

Electro-osmosis stabilisation of slopes

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ABSTRACT

Slope failure is a major concern in New Zealand roads. Applying conventional slope stabilisation techniques, such as slope repair, benching, wire netting and soil nailing, is not always practical due to financial and environmental concerns. Electro-osmosis (EO) consolidation technique can provide engineers with a low impact and economical solution for that purpose. EO induces water movement in the fine-grained soil body due to external electric potential gradient (voltage) by establishing a net water flow toward the cathode and creating negative pore water pressure that produces soil consolidation. The external electric potential gradient is normally applied by means of conductive electrodes which can be laid horizontally for slope stabilisation. In this paper, a systematic review of EO consolidation case histories and large-scale experiments have been presented with the aim of establishing an initial cost-effective design framework for EO consolidation scheme in slopes. The hydraulic permeability, electrical resistivity and EO permeability of soil have been identified as factors controlling the shear strength improvement, EO efficiency and power consumption. In addition, depending on soil and system properties, up to approximately 300% increase in shear strength has been achieved.

1 INTRODUCTION

Some parts of New Zealand are covered by fine-grained soils, such as Oamaru clay loam in Southland, Waikato silty clay and Taranaki/Manawatu humic clay. In many cases, these soils need to be improved for the purpose of slope stabilisation and structural support. The traditional preloading consolidation method is one of the effective ground improvement techniques; however, it is time consuming and is not applicable in all cases. For instance, this technique cannot be used to enhance slope stability. In fact, slope failure often occurs because of pre-loading and the effect of other factors, including pore water increases, ground water flow and seasonal climate changes. Several ground improvement and repair methods for slopes are available, such as changing slope geometry and using stabilising piles, though their feasibility depends on site situation and project budget. Hence, there is a need to find a method for slopes that could overcome most of the limitations of the conventional methods.

Electro-osmosis (EO) is one of the efficient techniques in geotechnical engineering that could be used for this purpose. In many situations, because of the limitation related to load application and environmental and financial constraints, this technique is identified as a unique option (Bjerrum et al. 1967). Simply put, EO works in the following way: generally, under the influence of an electric potential, the cations within the body of saturated soil mass are drawn to the cathode and the anions to the anode. Ions carry their water of hydration and exert a viscous drag on the water around them. When the soil is subjected to direct current (DC), electric potential gradient induces a net water flow toward the cathode and creates negative pore water pressure that produces soil consolidation (Mitchell and Soga 2005). This method has been proven as a low impact,

environmentally-friendly and cost-effective technique. In addition, EO could consolidate the soil without clearing trees in forested areas (Jones et al. 2011). The characteristics of electrodes, properties of the soil, level and duration of applied potential difference and power consumption control the improved soil behaviour (Mimic et. al. 2001; Jeyakanthan 2011). Unfortunately, lack of knowledge in the field of electro-hydro-mechanical (EHM) behaviour of EO-treated soils, power consumption and, consequently, cost of the EO ground improvement technique restricts the applicability of this method. In addition, although the laboratory-scale understanding of EHM behaviour of the soil has improved recently, case histories of electro-osmosis consolidation in large-scale play a significant role in understanding the in-situ EHM behaviour. Therefore, to have a thorough understanding of EO consolidation effects and efficiency, laboratory and field scale tests should be studied simultaneously.

In this paper, the application of EO consolidation for slope stabilisation purposes in laboratory and field scale is investigated. In addition, the post-treated soil behaviour is studied in order to propose a more efficient EO consolidation set up and to determine the feasibility of EO system on slopes.

2 ELECTRO-OSMOSIS SYSTEM PROPERTIES AND APPLICATIONS

Generally, the electric field is applied by means of installing electrodes in the body of the soil in various directions. Based on electrode alignments, the application of electro-osmosis consolidation can be categorised into two general cases; (1) ground improvement applications and (2) slope stabilisation. As shown in Figure 1, for ground improvement purposes the electrodes are usually laid in vertical alignment.

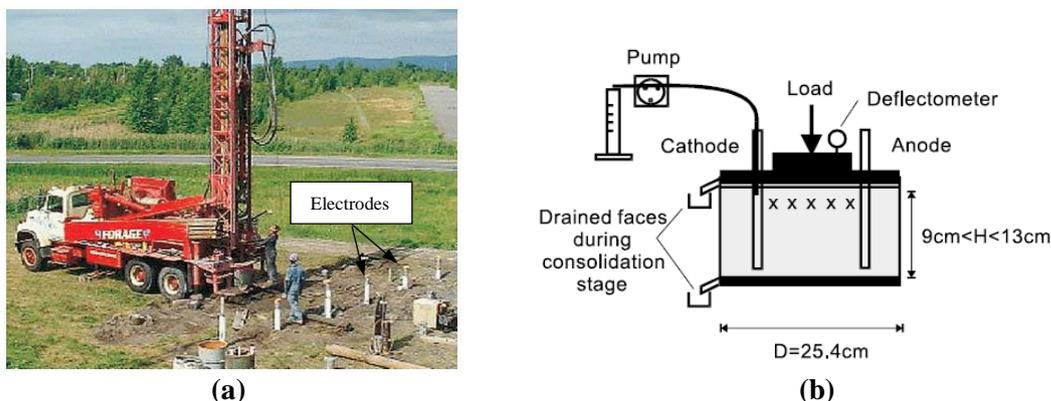


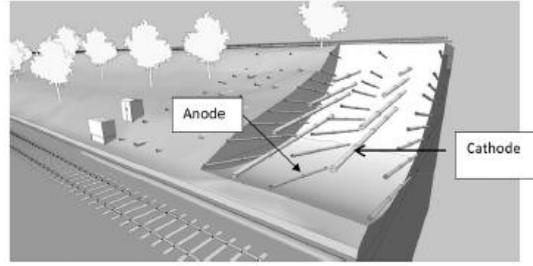
Figure 1: Electro-osmosis ground improvement tests: (a) field test (Burnotte et al., 2004); and (b) laboratory test (Lefebvre and Burnotte, 2002)

Therefore, to accurately model the EO consolidation, the laboratory apparatus should be designed to accommodate the electrodes vertically in the testing cell (Figure 1b). However, in case of slope stability the electrodes are installed in horizontal alignment as shown in Figure 2. In addition, a self-climbing rig can be used to install electrodes on the slopes with no deforestation, as shown in Figure 2a. In such a case, the metallic electrodes can also be maintained in place to confine the soil and provide further improvement after EO treatment. Therefore, to accurately model the EO slope stability application in the laboratory, the electrodes should be installed in horizontal direction, as shown in Figure 3.

In addition to the electrodes alignment, electro-osmosis system properties consisting of level of applied electrical difference (V), electrode length (L) and electrode spacing (S), govern the behaviour of post-treated soil and economics of the EO improvement project. Therefore, depending on level of required treatment, the system properties and cost of the project can be estimated.



(a) self-climbing rig to install electrodes



(b) electrode alignment in slopes

Figure 2: EO slope stabilisation (Lamont-Black et al., 2016)

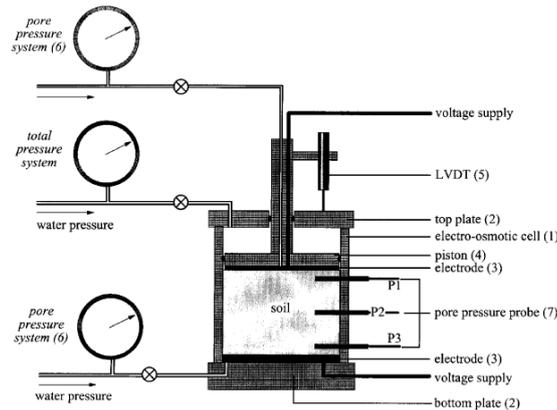


Figure 3: Typical laboratory EO cell for slope stabilisation application (Hamir et al., 2001)

3 BEHAVIOUR OF POST-TREATED SOIL

The properties of the EO system govern the characteristics of post-treated soil. Generally, the effect of system properties on post-treated soil behaviour is verified using post-treated soil response namely improvement depth (ID), undrained shear strength (S_u) of post-treated ground and soil settlement. In addition, the cost of a project depends on the level of power consumption which is governed by the electrical resistivity of soil. In terms of slope stability, ID , S_u and economics of the EO project are crucial factors which need to be fully investigated.

3.1 Improvement depth

Basically, ID is defined as a depth below which the shear strength of soil remains unchanged. Measurement of ID is not practical in laboratory tests as the specimen length is usually limited. Therefore, case histories have been used to accurately measure ID . In addition, results from vertical and horizontal alignment can be used to measure ID . A number of case histories, with various electrode materials, levels of V/S and improvement durations, show the ID to be exactly equal to the length of electrodes (Lo et al. 1991b; Ou et al. 2009). However, in case of quick clay of Norway, $ID = 7\text{m}$ has been reported for 9m long steel electrodes (Bjerrum et al. 1967) while $ID = 7\text{m}$ has been observed in soft Montreal clay with 5m long steel electrodes (Burnotte et al. 2004). The discrepancy observed in these cases can be attributed to the electrode diameter, D . Looking at the results, $D/L=0.02$ and $D/L=0.4$ correspond to $ID/L=0.75$ and $ID/L=1.4$, respectively. It should be noted that $D/L=0.1$ with acceptable level of V/S leads to $ID/L=1$ in EO system with metallic electrodes (Lo et al. 1991a; Ou et al. 2009). Therefore, by selecting $D/L > 0.1$ the treatment length L can be expected.

3.2 Shear strength of post-treated soil

Generally, a vane shear test is used to measure the shear strength of the pre/post-treated soil in the field and in the laboratory. For normally consolidated soil, the shear strength can be estimated

using the soil's preconsolidation pressure, as explained in Equation (1) (Bjerrum et al. 1967; Burnotte et al. 2004; Jeyakanthan et al. 2011):

$$C_u = \alpha_u \sigma'_p \quad (1)$$

where C_u is the undrained shear strength of the soil, σ'_p denotes preconsolidation pressure of the soil and α_u is the shear strength ratio. In addition, application of an electric potential gradient generates maximum negative porewater pressure at the anode side which is considered as the maximum generated preconsolidation pressure in the treated soil. Therefore, the level of increase in shear strength in post-treated soil can be computed as:

$$\Delta C_u = \alpha_u u_{max} \quad (2)$$

where u_{max} is maximum generated pore water pressure during EO consolidation, which is usually estimated based on an EO governing equation:

$$\partial^2 u_e / \partial y^2 + (k_e \gamma_w / k_h) \times \partial^2 V / \partial y^2 = (1/C_v) \times \partial u_e / \partial t \quad (3)$$

where k_e and k_h are the EO and hydraulic permeability, respectively. These parameters can be measured from an EO consolidation test similar to that shown in Figures 1 and 2. u_e and C_v denote the developed pore water pressure and coefficient of consolidation, respectively. By solving Equation (3), u_e can be found as:

$$u_e = - (k_e \gamma_w / k_h) \times V_x \quad (4)$$

Considering $V=0$ at the cathode and $V=V_{max}$ at the anode side, the maximum negative pore water pressure occurs in the anode side and no pore water pressure develops in the cathode. Therefore, maximum pore water pressure is:

$$u_{max} = - (k_e \gamma_w / k_h) \times V_{max} \quad (5)$$

It should be noted that the distribution of voltage across the electrodes is considered linear in majority of previous research. However, as the electrical resistivity of soil varies during consolidation, a linear voltage distribution cannot provide the most accurate results for calculation of maximum developed pore water pressure. Figure 4 shows the level of shear strength observed in the laboratory and field trials before and after EO consolidation. A list of utilised laboratory and field trials are provided in Table 1. Lo et al. (1991a) applied electric field intensity of 0.29 - 0.39 V/cm to Leda clay and an increase of 113.6 - 172.7% in average shear strength was observed. However, a maximum of 50.8% increase in average shear strength was reported in the field with similar electric intensity (0.1 - 0.4 V/cm).

Table 1: Properties of EO systems used in experimental tests

Test ID	Ave. Pore pressure developed (kPa)	Initial shear strength (kPa)	Final shear strength (kPa)	Reference
L-1	-75	11	30	Lo et al. (1991a)
F-1	-44.5*	18.2	27.4	Lo et al. (1991b)
L-2a	-101*	47	76	Lefebvre & Burnotte (2002)
L-2b	-98*	29	57	Lefebvre & Burnotte (2002)
L-2c	-263*	48	123	Lefebvre & Burnotte (2002)
F-2	-135*	30	60	Burnotte et al. (2004)
L-3	93	30	57.9	Win et al. (2001)
F-3	10	30	46	Chew et al. (2004)

*estimated by the authors based on Equations (1) – (3)

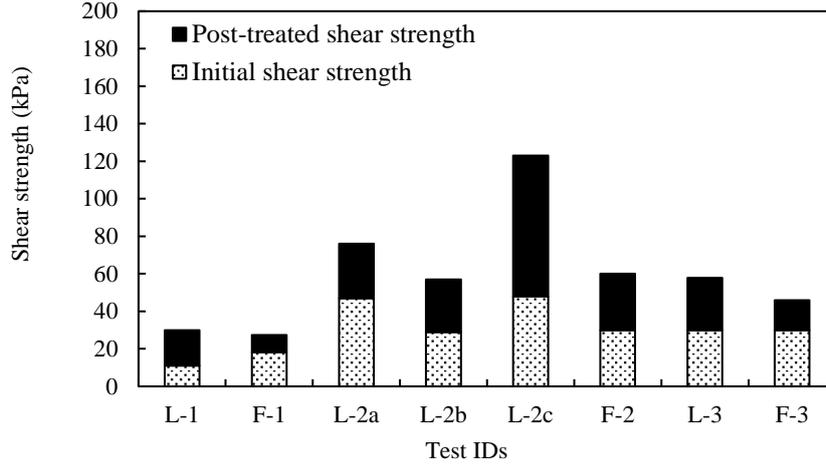


Figure 4: Comparison between measured initial and post-treated shear strength in laboratory and field trials

Lefebvre and Burnotte (2002) tested one specimen with $\sigma'_p=175$ kPa using the conventional method (test L-2a) and two other specimens with $\sigma'_p=105$ and 175 kPa using a treated EO system (tests L-2b & c). The average initial shear strengths of the soil with $\sigma'_p=105$ and 175 kPa were 29 kPa (test L-2b) and 47-48 kPa (tests L-2a & c), respectively. The post-treatment shear strengths of the specimen in test L-2b, L-2c and L-2a were reported to be 57, 123 and 76 kPa, respectively. Burnotte et al. (2004) reported 30 kPa for the initial shear strength of the soil in the field, which has been improved to an average of 60 kPa. A major improvement in shear strength has been observed in the anode vicinity. In the case of the Singapore marine clay, a maximum of approximately 50% shear strength increase was reported by Chew et al. (2004) in the field. However, Win et al. (2001) extracted a sample of similar clay from a depth of 17-17.8m (more or less similar to Chew et al. 2004) and tested it in the laboratory. Approximately $\sigma'_p= 93$ kPa achievement has been observed at the end of the EO process. Based on the results less deviation has been observed when the same electrode alignment is used in field and laboratory trials considering a more or less similar EO system. This fact signifies the importance of electrode alignment in estimation of EO system applicability in laboratory.

3.3 EO efficiency and power consumption

By definition, the EO efficiency is the amount of transported water per unit charge that passes through the soil. Thus, if efficiency is denoted by e , then:

$$Q = e I \quad (6)$$

where Q and I are water discharge and electrical current respectively. Based on Casagrande's relationship:

$$Q = k_e i_e A \quad (7)$$

where

$$i_e = V/L \quad (8)$$

Hence,

$$Q = k_e A \times (V/L) = e I \quad (9)$$

and

$$e = k_e \times (VA/IL) \quad (10)$$

This can be simplified to

$$e = \rho k_e \quad (11)$$

The electrical resistivity, ρ , of clays varies between 1 to 100 Ω .m whereas k_e ranges from 1×10^{-8} to 1×10^{-9} . Therefore, the maximum theoretical efficiency is $1 \times 10^{-6} \text{ m}^3/\text{C}$ where C is unit charge (coulomb). To represent the EO efficiency of each type of soils as a percentage and for more convenient comparison, the EO efficiency has been normalised by the maximum theoretical efficiency ($1 \times 10^{-6} \text{ m}^3/\text{C}$), which is assumed to correspond to 100% efficiency. Based on this definition, the isochrone for EO efficiency has been generated and shown in Figure 5 with dotted lines. Percentage of efficiency ($e\%$) has been defined as:

$$e\% = (e/e_{max}) \times 100\% \quad (12)$$

The EO efficiency for various tested materials is also shown in the figure. For all tested materials at low salinity levels, $e\%$ varies in a narrow range of 4 - 12%. In addition, the softer the soil, the higher the EO efficiency is. Soils which are categorised as soft show $e\% = 10 - 12\%$; however, all tested stiff clays show $e\% = 4 - 10\%$. Therefore, by determining either one of the parameters ρ or k_e , the other one can be estimated based on Figure 5.

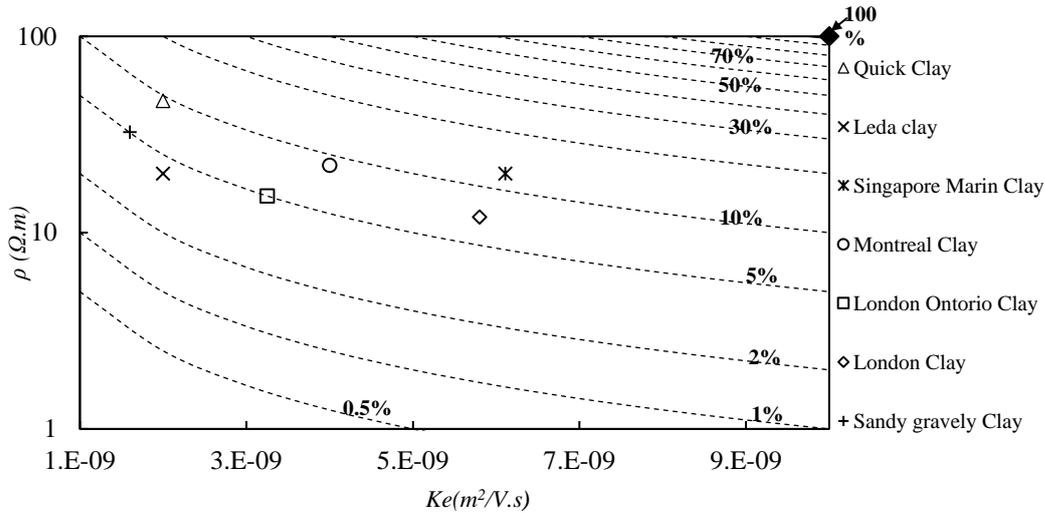


Figure 5: EO efficiency in various clays

Knowing the required level of improvement and accurate determination of EO efficiency leads to an estimation of the required voltage which holds a great importance in estimation of consumed power. In addition to the level of applied voltages, the level of power consumption depends on electrical response of soil to applied voltage (current). Based on Ohm's law, the level of power consumption in the EO system can be estimated as:

$$P = V^2/R \quad (13)$$

where R is soil resistance. To extend the estimated power consumption to the field, P is normalised by the volume of treated soil. Therefore:

$$P/vol = V_L^2/\rho \quad (14)$$

where V_L is electric field intensity which is defined as V/L (V/m) and vol denotes the volume of treated soil. In addition, based on experimental results in laboratory scale, approximately 40% of the applied potential will be lost in the soil-electrode vicinity due to loose soil-electrode connection and chemical processes. This potential loss should be considered in Equation (14). Therefore, considering 40% potential loss at soil-electrode interface, knowing the electrical resistivity of soil and applied electrical potential gradient, the level of power consumption can be estimated by Equation (14). Figure 6 shows the calculated power consumption based on the Ohm's rule considering the potential loss at the soil-electrode interface. Each dotted line shows specific level of power consumption in kW/m^3 . For comparison, the consumed power of available field trials is also shown. In the majority of the field trials, the field-measured consumed power indicates a higher level of power rather than that shown for calculated power consumption. These results show more than 40% of potential loss in the field rather than that observed in the laboratory tests. In other words, the level of potential losses observed in the field is much higher than those measured in the laboratory. The reasons for this difference can be attributed to the lack of voltage calibration in the laboratory, short term measurement of voltage drops and perfect contact of soil-electrode in horizontal electrode configuration in the laboratory.

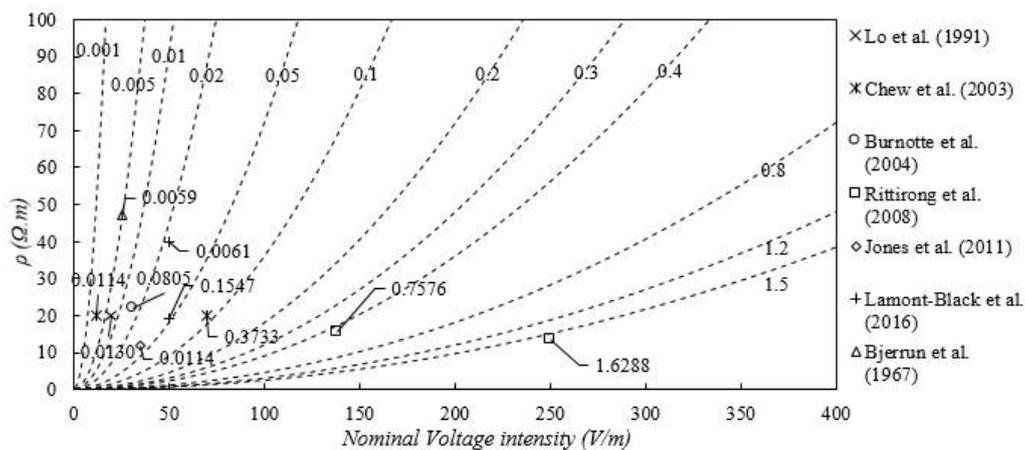


Figure 6: EO power consumption in various clays

4 CONCLUSIONS

EO consolidation can be used as a low-impact, environmental-friendly technique to stabilise slopes. A number of successful field tests had been carried out using voltage gradient of approximately 0.1 to 0.4 V/cm. Depending on soil types and electrode spacing, up to 300% increase in shear strength of the soil had been reported compared to the initial shear strength. In addition, in the case of an electrode dimension of $D/L > 0.1$ the effects of soil improvement have been observed up to a length equal to the electrode length (L). The efficiency of EO technique has been compared with the maximum theoretical efficiency and efficiency between 4 - 12% had been measured for various clays. In addition, the EO efficiency of soil implies the level of power consumption for a specific EO project from which the cost of a project can be estimated.

REFERENCES

Bjerrum, L., Moum, J. and Eide, O. (1967) Application of electro-osmosis to a foundation problem in a Norwegian quick clay. *Geotechnique*, 17(3): 214-235.

- Burnotte, F., Lefebvre, G. and Grondin G. (2004) A case record of electroosmotic consolidation of soft clay with improved soil-electrode contact, *Canadian Geotechnical Journal*, 41(6): 1038-1053.
- Chew, S.H., Karunaratne, G.P., Kuma, V.M., Lim, L.H., Toh, M.L. and Hee, A.M. (2004) A field trial for soft clay consolidation using electric vertical drains, *Geotextile and Geomembranes*, 22(1-2): 17-35.
- Hamir, R. B., Jones, C. J. F. P. and Clarke, S. (2001) Electrically conductive geosynthetics for consolidation and reinforced soil. *Geotextile and Geomembranes*, 19(8), 455-482.
- Jeyakanthan, V., Gnanendran, C.T., and Lo, S.-C.R. (2011) Laboratory assessment of electro-osmotic stabilization of soft clay, *Canadian Geotechnical Journal*, 48(12): 1788-1802.
- Jones, C.J.F.P., Lamont-Black, J. and Glendinning, S. (2011) Electrokinetic geosynthetics in hydraulic applications. *Geotextile and Geomembranes*, 29(4): 381-390.
- Lamont-Black, J., Jones, C.J.F.P. and Alder, D. (2016) Electrokinetic strengthening of slopes - Case history. *Geotextile and Geomembranes*, 44(3): 319-331.
- Lefebvre, G. and Burnotte, F. (2002) Improvement of electroosmotic consolidation of soft clays by minimizing power loss at electrodes, *Canadian Geotechnical Journal*, 39(2): 399-408.
- Lo, K.Y., Inculat I.I. and Ho, K.S. (1991a) Electroosmotic strengthening of soft sensitive clay, *Canadian Geotechnical Journal*, 28(1): 62-73.
- Lo, K.Y., Ho, K.S. and Inculat I.I. (1991b) Field test of electroosmotic strengthening of soft sensitive clay, *Canadian Geotechnical Journal*, 28(1): 74-83.
- Mimic, S., Shang, J.Q., Lo, K.Y., Lee, Y.N. and Lee, S.W. (2001) Electrokinetic strengthening of a marine sediment using intermittent current. *Canadian Geotechnical Journal*, 38(2), 287-302.
- Mitchell, J.K., and Soga, K. (2005) *Fundamentals of Soil Behaviour*, John Wiley and Sons Press
- Ou, C., Chien, S. and Chang, H. (2009) Soil improvement using electroosmosis with the injection of chemical solutions: field tests. *Can. Geotech. J.*, 46(6), 727-733.
- Win, B.M., Choa, V. and Zeng X.Q. (2001) Laboratory investigation on electro-osmosis properties of Singapore clay, *Soils and Foundations*, 41(5): 15-23.