norwegian quick clay near Oslo and they reported that the average undrained shear strength was increased by four times. More recently, Lo et al. (1991b) demonstrated in a field pilot test that by the appropriate design of electrodes and polarity reversal, pumping at the cathode was eliminated and that both the effective stress parameters and preconsolidation pressure increased (Lo and Ho, 1991). In the past, some investigators (Soderman and Milligan, 1961; Butterfield and Johnson, 1980) found that the shaft resistance of steel friction piles driven into a clay stratum could be increased significantly by the application of electrokinetics. Soderman and Milligan (1961) conducted a series of electroosmotic tests on 16.5-m long steel H-piles installed in a soft varved clay. It was reported that the shaft resistance increased from less than 300 kN to over 600 kN. Load tests were carried out again on the same piles 33 years after the electroosmotic treatment and the results demonstrated that the ultimate bearing capacity of the piles remains unchanged (Milligan, 1994). The results demonstrated convincingly that the increase in bearing capacity of steel piles by electrokinetic treatment is permanent.

All of the successful applications of electrokinetics reported in the literature involved soils of low salinity, i.e., the salt content in the pore water is less than 2 g NaCl/*l* or the equivalent. For clays of high salinity such as seabed sediments, no comprehensive and systematic study has been performed until recently. Following the work of using high voltage (20 to 30 kV) with insulated electrodes (Inculet and Lo, 1988; Lo et al., 1994), the effects of high voltage electrokinetic treatment on a marine sediment from the Texas Gulf Coast was studied by Shang and Dunlap (1996, 1998). Subsequently, El Naggar et al. (1997) showed that the bearing capacities of model steel piles under vertical, lateral and repeated loading were improved after high voltage electrokinetic treatment. Recently, extensive small-scale and large-scale laboratory tests were conducted on a marine clay recovered from Yulchon, South Korea, using low voltage (less than 100 V), non-insulated electrodes and intermittent current (Lo et al., 2000; Micic et al., 2001). The experiments were performed on soil specimens submerged in the seawater with the salinity approximately 30 g NaCl/*l*. The results have shown that the shear strength of the marine clay was increased considerably along with the increase of the preconsolidation pressure after electrokinetic treatment. The increases were more significant in the soil near both anodes and cathodes where the undrained shear strength was up to 3 times higher compared to untreated soil under identical consolidation pressure. Two major challenges of using electrokinetics for strengthening marine sediments are (i) high energy consumption due to the high electrical conductivity of marine sediments and (ii) rapid corrosion of metallic anodes. The authors have reported that the current intermittence has the advantage in reducing power consumption and prolonging the service life of electrodes (Lo et al., 2000, Micic et al., 2001). Furthermore, it was reported that the technique of electrode polarity reversal enables more uniform electrokinetic treatment (Gray and Somogyi, 1977; Lo et al., 1991a, 1991b).

Originated from the problem facing offshore engineering practice, the study is extended to the electrokinetic strengthening of a soft marine clay adjacent to offshore foundations. This paper reports the results of a series of electrokinetic tests conducted on a natural marine clay from Yulchon site in South Korea with a steel plate embedded in the soil to simulate a part of a skirted foundation. The objectives of this investigation are to examine the effects of (i) electrokinetics in the soil with the embedded steel plate, (ii) ionic diffusion after electrokinetic treatment and (iii) energy consumption and treatment efficiency as related to the intermittent current and polarity reversal on soil properties such as water content and undrained shear strength.

LABORATORY EXPERIMENTS

Design considerations

The followings were considered in laboratory experiment design:

- Submerged marine soil with an embedded steel plate is subjected to the pre-determined overburden pressure and, thus, consolidated to a specific void ratio.
- The previous research on electrokinetic strengthening of the marine sediment (Lo et al., 2000) showed that higher strengths were developed at vicinities of anodes and cathodes. Therefore, electrodes are vertically installed at vicinity of the steel plate. The steel plate is not served as either anode or cathode to avoid corrosion caused by electrochemical reactions and for safety consideration.
- Current intermittence and polarity reversal can be readily executed during a test. These procedures are intended to obtain uniform strength increase between electrodes, to reduce power consumption and to prolong the service life of electrodes.

Apparatus

The apparatus used for the electrokinetic tests with a skirted foundation model is shown in Figure 1. It consists of an electrokinetic cell (EK-cell), four electrodes poles connected to a direct current (DC) power supply, a steel plate to model a part of a skirted foundation, loading equipment and control/instrumentation devices. The apparatus was designed to investigate electrokinetic strengthening of clay soil submerged in water. The general design considerations were: (i) to apply a specific consolidation pressure and drainage condition; (ii) to enable easy replacement of corroded electrodes and (iii) to avoid short circuiting of the system.

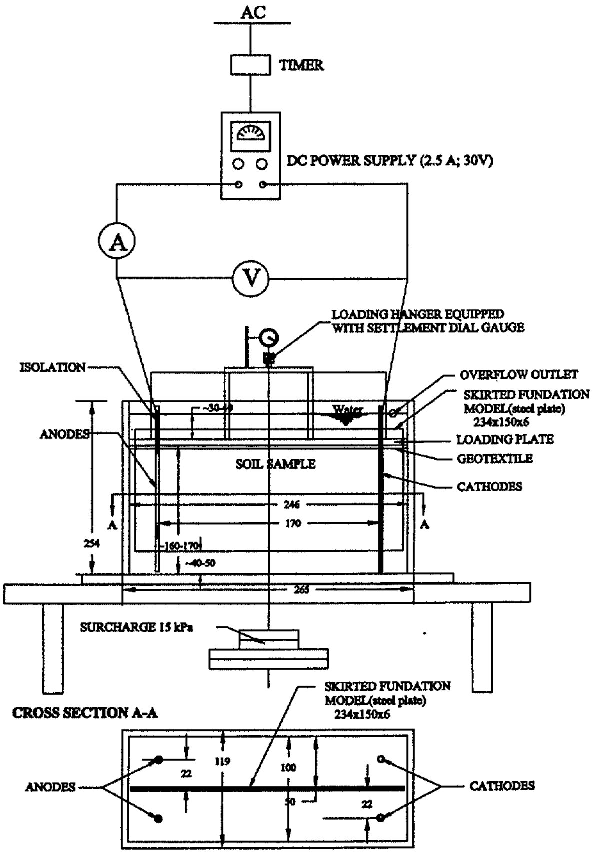


Figure 1. Experimental apparatus (all dimensions in mm)

The EK-cell is a rectangular tank 265 × 119 × 254 mm (L×W×D) made of 9.5 mm thick Plexiglass^{TM} plates. The cell can house a soil sample 246 mm long, 100 mm wide and up to 180 mm high. The drainage of the soil is through a geotextile placed on the top of the soil sample. On top of geotextile, a loading plate made of 10 mm thick Plexiglass^{TM} plate is placed to provide the vertical pressure through dead weights. A slot of 240 × 10 mm cut in the loading plate allows the vertical movement of the loading plate without pressing the steel plate when the soil settles.

A steel plate 234 mm long, 150 mm high and 6 mm thick is used to simulate a part of a cylindrical skirted foundation. In the test series, the

Table 1. Summary of test conditions

		Consolidation		**EK Treatment**								**Diffusion**
	Test #	Time (hrs)	Consolidation pressure p (kPa)	Total EK treatment time t_T (hrs)	Power-on time/Power-off time t_{on}/t_{off} (min/min)	Current intermittence ratio^a τ (min/min)	Number of polarity reversal N_R	Treatment time under one polarity t_R (hrs)	Area under current-time curve^b $\int I(t)dt$ (A·hrs)	Applied voltage V_o (V)	Energy consumption^c W (kWh/m^3)	Time t_{AT} (hrs)
a	b	c	d	e	f	g	h	i	j	k	l	m
Test series 1	**MO 1**	360	15	168	Constant	1	1	168	75.1	6.2	181.8	1080
	MO 2	360	15	168	4/2	0.67	1	168	110.6	6.2	178.6	1080
	MO 3	360	15	168	4/4	0.5	1	168	127.7	6.2	154.7	1080
	MO 4	360	15	168	4/8	0.33	1	168	170.9	6.2	138.0	1080
	MO 5	360	15	168	4/16	0.2	1	168	219.6	6.2	106.4	1080
Test series 2	**MO 6**	360	15	168	4/2	0.67	4	42	146.5	6.2	236.5	1080
	MO 7	360	15	168	4/2	0.67	6	28	167.4	6.2	270.3	1080
	MO 8	360	15	168	4/2	0.67	8	21	179.2	6.2	289.4	1080
Control	**C 1**	360	15	168^d	0	0	0	0	0	0	0	1080
	C 2	360	15	168^d	0	0	0	0	0	0	0	1080

a - From Eq. (2); *b* - Area under current-time curve (Figure 2) is $\sum_{i=1}^{N_R} \int_0^{t_R} I(t)\,dt$; *c* - From Eq. (3); *d* - Testing time , but no electric power.

plate was embedded approximately 120 mm into the soil and the space between the bottom of the cell and the tip of the plate was about 40 – 50 mm (see Figure 1).

Four electrodes, 240 mm in length, were used to generate an electric field in the soil sample at both side of the steel plate, as shown in Figure 1. The anode-cathode spacing is 170 mm, while the distance between the steel plate and electrodes was approximately 22 mm. The anode is made of a 5 mm diameter solid steel rod and the cathode is made of a 5 mm diameter steel pipe with wall thickness of 1 mm. Holes of 2 mm are drilled at 20 mm spacing along the pipe to allow the water driven to the cathode to discharge to the surface. To treat the soil around and bellow the steel plate, the embedded length of electrodes was approximately 170 mm, which was greater than the embedded depth of the steel plate. The top 50 mm of the electrodes was insulated by a shrinkable plastic tube. In this way, the electric current is flowing only through the soil to avoid short circuiting of the system due to the higher conductivity of seawater on the top of the soil.

The DC power supply (BK Precision, Model 1670) used in the test series has a maximum capacity of 2.5 A and 30 V. The voltage and current during a test are monitored through a voltmeter and an ammeter. The current intermittence intervals are set by a automatic switch timer, as shown in Figure 1.

Soil Properties

The soil used in this study is a remoulded marine clay dredged from the surface of the seabed at the Yulchon land reclamation site on the north-west coast of Korea. The soil is a dark grey silty clay with very low shear strength. The remoulded soil has the undrained shear strength of about 1 kPa, corresponding to the soil water content between 110 % and 120 %, well above the liquid limit of 66 %. The undrained shear strength of remoulded Yulchon soil is related to the water content by the exponential expression,

$$c_u = 551.22e^{-0.0521w} \tag{1}$$

where c_u is the undrained shear strength in kPa and w is the soil water content in percent (Micic et al., 2001). Results of isotropically-consolidated-undrained triaxial (CIU) tests conducted on the untreated soil showed that the ratio of the undrained shear strength over preconsolidation pressure, c_u/p_c', is 0.3 (Micic, 1998).

The pore water salinity is equivalent to 30 g NaCl/*l*, typical of seawater. The pH of pore water is 7.6. The X-ray diffraction analyses identified illite and kaolinite as the predominant clay minerals with some quartz and K-feldspar as the non-clay minerals. The carbonate content and organic mater content are 2.6% and 10.5%, respectively.

Testing Procedure

Two test series of eight electrokinetic tests in total were performed on the Yulchon clay with the embedded steel plate as the skirted foundation model. The tests were designed to investigate the effects of electrokinetics in the soil surrounding the embedded steel plate, as well as post-treatment changes of soil properties due to ionic diffusion. The variables in test series 1 and test series 2 were the current intermittence and electrode polarity, respectively. Two control tests with the same consolidation pressure, drainage condition and testing duration but without the application of the electric field were performed simultaneously for comparison. The test conditions for the tests are shown in Table 1.

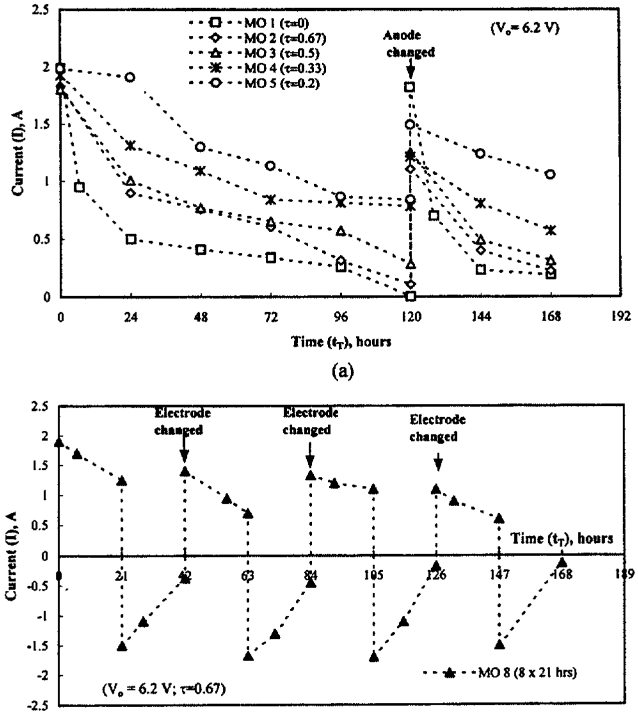
All tests were performed in three phases: consolidation, electrokinetic treatment and diffusion. The Yulchon clay was first deposited into the EK-cell and consolidated via the loading plate. Before the loading plate was placed the on the top of the soil sample, the steel plate was installed vertically in the soil sample through the cut on the geotextile. The position of the steel plate is shown in Figure 1. Then a consolidation pressure of 15 kPa was applied gradually within 2 hours. The consolidation phase lasted until the primary consolidation of the soil sample was virtually completed. After consolidation the soil void ratio and water content were approximately 2.8 and 97.8 %, respectively.

The second phase of the test, i.e., electrokinetic treatment, was started after 15 days of primary consolidation. First the electrodes were inserted into the consolidated soil and connected with the DC power supply. For all EK tests conducted, the applied voltage, V_o, was 6.2 V and remained constant throughout. During the EK treatment phase the current, I, was monitored with time. The electrokinetic treatment was terminated after 7 days.

Test series 1 was conducted to study the effects of current intermittence on the treatment efficiency. Five electrokinetic tests were performed with the different current intermittence ratios, τ, defined as

$$\tau = \frac{t_{on}}{t_{on} + t_{off}} \tag{2}$$

where t_{on} – power-on time (min); and
t_{off} – power-off time (min).



(a)

(b)

Figure 2. Current versus time: (a) test series 1: current intermittence tests and (b) test series 2: typical polarity reversal test

The current intermittence was exercised in four tests, i.e., MO 2 - MO 5 (τ=0.67 to 0.2, see Table 1), while a constant DC current (τ=1) was used in Test MO 1. The electric current versus time during the five tests is presented on Figure 2 (a). The figure clearly shows that the current, with the initial value of approximately 1.8 A, decreased with time. The decrease of the current with time under a constant applied voltage is well known in aqueous electrolyte systems (Oldham and Myland, 1994). The current drop was most drastic in the test with constant current (Test MO 1, τ=1) and the decrease in current became less with the decrease in current intermittence ratio, as shown on Figure 2 (a). All the tests in test series 1 were carried out with the anode closed (solid steel rod) and the cathode opened to the drainage (perforated pipe). The anodes were replaced after 120 hours in all tests, as shown in Figure 2 (a). At the time of replacement, the anodes used in Test MO 1 were completely corroded and the current dropped to zero. The anodes used in other tests were significantly less corroded which was reflected through the higher electric current at the time of the anode replacement. As evidenced, the application of the intermittent current significantly extended the service life of the anode.

The effect of polarity reversal was studied in test series 2 under the test conditions as shown in Table 1. Typical current versus time data for one polarity reversal test (Test MO 8) is presented in Figure 2 (b). Again, it can be seen that the current decreased with time. However, by increasing the frequency of polarity reversal the decrease of current with time became less, as represented by Column j in Table 1. The polarity reversal tests were carried out using perforated pipes as the anode and cathode, hence, the drainage was available at both electrodes. The perforated pipes corroded rapidly in all tests and it was replaced after maximum 42 hours of treatment.

After electrokinetic treatment, the loading plate was removed and the undrained shear strength and water content of the soil were measured at one side of the steel plate, while the other side was reserved for the study of ionic diffusion after EK treatment. Due to the limited sample size, a laboratory vane (PILCON Hand Vane Tester, English Drilling Equipment Co. Ltd) was used to measure the undrained shear strength.

The third phase of a test, i.e., diffusion, lasted 45 days. After electrokinetic treatment, the soil samples were set aside and sealed to further study the post-treatment effects due to the ionic diffusion and other electrochemical reactions.

Energy Consumption

For the application of constant applied voltage the energy consumption per unit volume of treated soil during a test, W (Wh/m^3), can be evaluated based on the following relationship:

$$W = \frac{\tau V_o}{v} \sum_{i=1}^{N_R} \int_0^{t_{Ri}} |I(t)| dt \qquad (3)$$

where V_o – applied voltage (V);
τ - current intermittence ratio;
t_{Ri} – treatment time under one polarity (hours) (i=1, 2, ….,N_R);
N_R – number of polarity reversal (N_R=1 for no reversal);
I (t) – electric current as a function of time t (A);
v - volume of treated soil $v = A \times H$ (m^3);
A - treatment area (m^2); and
H - electrode insertion depth (m).

Figure 3 shows a schematic of an electrokinetic test with current intermittence and polarity reversal. Since the laboratory tests were designed to have fixed configuration of electric field, electrode layout, applied voltage, consolidation pressure (soil void ratio) and total EK testing time including electrokinetic treatment (t_T=t_R x N_R) and ionic diffusion after EK treatment (t_{AT}) (Figure 3), the effectiveness and efficiency of electrokinetics can be evaluated based on relationship between energy consumption per unit volume of soil and improvement of soil properties such as the increase in the undrained shear strength and decrease in the soil water content. The variables in the test series are current intermittence ratio (τ) and polarity reversal intervals (N_R and t_{Ri}), which will be discussed in the next section.

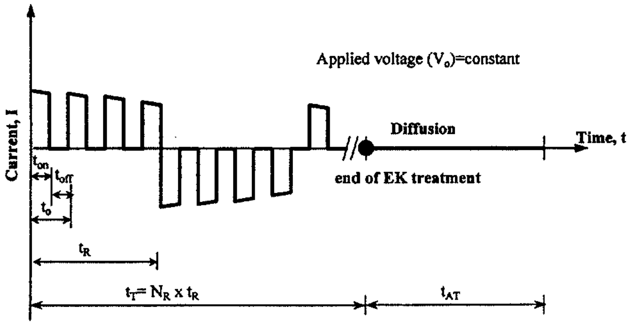


Figure 3. A schematic of electric current during treatment time

RESULTS OF TESTS

After the first two phases of a test, i.e., consolidation and EK treatment, the soil vane shear strength and water content were tested near the anode, cathode and at the centre of the sample at two depths: 60 mm (in the middle of the steel plate) and 130 mm (beneath the steel plate tip) in one side of the steel plate. The tests were repeated on the other side of the steel plate 45 days later after the third, diffusion phase. The test results were compared and discussed with results of the control tests.

Test Series 1: Effects of Current Intermittence

Figure 4 shows the distribution of the soil shear strength along the soil sample after electrokinetic treatment in test series 1. Figures 4 (a)

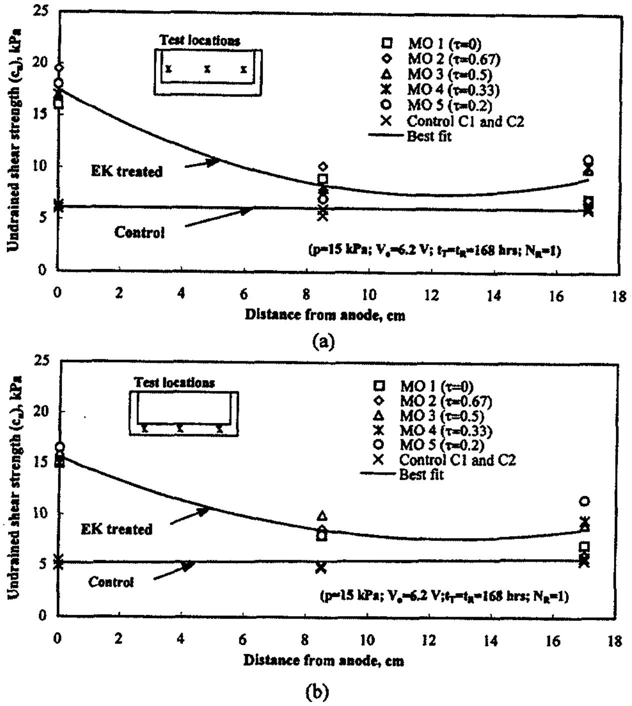


Figure 4. Distribution of undrained shear strength across the soil sample after EK treatment in test series 1: (a) adjacent to the steel plate and (b) beneath the steel plate

and (b) show the results of vane tests performed at depths 60 mm and 130 mm, respectively. From the figures it is evident that the undrained shear strengths of the soil adjacent to the embedded steel plate at both depths increased considerably after the electrokinetic treatment. The highest increase of the undrained shear strength was observed at the anode, which was approximately 185%, while the increases of the soil shear strength at the cathode were between 5% (Test MO 1) and 80% (Test MO 5). In the centre of the soil the shear strengths increased from 15% (Test MO 5) to 30% (Test MO 1).

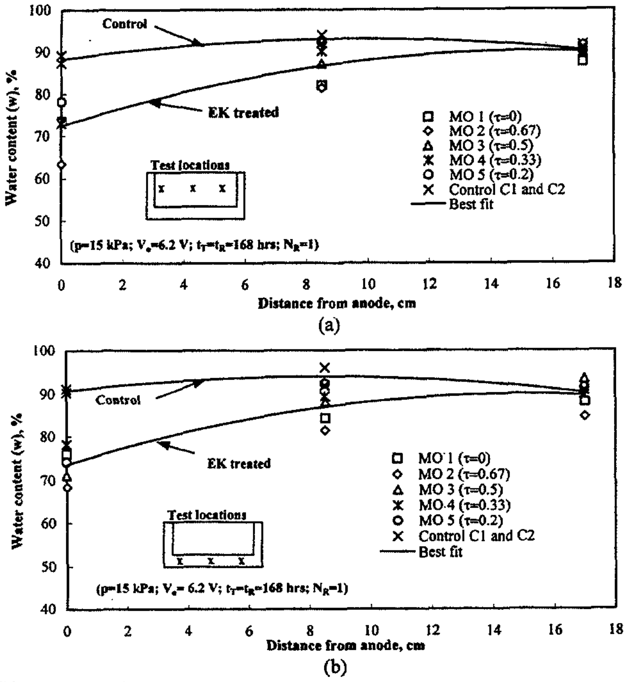
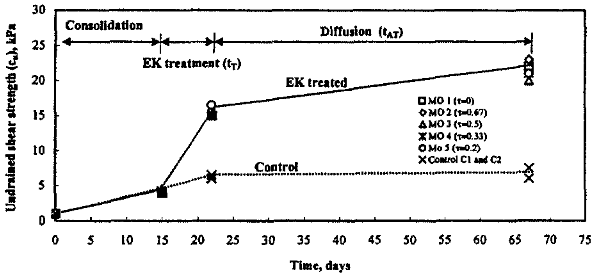


Figure 5. Distribution of water content across the soil sample after EK treatment in test series 1: (a) adjacent to the steel plate and (b) beneath the steel plate

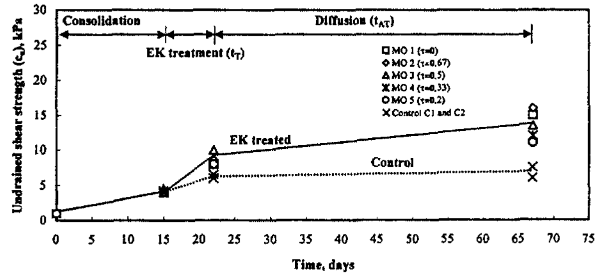
The water contents after electrokinetic treatment at 60-mm and 130-mm depths are presented in Figures 5 (a) and 5 (b), respectively. The figures show that the water content distribution was consistent with the shear strength distribution, i.e., the maximum decrease in the soil water content was at the vicinity of the anode. There was no notable change in the soil water content at the cathode comparing to the control.

During the treatment, small cracks were observed around the anodes although the soil sample was submerged. The cracks were probably produced by negative pore pressure and consequent tensile stresses occurred in the vicinity of the anode due to electroosmosis (Mitchell, 1993). Fissures up to 0.5 mm width extended from the anode toward the halfway between the electrodes. The cracks might have reduced the effectiveness of electrokinetics in terms of strengthening.

(a) Anode



(b) Centre



(c) Cathode

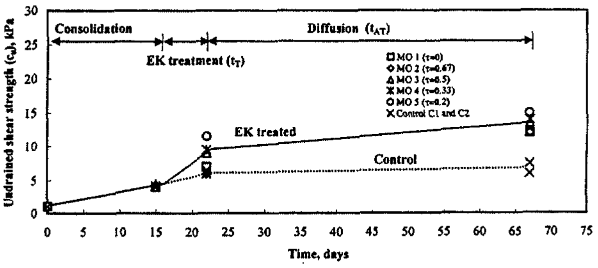


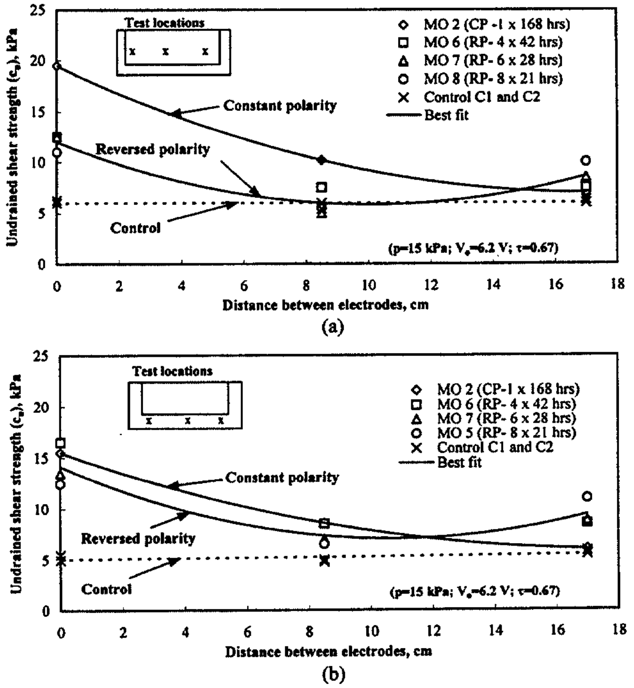
Figure 6. Changes in undrained shear strength of the soil during the testing – Test series 1

After the treatment it was observed that the soil around the anodes was reddish in colour due to intensive anode corrosion, while the soil in contact with the cathodes was greyer in colour than it was before the treatment. These changes in soil colour indicated intensive electrochemical reactions in the soil during electrokinetic treatment. In particular, the acidic front and basic front developed at the anode and cathode, respectively. Iron oxidation, dissociation and precipitation reactions occurred at the anodes resulted in corrosion of the steel. The anodes used in Test MO 1 with the constant current were completely corroded after 120 hours of treatment and they had to be replaced (Figure 2 (a)). The service life of the anode could be significantly extended by the application of intermittent current, as observed in the experiments. The cathode remained intact in all tests, as it is well understood from the theory of electrochemistry. The inspection after all tests indicated no significant corrosion of the embedded steel plate.

After 7 days of electrokinetic treatment the soil samples were set aside for 45 days to allow ionic diffusion and other electrochemical reactions. Figure 6 shows the changes in shear strength with time during the three phases of the tests. From the figure it is noticed that the soil shear strength was further increased with time in the diffusion phase. The strength increases were observed at the anode, centre and cathode. After 45 days the soil shear strength further increased 3 to 8 kPa compared to those measured immediately after the power was turned off.

Test Series 2: Effects of Polarity Reversal

The effects of polarity reversal were studied in test series 2. As shown in Table 1, three tests, namely MO 6, MO 7 and MO 8, with different polarity reversal intervals and same current intermittence of 4 min on/ 2 min off (τ=0.67) were conducted. The results are compared to the results of Test MO 2, which was conducted with the same current intermittence and treatment time, but without polarity reversal.

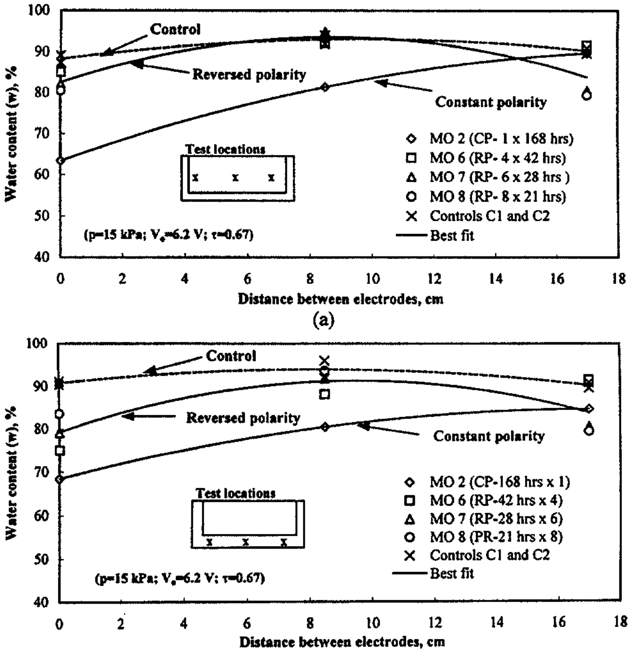


(a)

(b)

Figure 7. Distribution of undrained shear strength across the soil sample after EK treatment in test series 2: (a) adjacent to the steel plate and (b) beneath the steel plate

For these four tests, the variations of the soil undrained shear strength across the electrodes at two depths, i.e., 60 mm and 130 mm, are shown in Figure 7 (a) and (b), respectively. The experiment without polarity reversal produced uneven increase in the shear strength, as clearly shown in Figure 7. Compared to Test MO 2 in which the significantly higher increase in the undrained shear strength was observed at the anode, a more uniform increase in the shear strength was observed in tests with polarity reversal. The shear strength midway between electrodes measured after electrokinetic treatment was lower comparing to these closer to the electrodes. In all tests conducted with polarity reversal the undrained shear strengths at electrodes were somewhat lower than that at the anode in Test MO 2, but it was higher than the shear strength measured at the cathode. The polarity reversal also lead to more uniform water content profiles, as shown in Figure 8. However, dewatering effect of electrokinetic treatment was reduced because the soil water was driven toward the centre of the soil sample by the periodically reversing electric field.



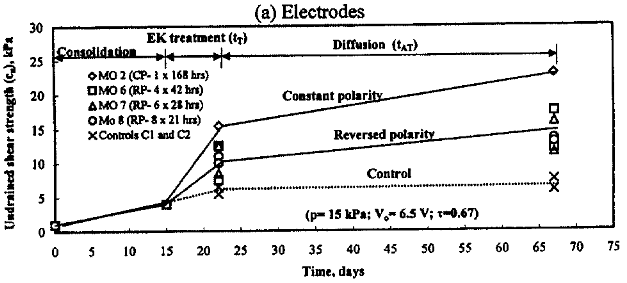
(a)

(b)

Figure 8. Distribution of water content across the soil sample after EK treatment in test series 2: (a) adjacent to the steel plate and (b) beneath the steel plate

The colour of the soil around the electrodes was not changed after electrokinetic treatment indicating that the polarity reversal reduced electrochemical reactions. Since the polarity reversal was viable only if drainage is available at both anodes and cathodes, the perforated pipes with the wall thickness of 1 mm served both as the anodes and cathodes in these tests, as mentioned earlier. Although it could be expected that electrode corrosion should be retarded by polarity reversal, the thin-wall perforated pipes still corroded rapidly and had to be replaced after maximum 42 hours of treatment.

(a) Electrodes



(b) Centre

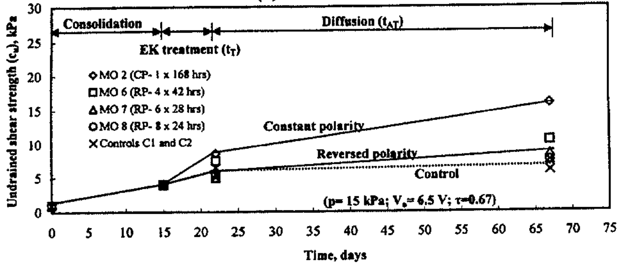


Figure 9. Changes in undrained shear strength of the soil during the testing – Test series 2

Figure 9 shows the typical changes in shear strength with time during the three phases of testing in test series 2. The figure shows that the soil shear strength was further increased with time in the diffusion phase at the electrodes and centre by approximately 1 to 5 kPa compared to right after the electrokinetic treatment. However, the results shows that using the polarity reversal in electrokinetic treatment, the soil strengthening effects during the diffusion phase were smaller comparing with those with the constant polarity.

Further Discussion on the Effectiveness of EK Treatment

The tests in test series 1 and 2 were conducted under the same electrode arrangement and applied voltage, but under the different current intermittence or polarity reversal which resulted in different energy consumption. The energy consumption for each test was calculated using Eq. (3) and summarised in Table 1. To examine the efficiency of the electrokinetic treatment the relationships between the energy consumption per unit volume of the soil, W, and the soil undrained shear strength, c_u, after test series 1 and 2, are plotted in Figure 10.

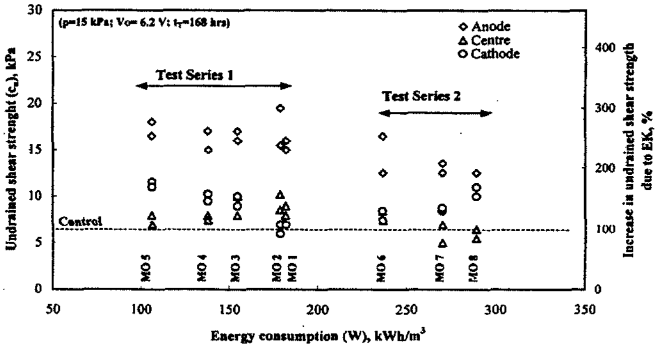


Figure 10. Improvement of undrained shear strength with energy consumption after EK treatment

Figure 10 shows the improvement in the undrained shear strength with energy consumption during the EK treatment. The figure clearly shows again that the application of electrokinetics generated significant strengthening effect in the soil. In test series 1 with constant polarity, the energy consumption was reduced using intermittent current (see Table 1 for values). However, there was not much difference in the undrained shear strength of the soil for various current intermittence ratios. For example, in Test MO 5, τ=0.2, the increases in the undrained shear strength are 190% at the anode, 80% at the cathode and 15% at the centre, while in Test MO 1, τ=1, increases in the undrained shear strength are 170%, 30% and 5% at the anode, centre and cathode, respectively. The energy consumption in Test MO 5 was however 70% less than that in Test MO 1. This indicates that the application of intermittent current can significantly reduce the energy consumption of electrokinetic treatment without reduction in the effectiveness of the soil strengthening. On the other hand, test series 2 conducted with electrode polarity reversal resulted in the increase of power consumption (Figure 10; see Table 1 for values). The results of the undrained shear strength after EK treatment plotted on Figure 10 show that the overall increase in the shear strength was reduced by increasing the power consumption by polarity reversal. However, more uniform strength increase at the electrodes was achieved.

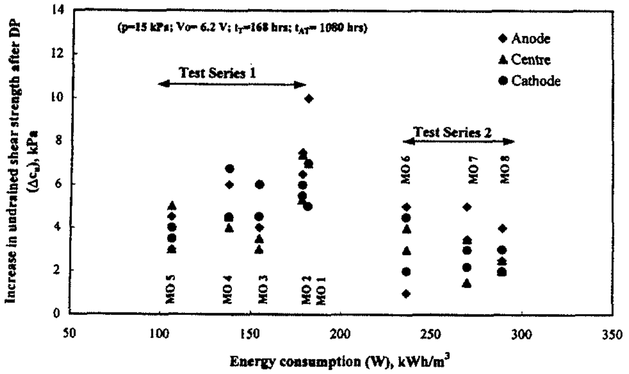


Figure 11. Improvement of undrained shear strength with energy consumption after diffusion

The improvement in the undrained shear strength during the diffusion phase is shown on Figure 11. The figure shows that the greatest increase in strength was accomplished after Test MO 1 with continuous DC application. Figure 11 also clearly shows that the polarity reversal diminished the increase in the undrained shear strength during the ionic diffusion phase.

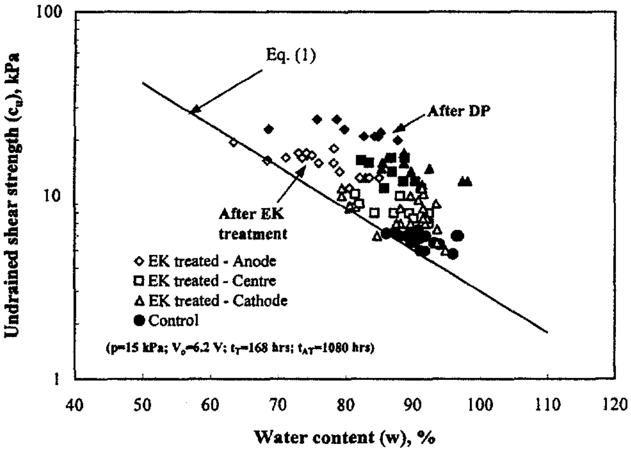


Figure 12. Undrained shear strength versus water content after EK treatment and diffusion

The relationship between the water content and undrained shear strength after electrokinetic treatment and diffusion phases in all tests is shown in Figure 12, along with the relationship defined by Eq. (1). After electrokinetic treatment, the decrease in the water content and corresponding increase in the undrained shear strength were observed at anode side of the soil sample. These changes can be mostly attributed to electrokinetics induced dewatering, but from the results it is obvious that the increase in the strength was more than what was expected just from the electroosmotic consolidation. On the other hand, the data at the cathode-side demonstrate the increase in the shear strength without significant decreases in the water content. This is likely attributed to cementation bounding generated by electrokinetics. The possible causes of this cementation could be selective sorption and ionic exchange of ionic species on clay particle surfaces and precipitation of amorphous chemical compounds serving as cementation agents (Quigley, 1980). The results of vane tests and water content tests after the diffusion phase are also included in Figure 12 and show significant increase in the undrained shear strength during that stage. Again, it is evident that dramatic changes due to electrochemical reactions caused by electrokinetics produced greater strengthening of the soil than that due to electroosmotic consolidation only. Therefore, the significant shear strength increase after the diffusion phase can be attributed to cementation bonding of soils particles by precipitation of ionic species. It has be long recognized that cementation increases the undrained shear strength of the soil and reduces the compressibility. Figure 11 shows that the water content increased in the soil during the diffusion phase. This increase could be attributed to osmosis which is counter process of diffusion in the soil-water-electrolyte system with the high ionic-concentration gradient. The results from the polarity reversal tests confirm that both electroosmosis and electrochemical processes contribute to soil strengthening of marine sediment. Polarity reversal can produce more uniform treatment and reduce electrochemical effects.

CONCLUSIONS

Electrokinetic strengthening of soft marine clays adjacent to skirted foundations was studied in an experimental project. From the results presented, it is evident that the undrained shear strength of the soil around the embedded skirted foundation model was increased considerably after electrokinetic treatment. The increase in the shear strength at the anode vicinity of 185 % was predominately resulted from electroosmosis, whereas the increase in the shear strength at the cathode vicinity which varied from 5%–80% depending on the current intermittent ratio, was resulted from cementation of soils particles due to intensive precipitation of amorphous cementing agents. From the results it is also evidenced that the soil shear strength was further increased with time after the electric field was withdrawn. This increase was attributed to cementation during post-treatment ionic diffusion. The results also suggested that the technique of current intermittence can significantly reduce the energy consumption and electrode corrosion while it still generates strengthening effects comparable to constant electricity application. It is shown that the polarity reversal can generate more uniform increase in the undrained shear strength during the electrokinetic treatment, but it also increases the energy consumption and reduces the electrochemical strengthening effects of ionic diffusion during and after the treatment.

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