Soft Clay Drainage Consolidation Using Electrically Conductive Wick Drains (ECWD)

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Challenges from North to South
Des défis du Nord au Sud

Wei-lie ZOU, Yan-feng Zhuang
Wuhan University, Wuhan 430072, Hubei, China
Xie-qun Wang
Wuhan University of Technology, Wuhan 430070, Hubei, China
Sai K. Vanapalli
University of Ottawa, Ottawa, ON, K1N 6N5, Canada

ABSTRACT
Electro-osmosis (EO) methods have not been widely used for the drainage consolidation of soft clay in practice because of two key problems; (i) metal electrode corrosion, and (ii) high electric energy consumption. With the recent advancements in the conductive plastics, there has been interest in using conductive plastic electrodes instead of metal electrodes to accelerate the drainage of soft clay. This paper presents the details of an in-situ EO test using a new patented electrically conductive wick drain (ECWD) and a specially designed power supply system on a hydraulically-filled sludge ground in Jiangsu Province, China. Field and laboratory tests were conducted to evaluate the improvement effectiveness after performing EO for a period of 21 days. The results suggest that the EO method, i) decreased the average moisture content of the sludge from 62% to 36%; ii) increased the dry density and the vane shear strength, respectively from 1030 to 1500 kg/m^3 and from 0 to 25.5 kPa. In addition, the ground bearing capacity also increased from 0 to 74 kPa. The electric energy consumption for this EO treatment is 5.2 kwh/m^3, which is a relatively low value with respect to power consumption. Moreover, prediction models for electric current, and cumulative drainage, *Q* during EO are also proposed based on the undertaken studies. Investigations to date suggest that the new ECWD presented in this paper is encouraging for consolidating the soft clays with relatively high water content and high plasticity index to achieve favorable conditions with respect to increase in shear strength at a relatively low cost.

RÉSUMÉ
Les méthodes d'électro-osmose (EO) n'ont pas souvent été utilisées lors de la consolidation d'argile molle à cause de deux facteurs; (i) la corrosion de l'électrode métallique, et (ii) la forte consommation d'électricité. Dû aux récents progrès effectués dans la recherche des plastiques conducteurs, il est devenu envisageable d'utiliser des électrodes en plastique conducteur à la place d'électrodes métalliques, afin d'accélérer le drainage d'une argile molle. Cet article présente les détails d'un essai in-situ d'EO utilisant une nouvelle technique brevetée de drainage capillaire électriquement conducteur (DCEC) et un système d'alimentation conçu sur un terrain rempli de boue, dans la province du Jiangsu en Chine. Des essais in situ et en laboratoire ont été effectués pour évaluer le gain d'efficacité après 21 jours d'essais avec l'EO. Les résultats suggèrent que la méthode d'EO provoque, i) une diminution de la teneur en eau moyenne de la boue de 62 % à 36 %; et ii) une augmentation de la densité sèche et de la force de cisaillement résiduelle, respectivement de 1030 à 1500 kg/m3 et de 0 à 25,5 kPa. En outre, la capacité portante du sol a également augmenté de 0 à 74 kPa. La consommation d'électricité pour cet essai d'EO est de 5,2 kwh/m3, ce qui représente une valeur relativement faible par rapport à la consommation d'énergie. De plus, des modèles de prévision en courant électrique, et drainage cumulatif, Q pendant l'essai d'EO sont également proposés sur la base des études effectuées. Les enquêtes menées à ce jour suggèrent que le nouveau DCEC présenté dans ce document est adapté à la consolidation des argiles molles avec une teneur en eau relativement élevée et un grand indice de plasticité pour obtenir des conditions favorables tout en augmentant la résistance au cisaillement à un coût relativement faible.

1 INTRODUCTION

Soft clays and super soft clays (i.e. dredged sludge, tailings) comprise of fine particles, with medium to high plasticity, low coefficient of permeability, and high compressibility. When the ground is composed of these types of soils they are conventionally improved using the consolidation methods, such as the surcharge preloading with vertical wick drains, the vacuum preloading, or the vacuum combined with surcharge preloading. These methods, however, are not effective in many scenarios. The performance of these methods is remarkably good both with respect to consolidation and increase in shear strength with respect to time; however, the performance dramatically drops later (i.e. the settlement of ground is rather low and the strength of ground soil doesn't improve at a rate that is expected). Some constructed facilities built on super soft clay grounds improved using the above methods have even failed.

The electro-osmosis (EO) method was first successfully applied for stabilizing a railway cut slope in Salzgitter, Germany (Casagrande 1948). Since then this method has been used for many engineering purposes such as rapid drainage consolidation of soft soil grounds and foundation pits, as well as enhancing the bearing capacity of soft soils in Canada, U.S.A., Norway, U.K., and China (Hicky et al. 1959; Casagrande et al. 1961; Soderman and Milligan 1961; Bjerrum et al. 1967; Petzer

1967; Casagrand et al. 1981; Casagrande 1983; Xi 1983). These studies suggest soft clays can be more effectively improved using the EO method in a shorter period of time (Casagrande 1983) in comparison to other conventional drainage consolidation methods. One advantage is that the pore water pressure in soil is typically negative during the period of EO, which significantly contributes to the increase in strength. For this reason, there will be no failure of foundation or slope during the construction phase while using the EO method (Nettleton et al, 1998).

In spite of several advantages of the EO methods, it was not widely used because two key limitations. The first limitation is related to the serious corrosion of the metallic anode after a certain period using it for the EO. The EO efficiency significantly reduces due to the corrosion effects. The second limitation is related to the high power consumption.

In order to overcome the corrosion of metallic anode, a new material, Electro-Kinetic Geosynthetics (EKG) was proposed (Nettleton 1998). This material essentially combines the advantage of the drainage function of geosynthetics and the EO technique. Since then, especially from start of the present century, the EO experimental studies have used several kinds EKG electrodes both in the laboratories and in-situ (Bergado et al. 2000; Fourie et al. 2002; Karunaratne et al. 2002; Wang and Zou 2002; Zou et al 2002; Chew 2004; Zhuang 2005; Hu 2005). However, a real practical EKG commercial product had not emerged because it was not easy to address all the limitations.

In this paper, the details of a field EO test with a new patented electrically conductive wick drain (ECWD) and a specially designed power supply system, that was performed on hydraulically-filled sludge ground in Jiangyin, Jiangsu Province, China, is presented. The test results suggest that the ECWD is promising for rapidly dewatering and consolidating the soft clays with high water contents.

2 FIELD TEST

The ground soil that needs to be improved is a hydraulically-filled sludge with an average thickness of 5.8 m, while the area of the test plot provided by the contractor to the investigators for investigation studies was 19 m × 15 m.

2.1 Properties of Ground Soil

The physical properties of the hydraulically-filled sludge are presented in Table 1. The particle size distribution curve is shown in Figure 1. The natural water content and plasticity index are 62% and 28%, respectively. The percentages of fine particles with size less than 0.005 mm and colloidal particles with size less than 0.002 mm in this soil are as high as 70% and 65%, respectively. The conventional drainage consolidation methods at this site required a large time period to achieve the required strength. These techniques were found to be expensive. For these reasons, the contractor decided to use the EO method.

Table 1 Soil and index properties of the undisturbed hydraulically-filled sludge

Liquid limit（%）	Plastic limit（%）	Water content（%）	Dry density (Mg/m^3)	Specific gravity of solid	Coefficient of permeability (cm/sec)
50	22	62	1.03	2.61	3×10^{-9}

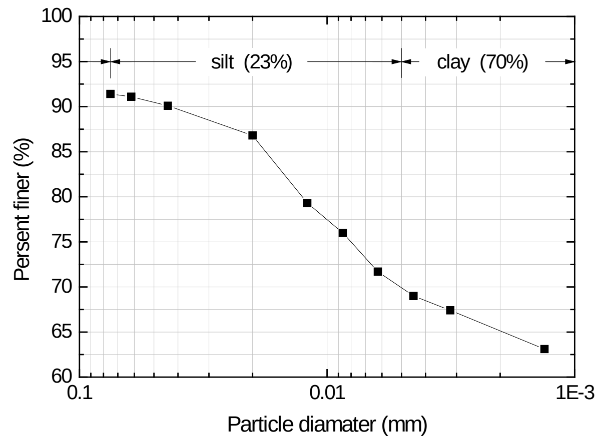


Figure 1. Grain size distribution curve

2.2 ECWD and Its Layout

The EO field test was conducted in 2011 in Jiangyin, Jiangsu Province, China to examine the effectiveness and feasibility of a new type of patented electrically conductive wick drain (ECWD) with an electrical resistivity of 10^{-3} Ω·m and a specially designed power supply system with a control program. The ECWD has similar appearance and cross-sectional shape to the commonly prefabricated vertical drains (PVDs) (Figure 2a). The ECWD is made from a conductive plastic for this study.

(a) (b)

Figure 2. Picture showing: (a) ECWD; (b) connection of two copper wires wrapped in ECWD with the electric wires

Two copper wires are wrapped along the length of the ECWD such that the ECWD is an equipotential body when it serves as an anode/cathode of EO. This technique also facilitates connecting with the adjacent anode/cathode by electric wires (see Figure 2b). In other words, it can be used as the anode/cathode of EO and also serves as the vertical drain channel of soft clay ground.

The hydraulically-filled sludge ground almost behaves like a liquid with little or no shear strength and has very low bearing capacity. For this reason, construction machinery cannot be used for the installation of the ECWD on the test plot. The installation of the ECWD had to be carried out manually. The depth of penetration of ECWD was equal to the thickness of hydraulically-filled sludge, and the longitudinal and transverse intervals of ECWDs were all 1.0 m. Figure 3a shows the details of the installation technique of the ECWDs, and Figure 3b shows the layout after placing the sand mat on the whole test plot. In order to prevent the sludge getting squeezed into the sand, a non-woven geotextile mat was placed underneath the sand for isolation.

(a)

(b)

Figure 3. Pictures showing the ECWD installation in the field: (a) After completing the ECWD installation; (b) After placing the sand mat and the connection of electric wires.

2.3 Specially Designed Power Supply System

Figure 4 shows the panel of the control cabinet of a specially designed power supply system in this study. This power supply system has dedicated software programmed by Dr. Yan-feng Zhuang from Wuhan University. This software has features to remote-control of EO techniques including the polarity conversion, intermittent electricity, constant electric current / voltage output modes and the switchover between these two output modes. This power supply also has the overload protection function for itself.

2.4 EO Test Process

Figure 4. Picture showing the panel of a control cabinet of the power supply system used in this study

The EO testing was performed in two stages. The first stage was initiated from August 15, 2012. A constant electric current output mode had to be employed because only a low power supply of 100V/300A was available. Namely, the electric current was only maintained at 290 A until August 24 when the effectiveness of drainage became poor. During this period, the polarity shift mode was alternatively used between long time reverse current and short time forward current. From August 25 to 26, the output mode of the power supply was switched to the constant voltage of 50V; however, the effectiveness of drainage did not show any improvement. For this reason, the EO test had to be paused.

The second stage started from September 16, 2012. An output mode of constant voltage of 80V was employed because a high power supply of 80V/2000A provided by a manufacturer in Shanghai, China was available. There was significant improvement with respect to the effectiveness of drainage (see Figure 5) compared to the first stage, using low power supply. During the second stage of testing, the polarity shift mode was the alternation between long time forward current and short time reverse current. But by the end of September 25, the drainage effectiveness also became poor, so the EO test was finally terminated.

Figure 5. Picture showing the drained water in the drainage ditch using the high power supply of 80V/2000A

3 TEST RESULTS

After EO termination，the drilling and sampling (see 1#–5# in Figure 6) for the laboratory soil experiments, as well as the in-situ tests including vane shear test (VST) and cone penetration test (CPT), were conducted to quantitatively analyze the effectiveness of this EO treatment using the EWCD and the dedicated power supply system on the hydraulically-filled sludge ground.

The testing results indicate that the ground soil was in a plastic state from the original liquid-plastic state, and the total electric energy consumption for 21 days was 8652 kilowatt-hour (kwh). The average unit electric energy consumption was 5.2 kwh/m^3, which approached the value of 6.9 kwh/m^3 derived from the laboratory model test (Zou and Zhuang 2012).

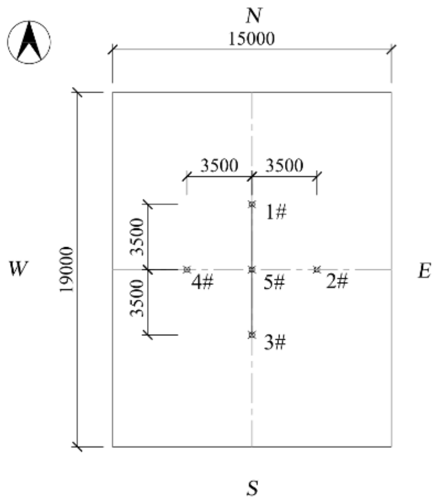


Figure 6 Distribution of the drilling holes after EO (All dimensions are in mm)

3.1 Dry Density and Water Content

Table 2 presents the dry densities and water contents of the specimens derived from the different depths of each drilling hole. Figure 7 shows the water content isograms along the two central cross sections. It can be seen from Figure 7 and Table 2 that after EO the distribution of the water contents for the entire test plot is not uniform. The test data collected from the west side were the highest (54.77%) and south side of the test plot was the lowest (23.99%).

These results may be attributed to a fact that the west side of the test plot was adjacent to an existing pond while the south side is close to an existing highway. Compared with the average water content before EO (62%, see Table 1), the average water content of the specimens derived from 5# drilling hole, which is located in the centre of the test plot, was reduced to 36.27%, i.e., its decreasing amplitude reached to 42%.

It can be seen from Table 2 that the drying density of the whole test plot was increased from 1.03 to 1.20-1.63 Mg/m^3.

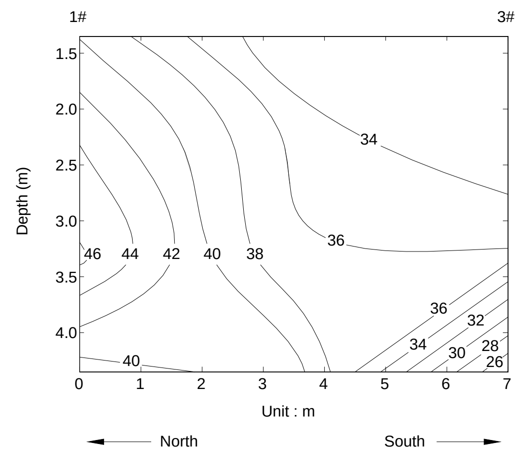
3.2 Bearing Capacity

The bearing capacity, f_{ak} of the ground after EO can be estimated using an empirical equation that was developed based on local experience (Equation 1) (Liao et al. 2007).

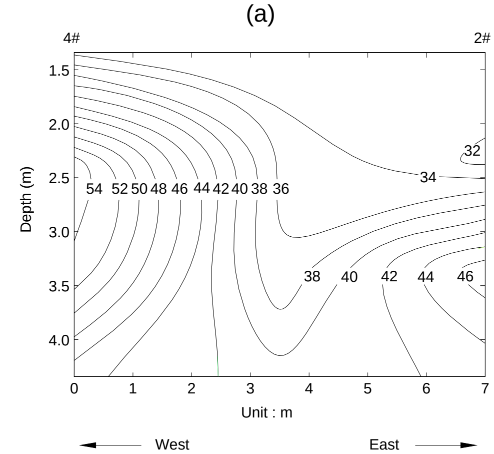
Table 2 Dry densities and water contents after EO

1#	Sampling depth [a]	1.2-1.5	2.2-2.5	3.2-3.5	4.2-4.5
	Dry density [b]	1.33	1.25	1.22	1.35
	Water content [c]	39.86	44.08	46.34	39.08
2#	Sampling depth	1.2-1.5	2.2-2.5	3.2-3.5	4.2-4.5
	Dry density	1.41	1.48	1.18	1.25
	Water content	33.76	31.51	47.28	42.49
3#	Sampling depth	1.8-2.1	2.8-3.1	3.8-4.1	4.8-5.1
	Dry density	1.42	1.45	1.38	1.63
	Water content	32.27	32.24	36.42	23.99
4#	Sampling depth	1.2-1.5	2.2-2.5	3.2-3.5	4.2-4.5
	Dry density	1.56	1.24	1.20	1.25
	Water content	33.59	54.77	53.73	44.63
5#	Sampling depth	1.2-1.5	2.2-2.5	3.2-3.5	4.2-4.5
	Dry density	1.49	1.36	1.37	1.33
	Water content	32.19	35.69	36.29	40.89

Note: [a,b,c] the units of sampling depth, dry density and water content are m, Mg/m^3 and %, respectively.



(a)



(b)

Figure 7 Water content isograms of central cross sections along: (a) east-west direction; (b) south-north direction

$$f_{ak} = 86p_s + 45.3 \quad [1]$$

The average specific penetration resistances, p_s for 4 testing holes are 0.18, 0.21, 0.44 and 0.48, so the estimated values of f_{ak} vary from 60.78 to 86.58 kPa, with an average value of f_{ak} is about 74 kPa. This result can be derived from the fact that during the field inspection after EO, an excavator, which has 21 tonnes weight with two crawler belts of 0.5 m wide and 3 m long, could be operated forming only very shallow rut on the ground surface (see Figure 8). From this information, the bearing capacity of the soil taking account of the weight of the excavator is about 70 kPa. This value is close to the estimated value (74 kPa) from Equation 1.

Figure 8 Picture showing the excavator can run on the ground surface after EO

3.3 Shear strength and total settlement

According to the results of 20 in-situ VSTs, the average value of sheer strength, τ_f after EO is 25.45 kPa. The total settlement of the ground after EO is 0.25 to 0.30 m.

3.4 Other Parameters

3.4.1 Coefficient of Permeability

Table 3 summarizes the coefficient of permeability, *k* of specimens derived from the different depths of #5 drilling hole (see Figure 6) after EO. The results suggest that the average coefficient of permeability of the ground significantly decreased by one order of magnitude compared with that before EO (see Table 1). This demonstrates that the ground became more dense after EO, which is the reason that the sheer strength and bearing capacity of the ground increased.

Table 3 Coefficient of permeability, *k* after EO

Specimen No.	5#-3[a]	5#-4	5#-5
Coefficient of permeability, *k* (cm/sec)	2.65×10^{-10}	13.2×10^{-10}	7.27×10^{-10}
Ave. *k* (cm/sec)		7.72×10^{-10}	

Note: [a] in the specimen No. 5#-3, the symbol 5# refers to the drilling hole number, and the digit 3 refers to the sampling depth (unit: m) in the hole.

3.4.2 Compression Coefficient

The compression coefficients, $a_{1\text{-}2}$ of the specimens derived from the different drilling holes and depths are presented in Table 4. It can be seen that the $a_{1\text{-}2}$ value drops to an average of 0.60 MPa^{-1} from the initial value of 2.1 MPa^{-1}. In other words, the compressibility of the ground soil was improved to close to medium level from the original high level.

Table 4 Coefficients of compressibility of specimens after EO

Specimen No.	5#-2[a]	5#-3	5#-4	5#-5	2#-3	2#-5	4#-2	4#-4
$a_{1\text{-}2}$ (MPa^{-1})	0.37	0.64	0.61	0.93	0.39	0.74	0.49	0.90
Ave. of $a_{1\text{-}2}$ (MPa^{-1})=0.60								

Note: [a] in the specimen no. 5#-2, the symbol 5# refers to the drilling hole number, and the digit 2 refers to the sampling depth (unit: m) in the hole.

4 MODELS FOR PREDICTION OF ELECTRIC CURRENT AND CUMULATIVE DRAINAGE

4.1 Electric Current

The current EO theories are mainly based on the research undertaken during the period of 1950-1970's (Wang 1954; Esrig 1967; Wan & Mitchell 1976), i.e., between anode and cathode, the flow caused from electric potential gradient and the flow caused from hydraulic gradient are anisotropic. When the former and the later reach a balance, the EO will stop. The main factor controlling the EO progress is not the equilibrium between the EO flow and the anisotropic hydraulic flow, however, it depends on the amount of the ions that migrate in the pore water and the ease with which ion's can migrate.

For the design of a ground to be improved using EO method, the electric current, *I* and the cumulative drainage, *Q* are two key parameters. A large number of EO test results indicate that under constant voltage output mode the electric current, *I* in the EO progress would attenuate as a negative exponent function, which can be expressed using Equation 2 (Zhuang et al 2012).

$$I = (I_0 - I_\infty)e^{-at} + I_\infty \qquad [2]$$

where: *I* is the electric current during the EO progress (A); I_0 is the initial electric current of EO (A); I_∞ is the final electric current of EO (A); *t* is the EO time (s); and *a* is time factor (s^{-1}), which reflects the attenuation rate of electric current in the progress of EO, i.e., the greater the value of *a*, the faster the attenuation rate of electric current, the more disadvantage to the EO effectiveness.

Assuming the I_∞ does not have contribution to the drainage of EO, then the effective electric current, I_{eff} can be expressed in Equation 3.

$$I_{eff} = (I_0 - I_\infty)e^{-at} \qquad [3]$$

where: I_{eff} is the effective electric current (A).

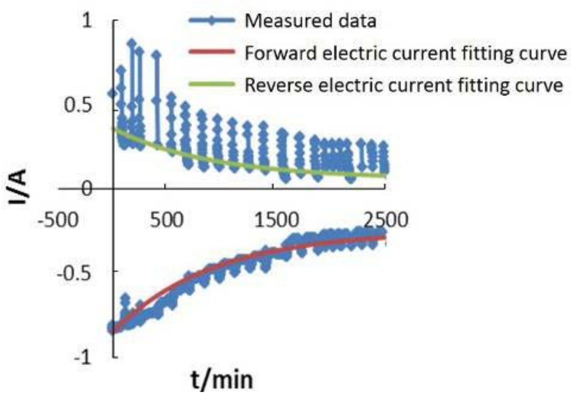
Equation 2 or 3 can be used to determine the power of power supply for EO.

4.2 Cumulative Drainage

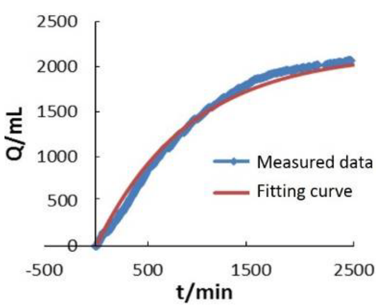
According to the energy gradient theory for EO (Zhuang, 2005), the cumulative drainage, Q during the EO process can be predicted using Equation 4.

$$Q=\frac{k_q U(I_0-I_\infty)}{a^2\,\Delta x^2}(1-e^{-at}) \qquad [4]$$

where: Q is the cumulative drainage (m^3); k_q is the flow coefficient ($m^2 \cdot p_a^{-1} \cdot s^{-1}$), which reflects the permeability of



(a)



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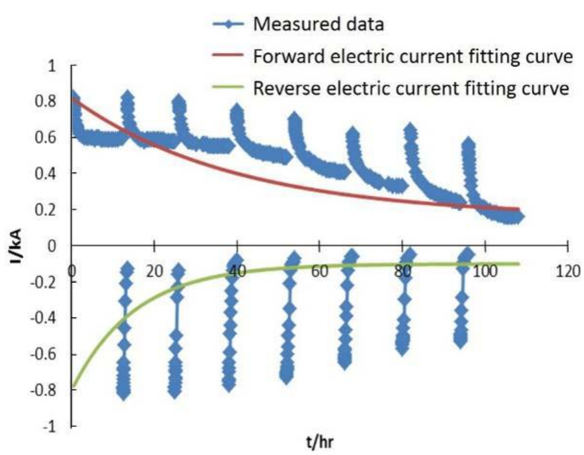

(c)

Figure 9 Laboratory and field tests: (a). electric current change with time in the laboratory; (b) accumulative drainage change with time in the laboratory; (c) electric current change with time in the field.

soils and the accumulation rate of energy in the soils. The greater the k_q, the greater is the coefficient permeability of soils or the lower the accumulative energy; Δx is the distance of between cathode and anode (m); and U is the voltage (V).

Equation 4 can be used to estimate both the effectiveness and the required time of EO.

A laboratory model experiment was conducted on the same soil derived from the field test plot. The size of the model box was 250 mm×263 mm×245 mm. Figures 9a and 9b show good comparisons between the prediction curves and measured data of both the I and the Q. According to Equations 3 and 4, Figures 9a and 9b, the values of k_q=1.8×10^{-15} $m^2 \cdot p_a^{-1} \cdot s^{-1}$, a=1.8×10^{-5} s^{-1}. Figure 9c shows a good comparison between the measured and predicted curves of I under the constant voltage of 80 V in this field test. According to Equation 3 and Figure 9c, a is equal to 0.7×10^{-5} s^{-1} under the forward electric current and 1.8×10^{-5} s^{-1} under the reverse electric current, respectively. Although the cumulative drainage of the field test during the EO process was unable to be measured accurately, according to the water contents of the ground soil before and after EO, k_q can be estimated to be 1.8×10^{-12} $m^2 \cdot p_a^{-1} \cdot s^{-1}$. Therefore, the change of fitting parameter a was small, but the change of fitting parameter k_q reached three orders of magnitude because of the dimension effect of EO test, namely, the difference of model dimensions between the laboratory test and the field test resulted in the difference of their k_q. Moreover, the difference value is just about equal to the ratio of the flow area of electric current between the laboratory test and the field test. These results however have to be verified with more test results.

5 CONCLUSIONS

The new patented ECWD and the specially designed power supply system when used combined can improve the soft clay ground properties with the following conditions:

(1) The ground soil has relatively high water content and has significant percentage of clay particles (i.e., suitable plasticity index).

(2) The electrical resistivity of ECVD being less than the order of magnitude of 10^{-3} Ω·m;

(3) It is important to employ constant voltage output model and strong electric current as far as possible in the initial stage of EO,

(4) A small scale laboratory model experiment is necessary for understanding the key parameters that influence the field behavior of the EO, including the time factor, a, the flow coefficient, k_q, the durations of both forward and reverse electric currents, as well as the interval time between them.

The field test in this study suggests that the average unit electric energy consumption (5.2 kwh/m^3) is acceptable owing to employing the suitable techniques during the progress of EO. The suggested the ECWD is encouraging for use in the drainage consolidation of soft clay with high initial water content and high plasticity index. However, the current cost of the ECWD is on the high side (about U.S. dollar 1.0/m). Further improvements and more studies are required before the proposed approach can be used in engineering practice applications.

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