COMPOSITE FOUNDATIONS ON MALAYSIAN SOFT CLAY SOIL: APPLICATIONS OF INNOVATIVE TECHNIQUES

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others

ABSTRACT

An innovative technique of electro osmosis coupled with vertical surcharge loading to accelerate the consolidation and stiffen Kaolin (China Clay Grade E) was investigated in this study. The geotechnical properties of this China Clay Kaolin Grade E and the design of electro osmotic consolidation chamber are discussed together with an explanation of the procedural concept of the electro osmotic consolidation chamber (i.e., the preparation of the apparatus and the clay sample, assembling of the electro osmotic consolidation chamber; and the experimental work).

The plastic limit, liquid limit and plasticity index were 35%, 53% and 18% respectively. Therefore, China Clay Kaolin Grade E is classified as MH soil, and it is predominantly a silt with high plasticity. The specific gravity of the soil is 2.65. To ensure the kaolin is saturated, all samples were prepared in a similar manner with deaired water to produce a slurry at 150% of the liquid limit (initial moisture content of 79.5%).

The electro osmotic consolidation chamber was cylindrical and consisted of the body, the base and the top cap. The body and the base of the chamber were constructed of polyvinyl chloride (PVC) tube with a wall thickness of 10.9 mm, 345 mm high and 251 mm inner diameter. The electro osmotic consolidation chamber was assembled together with a 45 mm thick flange and collar. The top cap of this chamber was based on that of a Rowe cell of similar diameter.

Twenty one tests were performed in this study with an applied voltage and one test was a control test. The test samples in the twenty one tests were all consolidated to three different phases. In Phases 1 and 2, the samples were consolidated at 15 kPa while in the Phase 3, 50 kPa was used. The electro osmotic process was only performed during Phase 2. The time of treatment, numbers of electrodes, the arrangement of electrodes, and the applied voltages were investigated in these tests.
Results from these tests indicated that the China Clay Kaolin Grade E in a 79.5% slurry form responded well to electro osmotic treatment and that electro osmotic process increased the overall stiffness of the soil as indicated by the reduced relative settlement in Phase 3 with a pressure of 50kPa.

The water content around the anodes was less than that at the cathode creating zones of higher average constrained stiffness. The tests demonstrated that the longer the time of treatment, the greater the numbers of anodes, the shorter distance between the electrodes and the higher the applied voltages associated with electro osmosis increased the average stiffness of the soil mass confirming the concept of an electro osmotic pile.

Keywords: electro osmotic merged vertical loading and electro osmotic, consolidation, electro osmotic consolidation chamber, stiffening.

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ABBREVIATIONS AND SYMBOLS

K_2O, Na_2O	alkalis (%)
Al_2O_3	aluminium (III) oxide (%)
V	applied voltage (V)
φ_{max}	applied voltage (V)
ΔE	applied voltage (V)
a	area (m^2)
A_{cell}	area of cell
$E_{stiffness}$	average constrained stiffness (kPa)
CAN	Canadian dollar
q_a	capillary of flow rate (V/m per m^2)
k_e	coefficient of electro osmotic permeability (m^2/Vs)
k_h	coefficient of hydraulic conductivity (cm/s or m/s)
m_v	coefficient of volume compressibility (m^2/MN)
H_s	comparable height of surcharge (m)
C_1	cost of electrodes per unit length ($\$L^{-1}$)
C_3	cost of electrodes of the chemical agent ($\$M^{-1}$)
C_4	cost of treatment per unit volume of the electrolyte (effluent) collected ($\$L^{-3}$)
nA	cross-sectional area of a void
I	current (A)
U	degree of consolidation (%)
R_d	delaying factor (dimensionless)
DC	direct current
δ	distance between the wall and the centre of the plabe of mobile charge
x	distance to the cathode (m)
Q	drainage rate (cm^3/s)
σ^*	effective electric conductivity of the soil medium
u^*	effective ionic mobility of the ion (m^2 per sec-V)
C_2	electric energy cost ($ per kWhour)
$\in$	electrical energy requirements per gallon discharged (kWh)
$\frac{dV}{dL}$	electric field, or known as voltage gradient (V/m)

V(x)	electric potential at position x relative to the potential at the cathode at x = 0 (V)
k_i	electro osmotic transport efficiency (cm^3/Ampere-hours)
L	electrode spacing (m)
R_e	electrode radial spacing (m)
E	energy consumption (kWh per m^3)
u_a	excess pore pressure (kN/m^2)
F	Faraday's constant (96485 C/mol-electron)
α	factor depending upon the stoichiometry of the neutralizing reaction, dimensionless;
Fe_2O_3	ferum (III) oxide (%)
ν	flow velocity
Q_h	flow rate induced by hydraulic gradient
Q_e	flow rate induced by voltage gradient
η	fluid viscosity (Ns/m^2)
i_e, i_r	gradients
A	gross total cross-sectional area normal to the direction of flow (m^2)
A_{ineff}	ineffective area
u_o	initial excess pore pressure due to fill loading (kN/m^2)
L	length of the sample (m)
ΔL	layer thickness difference
w_L	liquid limit (%)
MHA	Malaysian Highway Authority
M_w	molecular weight of the neutralizing chemical (M/W)
H_e	negative pore water head generated by electro osmosis at x = L/2 (m)
Ψ	negative potential
N	number of capillaries (non dimensional)
F_1	number of electrodes per cell
N	number of electrodes per unit surface area ($\$L^{-2}$)
ε	permittivity of fluid (F/m)
w_p	plastic limit (%)
I_p	plasticity index (%)
PVC	polyvinyl chloride
u	pore water pressure (kN/m^2)
ζ	potential across the capillary, or known as zeta potential (V)
Ψ_o	potential at the surface

B	reactive transport rate of a species relative to the electric conductivity of a medium
v	sample volume (L)
SiO_2	silicon oxide (%)
G_s	specific gravity
c_v	Terzhagi's coefficient of consolidation (m^2/year)
T_v	time factor (non dimensional)
C_{total}	total costs per unit volume of soil to be treated ($\$L^{-3}$)
h	total hydraulic head (m)
t	total time (h)
Q	total water expelled (cm^3)
Q	total volume flow rate (m^3/s)
γ_w	unit weight of water (kN/m^3)
C_5	variable daily cost (monitoring, insurance, rentals, etc) ($\$L^{-3}T^1$)
v_h	velocity of water induced by hydraulic gradient
v_e	velocity of water induced by voltage gradient
e_o	voids ratio (nondimensional)
ΔE	voltage difference
H_2O	water
w_c	water content (%)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Soft clays and peat soils are two kinds of soils which are known to have low strengths and low stiffnesses. The first is often a product of weathered material deposited in a marine environment; the second is derived from the decaying process of animals and plants. The mechanical characteristics of these soils are a function of their composition, history and current state. Engineering solutions have to be considered to alter these characteristics when building on or in these materials. These solutions range from permanent, hard solutions such as piled foundations, to time dependent improvement of the soil through consolidation. Piled solutions are often preferred as it reduces the risk of failure and excessive settlement but they are expensive and not sustainable given the use of primary resources. The alternative is to improve the ground using techniques such as preloading, often combined with prefabricated vertical drains and vertical sand drains; stone columns; mixing the soils with lime/cement (dry mixed method); stiffened columns; vacuum consolidation; and electro kinetics dewatering. A flow chart (Figure 1.1) developed by Bergado, et al. (1994) is a guide to the selection of the most appropriate ground improvement technique.

One method not shown on that chart yet has been in use for many years is that of electro osmotic consolidation in which water is forced out of the soil by passing an electric current through the soil between two electrodes. The technique is known to be successful at improving the mechanical characteristics but there are a number of challenges to overcome which means that the techniques has not been widely used. One of the key challenges is the breakdown of the electrodes with time stopping the process and contaminating the groundwater. Recent developments in electrodes have overcome these problems offering an alternative ground improvement technique.

An alternative approach is to use electro osmotic consolidation to create stiff soil columns within soft clay and combine that with a stiff granular layer to create a composite foundation. There is potential to use this composite foundation in soft clays in many parts of the world including Malaysia where much of the infrastructure of mainland Malaysia is built on the coastal plain.

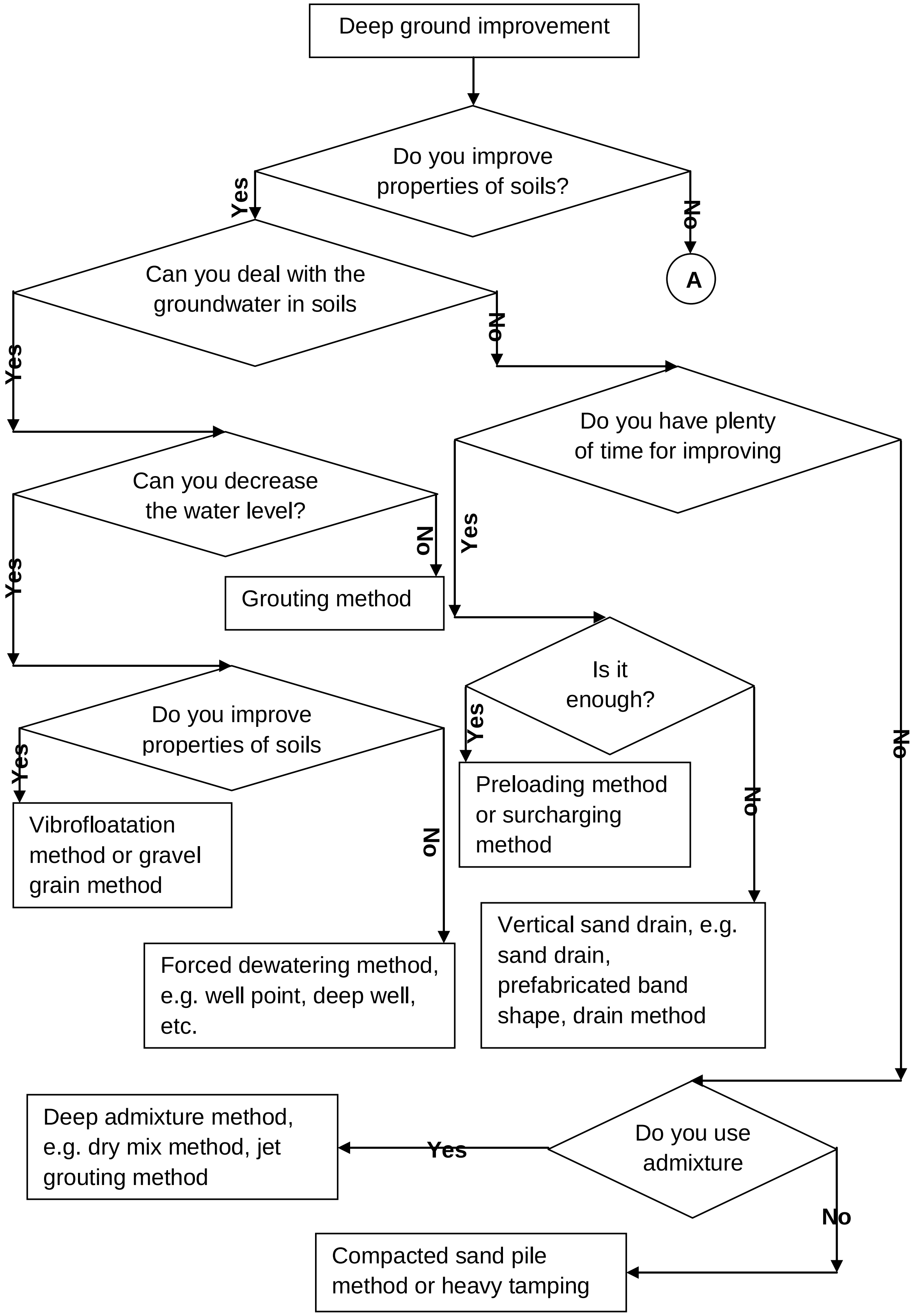


Figure 1.1 Flow chart to select appropriate deep ground improvement technique (reproduced from Bergado et al., 1994)

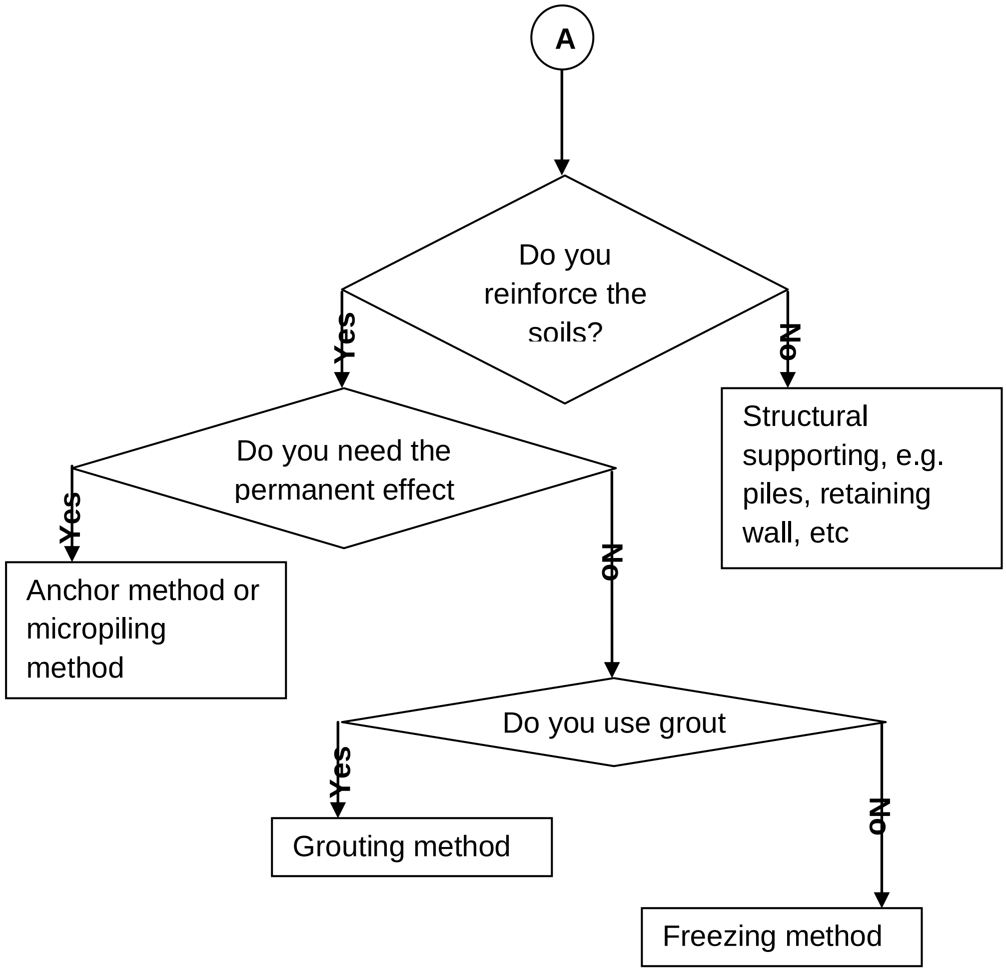


Figure 1.1 Flow chart to select appropriate deep ground improvement technique (reproduced from Bergado et al., 1994)

1.2 BACKGROUND TO THE PROBLEM

It is difficult to build on or in soft fine grained soils because of the pore pressures generated during loading or unloading and subsequent volume changes as the pore pressures dissipate. This can lead to catastrophic failure and excessive deformation. Yet these soils are common especially in floodplains where there is significant development of the built environment. A hierarchy is followed in order to develop on these soils as indicated in Table 1.1. The first solution, to excavate and replace, is the most costly and damaging to the environment; consolidation either by preloading or electro osmosis is the least damaging to the environment but there is a time element to consider.

The main advantage of electro osmotic consolidation over preloading is that there is no need to import fill and failure will not occur during ground improvement. Degradation of the electrodes and potential contamination of the ground water are no longer issues as a result of recent developments in electrically conductive polymers used as electrodes.

Table 1.1 The hierarchy for construction on soft clays

Technique	Description	Disadvantage	Advantage
Excavate and replace	The soft clays are excavated by mechanical means and either used as landscaping material or disposed to landfill. Granular material is used as a replacement	Cost of excavation and disposal of soft clay; stability of excavation; cost of fill and placement of fill; use of primary resources	Removes problem completely
Concrete, steel or timber piles	Piles are driven or bored through the soft clays into the underlying bearing strata.	Working platform for pile construction; potential negative friction on piles; material, transportation and installation costs.	Bypasses problem; provides permanent hard solution
Stone columns	Stone columns created by vibro compaction transferring the load into the underlying bearing strata.	Working platform for stone column construction; use of primary resources which may not be available locally; potential negative friction on stone columns; potential failure of stone columns due to insufficient lateral support	Bypasses problem;
Lime/cement columns	Lime/cement soil columns created by in situ nixing techniques transferring the load into the underlying bearing strata	Working platform for construction plant; use of manufactured material; potential contamination; potential negative friction on columns.	Bypasses problem; reduced quantity of imported material

Chemical stabilization	Chemicals mixed in place or injected into the soil to react with the water thus reducing the water content or cementing the soil particles together.	Working platform for construction plant; use of manufactured material; potential contamination	Uniform modified/stabilised soil with known properties
Preloading	Imported fill used to increase the pore pressures which dissipate with time as the clay consolidates	Cost of importing fill and disposing of that fill; instability of preload; time for consolidation to occur; disposal of water.	Creates a permanent solution which relies on the improved properties of the soil
Electro osmotic loading	Create stiffened soil columns through electro osmotic consolidation	Working platform for construction plant; disposal of water; cost of electrodes and electricity; degradation of electrodes limits life of process	Creates a composite foundation using modified soil

1.3 OBJECTIVES OF STUDY

The aim of this work is to establish whether electro osmotic consolidation can be used to create a composite foundation in soft fine grained soils. The objectives of the programmes are:-

1. to undertake a critical assessment of the literature on the use of electro osmosis in geotechnical engineering;
2. To introduce the concept of osmotic piles which are created by vertically installed anodes and their part in a composite foundation in which a working platform spreads the load onto the soil reinforced by the osmotic piles;
3. To establish from the literature review the criteria that governs the behaviour of the composite foundation;
4. To design an experiment to determine the relationship between the performance of the composite foundation and applied load using the criteria established from the critical assessment of the literature;
5. To undertake experiments to determine the relationships between the treatment needed to create the osmotic piles and the improvements in the mechanical characteristics of the soft clays.

1.4 THE COMPOSITE FOUNDATION

The composite foundation is a combination of electrically stiffened soil columns with a granular capping layer. This is comparable to a foundation created with stone columns but it avoids the use of primary resources and relies on the intrinsic strength and stiffness of the soil. For those reasons it is considered a sustainable solution.

Electro kinetic vertical drains installed on a grid pattern create a number of stiffened soil columns. The drains acted as electrodes and by passing current between the electrodes it is possible to dewater the soil through a process of osmosis thus increasing the strength and stiffness of the soil. The grid can be varied to determine the optimum array which, with a granular raft to spread the load of the structure onto the soil columns, should produce an economical composite foundation.

1.5 SCOPE OF THESIS

The thesis contains six chapters and seven appendices.

Chapter 2 presents the literature review of Peninsular Malaysia soft clay soils showing the relationship between the distribution of these soils and the built environment; and the principle of electro osmosis and its application to geotechnical engineering.

Chapter 3 describes principles of the experiment used to validate the concept of osmotic piles. A description of the equipment and how it was used are presented.

The experimental results are presented in Chapter 4. It covers the effects of electrode spacing, time of treatment and voltage.

Chapter 5 draws together the results of the tests to make observations of how this technique can be used in ground improvement

Chapter 6 includes a summary of the studies, conclusions and recommendations for future study.

Appendix A summarises in tabulated forms. It briefly describes the soil improvement approaches about its principle, most suitable soils and types, suitable depth that can be installed by certain types, and also discusses its advantages and limitations.

Appendix B and Appendix C describe the range of particle sizes for various soil improvement approaches, and outlines of several of the earlier electro osmotic experiments.

Appendix D compiles of the drawing details for the electro osmotic chamber and certain important parts.

Appendix E describes the summary data for the tested samples under series of time of treatment, numbers and arrangement of electrodes, and different applied voltage. Analyses graphs are presented, i.e., water expelled versus time curves, settlement*area versus water expelled, water expelled and current versus time, and also water content versus distance.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This thesis describes the potential of using electro osmotic piles in Peninsular Malaysia. The review centres around three major topics; Peninsular Malaysia soft clay soils, electro osmosis piles, and effective and efficient of electro osmosis treatment.

2.2 PENINSULAR MALAYSIAN SOFT CLAY SOIL

In Peninsular Malaysia, soft soil can usually be found along the west coast, i.e., in Johor, Melaka, Port Kelang, Alor Setar and some parts of the east coast, such as Port Kuantan and Terengganu. Soft soil thickness in these areas can reach 40 m in thickness. Figure 2.1 shows the soft deposits distribution in Peninsular Malaysia.

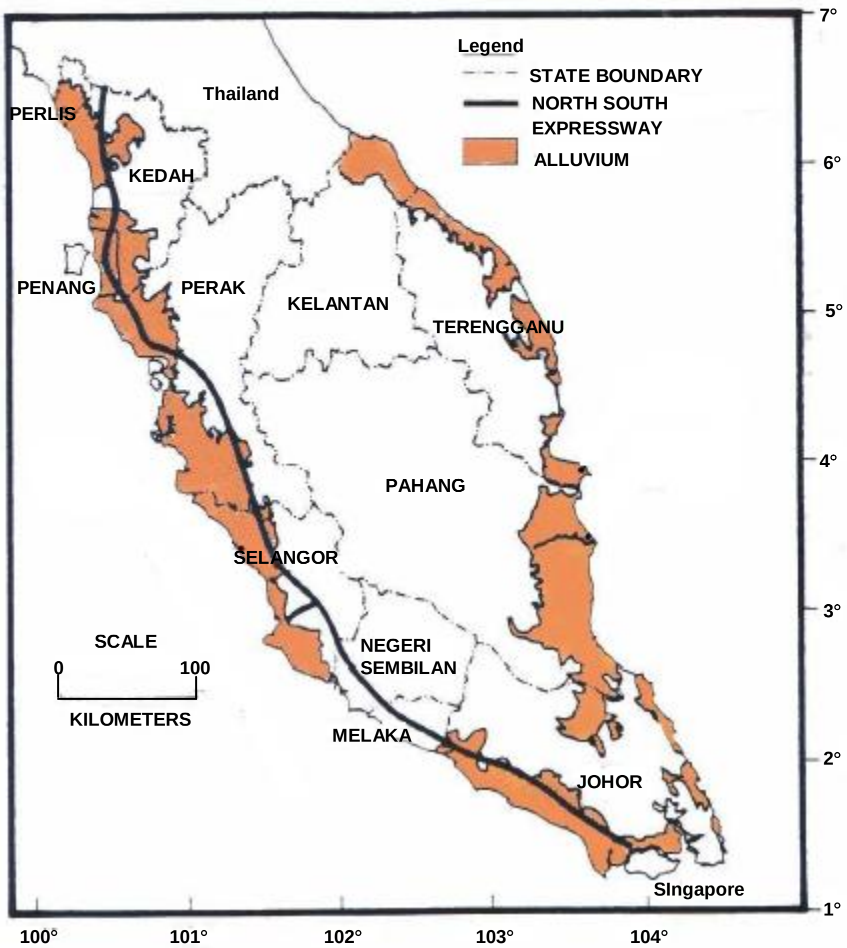


Figure 2.1 Soft deposits distribution in Peninsular Malaysia map (Malaysian Highway Authority, 1989)

Due to industrialisation and drastic urbanisation growth, the majority of future planned construction projects are located on these soft soil deposits. These coastal areas consist of soft soils alluvial sediments which originated during the Cainozoic era. The time scale would probably 1.5 million years ago. This area covers 20% of the Peninsular Malaysia (Aziz, 1993).

Coz (1968, 1970) studied the formation and engineering characteristics of clay soils in East Asia. Most of the primary research works that were carried out on the clay soils in Malaysia were focussed on construction projects. Among these was primary research into the Muda Irrigation Planning in northern part of Peninsular Malaysia. Ledgerwood (1961) investigated geology in the area, whilst Taylor and James (1967) discussed the geotechnical characteristics. Howell (1970) explained the methods used to construct a canal and a dam in these soils.

More detailed studies of soft clay behaviour were carried out by investigating wooden pile installation in soft clay soils in the Prai area (Ting and Chan, 1971). Ting *et al*. (1975) who analysed pile behaviour in a similar area reported at least 6.0 m thick of fine and coarse sand layers separating the soft sediment layers at the upper layer and the hard sediment at the bottom layer.

In 1977, Ting and Ooi carried out research into coastal clay soil engineering at four different locations. One aspect of their studies was the sensitivity of the soft clay soils in Peninsular Malaysia which were classified between medium sensitive and quick types.

A trial embankment was constructed in Muar as part of the North-South Highways project and in Kuala Perlis in the early 80's. These crossed over soft clay soils along the west coast of Peninsular Malaysia. The Malaysian Highway Authority (MHA) used several soil improvement techniques (MHA, 1989).

In another major study, Abdullah and Chandra (1987) extended the research works on soft clay engineering to include the east coast of Peninsular Malaysia for the first time. They found that these soils displayed different behaviour and characteristics from the west coast of Peninsular Malaysia. Kobayashi *et al*. (1990) also investigated the marine soft clay soils in Singapore, Malaysia and Indonesia. They concluded that the soft clay soils in these three areas were widely distributed.

2.2.2 Soft clay definition

In geotechnical engineering, clay soil is a type of soil that contains particles which are less than 2 μm. Clay is formed from the weathering process, hydrothermal activity or through settled sediment. According to the Unified Soil Classification System, clay is a fine material of soil of which 50% weight can pass through a No. 200 or US standard of 0.074 mm sieve. Clay contains clay particles usually in the shape of platelet, when examined under the scanning electron microscope. Normally consolidated clay are usually soft.

Soft clay soil is classified as a soil that has unconfined shear strength between 25 kPa and 50 kPa. It is a fine natural material which produces plasticity characteristics when it is mixed with water, i.e., non-reversible changes of shape when forces are applied. Soft clay soils also have very high water content of over 85%. It has also been found to be sensitive to compression and can easily be disturbed (Brand and Brenner, 1981).

2.2.3 Soft clay soil profiles in Peninsular Malaysia

Abdullah and Chandra (1987) claimed that the soft clay soil thickness varied as shown in Table 2.1. This table shows that the soft clay soil stratum on the west coast has a thickness from 5 m to 35 m whilst on east coast it varies 3 m to 20 m.

Table 2.1 Soft clay soils thickness in Peninsular Malaysia (Abdullah and Chandra, 1987)

Locations		Thickness (m)
Perlis – Kedah	West	5 – 12
Sungai Kedah dam area		8 – 12
Alor Setar airport area		12
Prai area and Pulau Pinang bridge		12 – 25
along the Butterworth – Changkat Jering highways		5 – 15
Sungai Kerian area		10
Bagan Datoh road – Teluk Intan		5 – 11
Port Klang area		8 – 30
Kg. Acheh area – Port Merin	East	3 – 7
West Johor agricultural development projects area		10 – 35
Kuantan area		3 – 20
Sungai Kuantan bridge area		5 – 12
Port Kuantan area		3 – 15
Chukai area		4 – 8
Semerak – Kemasin area		3 – 10

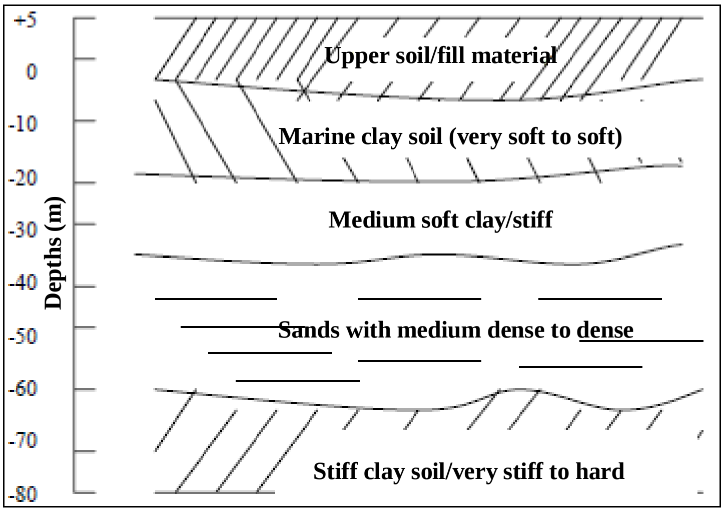


Figure 2.2 Soft clay soils profile in Peninsular Malaysia (Abdullah and Chandra, 1987)

Figure 2.2 shows a typical profile of soft clay in Peninsular Malaysia. The upper layer with thickness of 5 m to 7 m is the upper soil or fill material, and below it there is typically 18 m of soft to very soft marine clay soil. The next layer is medium soft clay or stiff clay which is approximately 15 m thickness. Below that there are 25 m and 20 m of medium dense to dense sands, and stiff clay and very stiff to hard clays.

Soft clay soils are split into upper clay soil and lower clay soil shown in Table 2.2. According to Aziz (1993), the upper and lower soft clay soil layers occurred because of sea level changes in the Pleistocene era. This could be due to weathering. These changes produced thin sand layers which divided those upper and lower soft clay soils. Balasubramaniam *et al*. (1985) concluded that soft clay soils were generally light gray in colour and contained sea shells fragments. Their classification can be seen in Table 2.3.

Table 2.2 Upper and lower depth ranges for west coasts deposits of Peninsular Malaysia (Aziz, 1993)

Locations	Depth Ranges (m)	
	Upper	Lower
Kuala Perlis, Perlis	0 – 6	6 – 9
Alor Setar, Kedah	0 – 9	9 – 16
Prai, Juru, Pulau Pinang	0 – 12	12 – 22
Bagan Datok, Perak	0 – 11	11 – 22
Sabak Bernam, Selangorr	0 – 10	10 – 23
Port Klang, Selangor	0 – 11	11 – 20
Muar, Johor	0 – 9	9 – 18
Pontian, Johor	0 – 10	10 – 17

Table 2.3 Upper and lower depth ranges for west coasts deposits of Peninsular Malaysia (Aziz, 1993)

Soil layer	Thickness (m)	Colour	Remarks
Upper	2 – 6	Light grey or light brown	Reclamation sand with shell fragments or upper soil
↓	10 – 32	Grey greenish or grey	With loose sand layers 2 m to 3 m thick, varying amount of shell and organic matter
↓	3 – 11	Light brown or brown greyish	With fine sand bands
↓	4 – 25	Light grey or grey yellowish	Not homogeneous, with medium or stiff clay layer, stiff or very stiff clay stiff layer
Lower	-	Light brown or grey	Varying from peat bands to sandy gravel bands

2.2.4 Problems with soft clay soils

Soft clay is a fine-grained soil which can undergo significant volume changes even with lightly loaded structures. The water content can be greater than the liquid limit. The amount of water that can be held by a soil increases with the clay content in the soil. These clays are strongly influenced by the presence of water due to their high surface activity (Miura and Ngaraj, 2001).

These soils can exhibit extreme variations such as heaving and loss of shear strength and settlement and shrinkage as the water content alters. The presence of organic matter also may increase the water content considerably. However, when a soil contains an appreciable quantity, say 20% or more by weight of material finer than 63 μm size, a description based on water content alone is insufficient. Atterberg's limits are empirical and somewhat arbitrary divisions, in term of water content between states of clay. The water content between the liquid and plastic states is known as the liquid limit. The water content between the plastic limit and semisolid state is the plastic limit. If the water content of natural firm clay is allowed to increase, the clay will soften and become more compressible. The plasticity of such a fine soil has an important effect on engineering properties such as shear strength and compressibility.

Generally, high plasticity clays are more compressible and tend to consolidate more over a period of time under load than clays of low plasticity. Additionally, according to Head (1992), high plasticity clays are more difficult to compact when used as a fill material.

2.2.5 Soil improvement in general

Malaysia has seen rapid economic expansion which requires additional land for housing, building and other related infrastructure in the coastal strip which is underlain by soft clay soil. It has been a normal practice to implement a structural solution using piles, or substitute inappropriate materials, i.e. soft clay soil, with properly compacted fill.

For construction in areas that are distributed with layers of non-engineered soil or natural deposits of inappropriate soils, the common method is to implement a solution with structural support or to eliminate and substitute the inappropriate materials with properly compacted fill. For a case of construction on an embankment, the solution would be partially structural where the positioning of piles are maintained with caps or rafts. The solution with substructural construction is too costly.

Coarse or fine granular materials can be used as a backfill material if the ground water level is below the excavation. Full replacement is appropriate in construction areas where they is a shallow deposit of inappropriate materials. Typically it can be used up to 3 m thick. For exceptional cases, it can be used up to 6 m thick provided the soil shear strength of the side slopes is adequate. In the main, the excavation could be able to retain side slopes of 1:4 in the problematic soils. For thicker layers of problematic soils it is more difficult to retain the stability of side slopes, to handle the soils and prevent the excavation from flooding. There is also the difficulty of disposing of the excavated materials especially in the municipal areas and the cost of imported materials. The viability and cost of this approach is questionable.

Several trials of ground improvement have been successfully implemented in Southeast Asia. They are: vertical drains and dynamic compaction in international airport at Changi, Singapore in 1975; sandwick drains in Bangkok Clay, in Bangkok, Thailand; vacuum consolidation in Bangkok, Thailand; vibro compaction in Pasir Panjang, Singapore; dynamic replacement columns in Kuala Lumpur, Malaysia; stone column in Hong Kong; grouting for a dam in Malaysia, transit system in Singapore, sewerage in Taipei city, and trial tunnel in Kowloon Peninsula; lime stabilisation for an embankment in Thailand and Singapore; electro osmosis in Singapore; reinforced earth for an embankment wall in Hong Kong, retaining wall to a slope in Johor, road embankment wall in Kuala Lumpur and Penang, Malaysia; soil nailing for a transit station in Singapore; and geotextiles for a highways in Singapore, Malaysia and Thailand.

Yee and Ong (2006), Lee *et al*. (1985), and Eggestad (1983) highlighted several characteristics that influence the factors; (1) types of soil and soil states; (2) impact of the construction progression on adjacent structures; (3) environmental aspects; (4) construction period; (5) acceptance after the construction displacement; (6) rate of construction; (7) accessibility of backfill matters; (8) expenditure and maintenance; (9) available equipment; and (10) local practice.

The alternative to excavate and replace the ground or provide a full structural solution is to improve the ground. Soil improvement includes densification, cementation, reinforcement, soil modification or substitution, drainage and other water content controls. An outline of existing methods for improving cohesive soils, can be seen in Table 2.4, and other types of soil improvement approaches can be seen in APPENDIXES A. Table 2.4 is a review of the processes and impact of the methods of improving cohesive soils and the range of soil particle sizes applicable for these soil improvement approaches is displayed in Table 2.5.

Table 2.4 Survey of existing methods for improving cohesive soils (after Eggestad, 1983)

Method	Basic effect				Primary improvement			Curing time days			Equipment size		
	Chemical	Physical	Mechanical	Structural	Bearing capacity	Rate of consolidation	Permeability	0 ~ 10	10 ~ 100	100 ~ 1000	Small	Medium	Large
Columns of stab. soil	●		○	●	●	○		○	●	○		●	○
Columns of pure chemical	○		●		●				●	○	●	○	
Hydraulic injection	●		○		●				●	○	●		
El. chemical injection	●	●			●				●	○	●		
Electro osmosis	○	●			●				●		●		
Freezing		●			○		●		●		○	●	
Heating		●			●			●	○		○	●	
Grouting			●				●	●			●		
Dynamic consolidation			●		●	○	○		●	○		○	●
Preloading			●		●					●	○	●	
Vertical drains			●			●			●	○		●	○
Stone columns			○	●	●	○		●	○			●	○
Embankment piles				●	●			●	○			●	○
Micropiles				●	●			●			●	○	
Nailing				●	●			●			●		
Reinforced earth				●	●	○		●			●		

●: primary; ○: secondary. (1) Chemical effects: chemicals introduced into the soil by mixing, flowing or diffusion, (2) Physical effects: freezing, heating or electric treatment, (3) Mechanical effects: loading, pore pressure release, etc, (4)Structural effects: all kinds of reinforcing elements, (5) Bearing capacity: includes also reduced compressibility, (6) Rate of consolidation: where increasing the rate itself is the objective, (6) Permeability: where an increase or decrease of permeability is the objective, (7) Curing time: the time necessary for a major part of the effect to develop, (7) Small equipment: equipment that can be lifted by a normal building crane, (8) Medium equipment: ordinary self moving construction equipment accessible at most sites, (9)Large equipment: very large or highly specialized equipment.

Table 2.5 Range of particle sizes for various soil improvement approaches (reproduced from Hausmann, 1990, Lee *et al*., 1985)

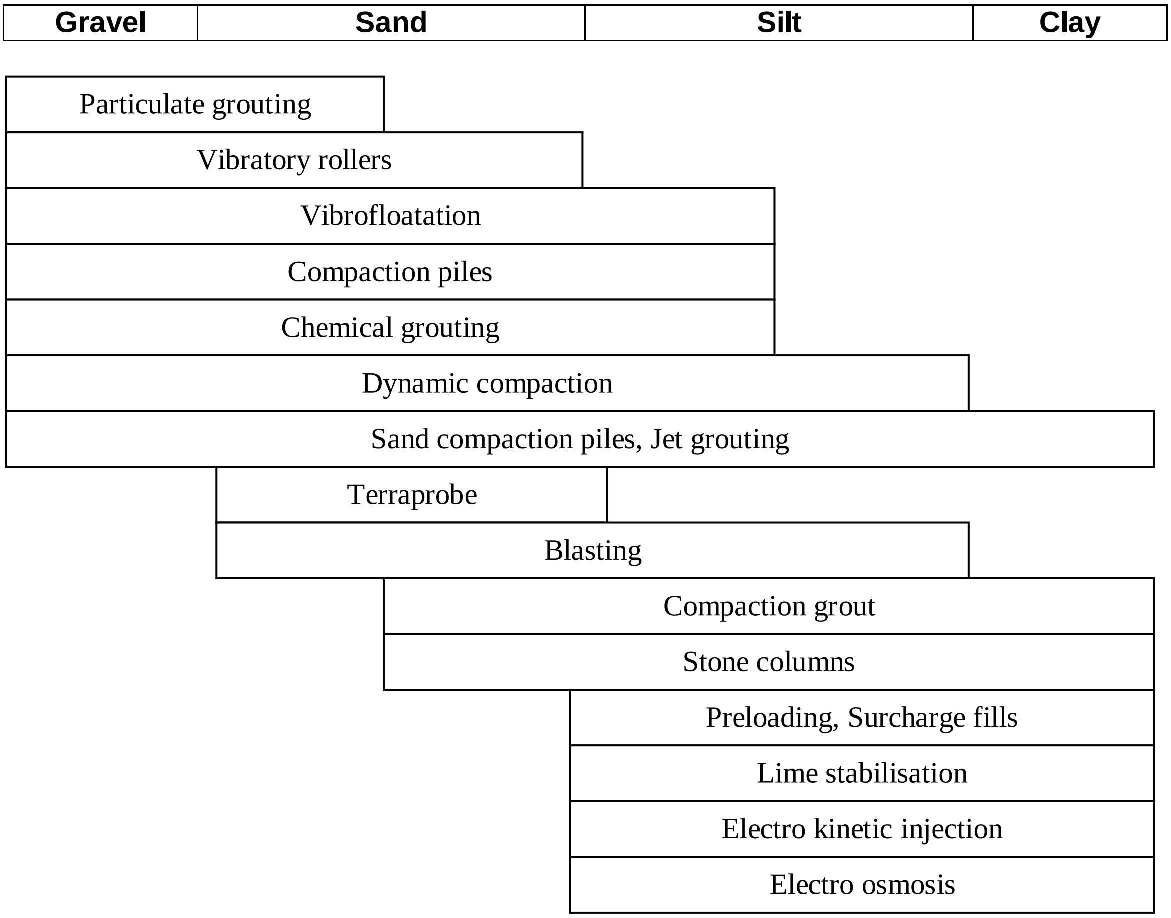


Table 2.4 shows that almost all of the methods of improvement increase the bearing capacity as a primary improvement. Table 2.5 shows that the electro osmosis method can be apply within silt and clay particle sizes. There are other types of improvement for these soils including preloading, surcharge fills, lime stabilisation, electro kinetic injection, stone columns, compaction grout, and sand compaction piles and jet grouting.

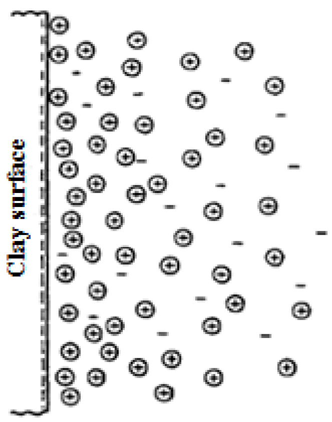
Although there are various types of soil improvement methods available the research is particularly interested in electro osmosis because there a lack of expertise regarding this type of improvement and it has not been implemented in any construction in Malaysia.

Hence, the scope of this study is to implement electro osmosis to stiffen soft clay soils which alters them from normally consolidated clays to overconsolidated clays leading to an increase in stiffness. Electro osmosis primarily affects its physical characteristics; chemical effects are secondary (Table 2.4). It only requires 10 days to 100 days to function and limited equipment size for installation purposes.

2.3 ELECTRO KINETIC OCCURRENCE IN CLAYS

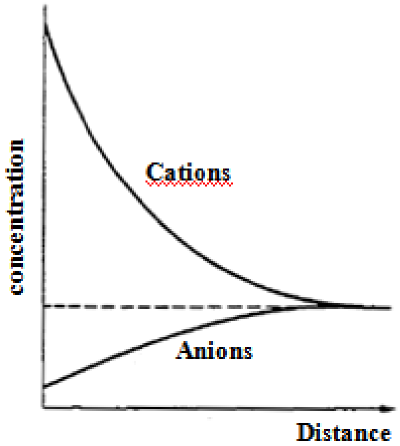
Mitchell (1993) states that clay particles are crystalline particles. Das (1999) states those clays minerals are principally hydrous alumina silicates. Mitchell (1993) notes that, for clay minerals, there is link between the clay mineralogical composition and the engineering properties. The clay particle surfaces are negatively charged due to replacement of isomorphous and the existence of fragmented bonds. Lambe (1958), through his studies on Guoy-Chapman theory, showed that when clay particles were in water, the adsorbed cations and the diffuse double layer on a surface will produce neutrality electrical. The established distribution for adjoining ions to a negatively charged clay particles is illustrated in Figure 2.3. In 1993, Mitchell maintained that the electro kinetic property for a mineral in the main is governed by a diffuse double layers structure on a wet clay surface.

Electro kinetics describes the behaviour of fluid and particles in an electric field. An external force acts on the double layer to generate movement. Electro kinetics includes electro osmosis, the movement of water; which is the most interesting for ground improvement as it can lead to a reduction in water content and hence an increase in stiffness.

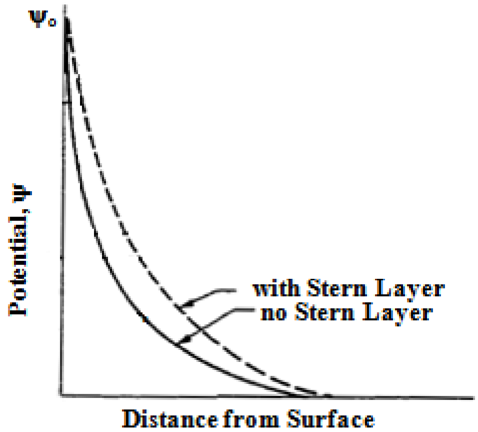


(a)

Figure 2.3 Variation of electrical potential with distance from a charged surface (reproduced from Mitchell, 1993)



(b)



(c)

Figure 2.3 Variation of electrical potential with distance from a charged surface (reproduced from Mitchell, 1993)

Figure 2.3(a) shows the distribution of cations and anions near to the surface of a clay particle. The concentration decreases with distance from the surface (Figure 2.3(b)). The Stern Layer is the term for those positively charged ions immediately adjacent to the clay surface (Figure 2.4). There is a gradual increase in the number of negatively charged ions with distance from the surface of the clay particle through the diffuse layer. Thus there is a drop in potential with distance from the surface of the clay particle (Figure 2.3c). The Stern Layer, predicted from the Guoy-Chapman theory, contributes to the inter particle repulsion (Mitchell, 1993). The Stern Layer remains attached to the clay particle; the diffuse layer is mobile thus forming a slip plane at the boundary with the Stern Layer. The potential at the slip plane governs the movement of the ions in the diffuse layer.

Figure 2.4 is a combination of the figures in Figure 2.3. It shows that the double layer structure on the surface of the clay particles is separated from the diffuse layer by the

Stern layer. The diffuse layer is a layer of free ions which move in the fluid under the influence of electric attraction.

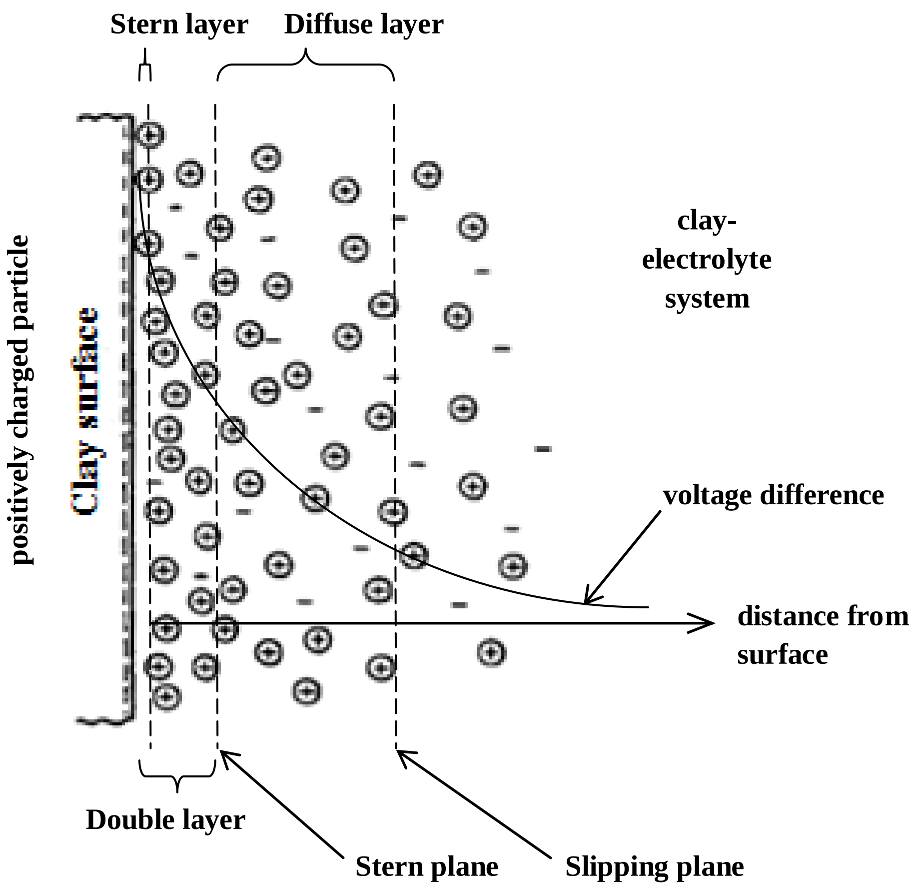


Figure 2.4 Double layer structures near the surface of the positively charged particles

The double layer leads to an electrically charged surface. This electrically charged surface then creates an electrostatic field, which affects the ions in the clay-electrolyte-system. By combining the thermal motion of the ion, the electrostatic field and thermal motion will develop a counter charge. This counter charge produces a net electric charge similar in magnitude to the net surface charge. However, the net electric charge has the opposite polarity to the net surface charge. As a result, the whole system is electrically neutral, where the cations and anions curves overlapped at some point far from the clay surface. This can be seen in Figure 2.3(b)..

If a voltage difference is applied across two adjacent clay particles, then the negative ions move towards the positive terminal (+) and positive ions towards the negative terminal (-). This can be seen in Figure 2.5. These two figures explain the movement of water, noted as velocity distribution, from the positive terminal to the negative terminal through the wall capillary.

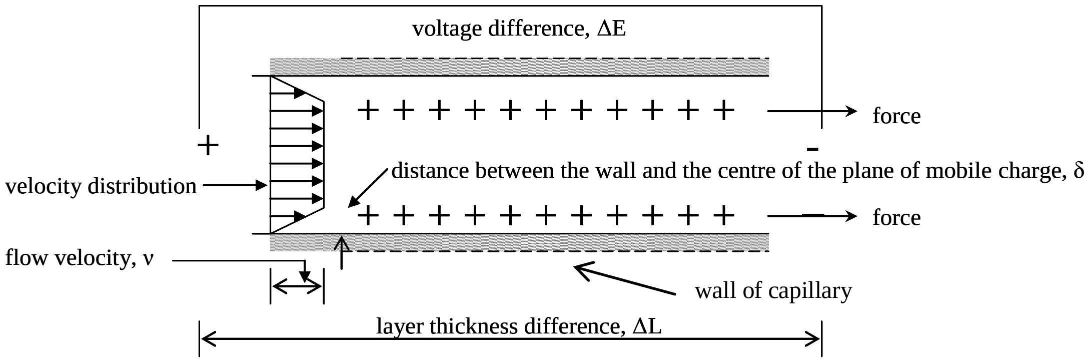


Figure 2.5(a) Helmholtz-Smoluchowski model for electro kinetic phenomena (reproduced from Mitchell, 1993)

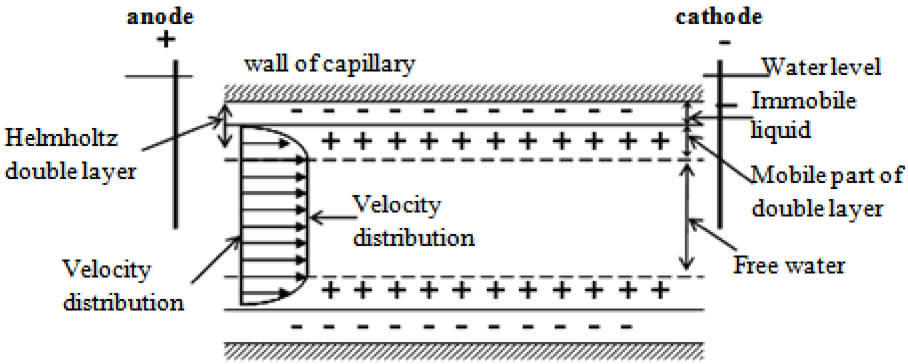


Figure 2.5(b) Electro osmotic flow in rigid-straight capillaries (reproduced from Casagrande, 1952b)

The discovery regarding the movement of water molecules with the presence of voltage difference was made by Reuss in 1807 and Helmholtz in 1879 (Mitchell, 1993, and Casagrande, 1952(b)). Reuss discovered that the water molecules moved through the capillaries towards the negative terminal with the application of voltage differences. Voltage difference marked ΔE in Figure 2.5(a) and the transportation of water molecules is via the mobile part of double layer in Figure 2.5(b). In Figure 2.5(b), Casagrande (1952(b)) labelled the mobile part of the double layer as the Helmholtz double layer. The idea of this double layer named after Helmholtz was from Helmholtz's theory which was an improvement on Reuss's theory of 1879. The detail of this mathematical model is described in Mitchell (1993).

The double layer lies between the wall of the capillary and free water. There are two parts to this layer. Adjacent to the wall of the capillary, there is a very thin layer which is the Stern layer. This very thin layer labelled as water immobile liquid on Figure 2.5b is negatively charged. The other layer within the double layer, or the thicker layer is known as the mobile part of the double layer. This thicker zone of double layer is developed when the voltage difference is applied to the system. As a result, the transportation of ions to the opposite electrode takes place. This process is known as electro migration. At the same time the water molecules are pushed from the positive terminal to the negative terminal, this process is known as electro osmosis.

Electro osmosis is the movement of liquid induced by an electric field, while electro migration is a process of the movement of ions under the influence of an electrical potential difference. In clays the liquid is the pore fluid, usually water, and the conduit is the connected pore space between the particles. This Stern layer, as can be seen in Figure 2.4, only exists with the presence of a voltage difference (Mitchell, 1993, and Casagrande, 1952(b)).

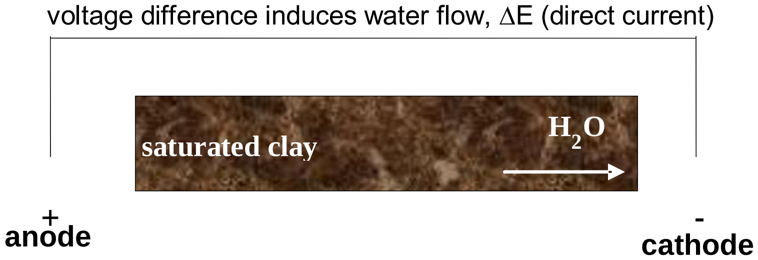


Figure 2.6 Electro osmosis (reproduced from Mitchell, 1993)

The voltage difference, as can be seen in Figure 2.6, creates electro osmosis flow as water moves from the positive terminal to the negative terminal. The velocity distribution of the free water, as in Figure 2.5, is constant. Two factors contribute to this constant rate. The first one is due to the cylinder of free water within the system. The second factor is due to the electro migration process; that is the transportation of ions to the opposite terminal (Figure 2.5). Electro migration means the movement of charged particles like clay is relative to its concentration, as an example during gravitational settlement. The effect it produces is a potential difference. This is due to viscous drag from water which retards the movement.

There are three other processes taking place in addition to electro osmosis and electro migration. There are the streaming potential, electrophoresis and sedimentation potential and Table 2.6 summarises the definitions of these three terms.

Table 2.6 Streaming potential, electrophoresis and sedimentation

definitions (reproduced from Mitchell, 1993)

Terms	Definitions
Streaming potential	The difference in electric potential between a diaphragm, capillary, or porous solid and a liquid that is forced to flow through it
Electrophoresis	The migration of charged colloidal particles or molecules through a solution under the influence of an applied electric field usually provided by immersed electrodes
Sedimentation	The process of depositing sediment

2.4 ELECTRO OSMOSIS

2.4.1 The theory of electro osmosis

When a direct current is applied to an electrolyte solution, cation or positive ions will move to the cathode and anion or negative ions will move to the anode. Water molecules will be dragged by the ions moving in the electric double layer due to the electro osmotic process. There are number of theories to explain the electro osmotic phenomena.

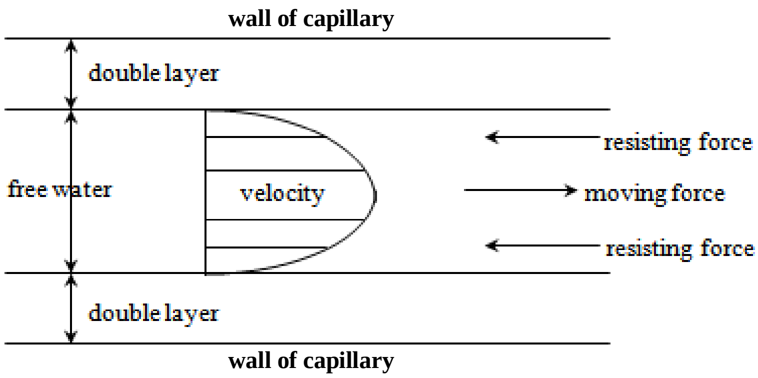


Figure 2.7 Hydraulic flows in a capillary (reproduced from Casagrande, 1952(b))

Figure 2.7, based on Figure 2.5, shows a simple interpretation of the electro osmotic flow of water. The Helmholtz-Smoluchowski's theory states that the rate of water flow caused by electro osmosis is governed by the electrical forces which results in the motion of water and the friction due to the double layer. Therefore, the velocity is given by:

$$\nu = \frac{\varepsilon\zeta}{\eta}\frac{dV}{dL} \tag{2.1}$$

where:
$\frac{dV}{dL}$ = electric field, or known as voltage gradient, unit in V/m;
ζ = potential across the capillary, or known as zeta potential, unit in V;
ε = permittivity of fluid, unit in F/m; and
η = fluid viscosity, unit in Ns/m^2.

Note that typical units are given. As Mitchell (1993) states: "for most cases in clay, the values of ζ are in the range of 0 mV to 50 mV and the charge of the mobile ions is positive, plus the lowest values are associated with excessive pore water salt concentrations". For a single capillary for area of $a = \pi r^2$, where r is the radius of the capillary. The flow rate, q_a, is:

$$q_a = \nu a = \frac{\varepsilon\zeta}{\eta}\frac{dV}{dL}a \tag{2.2}$$

where:
q_a = capillary of flow rate, unit in V/m per m^2; and
a = area, unit in m^2.

For a bunch of N capillaries of radius, r^2 within the total of cross-section area, A (m^2), grossly normal to the flow direction, the total volume flow rate, Q would be:

$$Q = Nq_a = \nu N\pi r^2 = \frac{\varepsilon\zeta}{\eta}\frac{dV}{dL}N\pi r^2 \tag{2.3}$$

where:
Q = total volume flow rate, unit in m^3/s; and
N = number of capillaries, non dimensional.

In a porous medium, the cross-sectional area of a void is nA, which must be equivalent to $N\pi r^2$, consequently equation (2.3) be converts into equation (2.4):

$$Q = \frac{\varepsilon\zeta}{\eta}\frac{dV}{dL}\eta A \tag{2.4}$$

Casagrande suggests: "by analogy with Darcy's law, the relationship between the volume flow rate, Q, and the imposed gradient $\frac{dV}{dL}$, for a porous medium defined in equation (2.4) may be re-defined as (Casagrande, 1952b: 289; 1949: 161):

$$Q = k_e \frac{dV}{dL} A \qquad (2.5)$$

where:
k_e = coefficient of electro osmotic permeability, unit in m^2/Vs; and
A = gross total cross-sectional area normal to the direction of flow, unit in m^2.

The coefficient of electro osmotic conductivity, k_e, is a characteristic of a porous medium, and is the average linear hydraulic flow velocity under a unit voltage gradient (Mitchell, 1993). It resembles the hydraulic conductivity which is an average linear hydraulic flow velocity under a unit of hydraulic gradient. The coefficient of electro osmotic conductivity, k_e, for Helmholtz-Smoluchowski's model is:

$$k_e = \frac{\varepsilon \zeta n}{\eta} \qquad (2.6)$$

The coefficient of electro osmotic conductivity, k_e, is not dependent on the pore size. This is unlike the coefficient of hydraulic conductivity, k. k_e depends on the zeta potential, ζ. The zeta potential has a very low value, and effects k_e, the k_e frequently reacts actively in the pore fluid if the pore fluid contains a very high salt concentration (Mitchell, 1993). Numerous researchers have studied electrokinetic reactions with various types of soils to resolve the k_e value. Table 2.7 summarises the published data. It shows that for most soils k_e varies between 1 x 10^{-5} cm^2/sV and 1 x 10^{-4} cm^2/sV. The value of 5 x 10^{-5} cm^2/sV was put forward by Casagrande (1952b) as a typical value for all soils. According to Mitchell: "measurement of k_e is made by determination of the flow rate of water through a soil sample of known length and cross section under a known electrical gradient" (Mitchell, 1993).

Table 2.7 Coefficients of electro osmotic permeability, k_e

No	Researcher and Materials	w_c (%)	k_e in 10^{-4} (cm^2/sV)	k_h (cm/s)*
Mohamedelhassan (1998)				
	Marine Sediment, Korea	65.5 ~ 127	0.3373 ~ 0.6289	5.28 x 10^{-8} ~ 3.44 x 10^{-7}
		81.3 ~ 142.7	0.6118 ~ 0.8082	6.118 x 10^{-7} ~ 8.082 x 10^{-7}
		80.9 ~ 143	0.4822 ~ 0.6591	1.63 x 10^{-7} ~ 4.11 x 10^{-7}

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