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Electrokinetic Dewatering and Consolidation of Dredged Marine Sediments

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Special thanks to my parent for their supports.

Abstract

Large amounts of marine sediments are produced every year as a result of capital and maintenance dredging works at major ports and these materials must be disposed of. Reuse of these dredged marine sediments for land reclamation is a sustainable and responsible method of disposal management. When the dredged sediments are utilized as a fill material in reclamation sites and are pumped into paddocks, there are two key concerns: 1) whether there is adequate storage capacity at the site 2) workability of the material. Since the dredged marine sediments possess a high water content, typically more than 250% and therefore are in the form of a slurry, self-weight settlement can take many years to complete. This is also due to the low permeability nature of the sediments. To improve the drainage of water and the settlement of these dredged muds, soil stabilization methods such as prefabricated vertical drains and vacuum preloading are commonly used. However, application of these methods is still time consuming and clogging during vacuum consolidation can be a limitation of this technique.

In this study the potential application of electrokinetic stabilization to improve the geotechnical properties of dredged mud in land reclamation areas is investigated as an alternative treatment method. In essence, electrokinetic stabilization is the application of electric potential to the soil through electrodes. When electric current occurs, the pore water flows from the anode to the cathode due to electroosmosis, soil particles move due to electrophoresis, and ions move toward the opposite charged electrode due to electromigration. The combination of all these three phenomena result in favourable and permanent changes in the soil. Electrokinetic stabilization is an environmentally friendly and time efficient method, however, a lack of standard design guidelines draws the attention of the geotechnical engineers away from this method.

In this study, key parameters influencing the efficiency of electrokinetic stabilization are investigated with the aim of maximizing the settlement of the dredged mud. For this purpose, a series of laboratory experiments have been undertaken to explore: (1) the most desirable electrode configuration, (2) effect of electrode materials, (3) the effective type and magnitude of the applied electric potential, and (4) the alteration of physiochemical properties. It is concluded that firstly, dredged marine sediments have significant potential to be improved by electrokinetic stabilization. Secondly, polyaniline coated anodes improve the technique at lower applied voltages. Thirdly, soil compressibility

reduces with depth, if the anode is placed at the bottom. Finally, higher settlement is achieved when the anode is placed at the bottom.

List of publications

Refereed Conference papers

Malekzadeh M., Lovisa J., Sivakugan N., Mathan B. (2014). "*Physiochemical changes during electrokinetic stabilisation of dredged mud*". 7th International Congress on Environmental Geotechnics (ICEG 2014). 10-14 November, Melbourne.

Malekzadeh M., Lovisa J., Sivakugan N. (2015). "*Consolidation of Cannington mine tailing*". The Changing Face of the Earth: Geomechanics & Human Influence- ANZ 2015 (ISSMGE). 22-25 February, Wellington.

Malekzadeh M., Sivakugan N. (2016). *"Assessing the use of Aluminium electrodes on the electrokinetic dewatering and stabilization of dredged mud slurries"*. Sustainability, Energy, and Geo-environment (Geo-Chicago). 14-18 August, Chicago.

Journal Articles

Malekzadeh M., Lovisa J., Sivakugan N. (2016). "*An overview of electrokinetic consolidation of soils*". Journal of geotechnical and geological engineering. 34 (1), pp. 1-18, DOI: 10.1007/s10706-016-0002-1. Published.

Malekzadeh M. and Sivakugan N. (2016). "*Effect of one-dimensional electrode configuration on consolidation parameters of dredged mud*". Marine Geotechnology and Georesources. Published.

Malekzadeh M. and Sivakugan N. (2016). "*Intermittent electro-consolidation of dredged sediments*". International journal of geotechnical engineering. Published.

Malekzadeh M. and Sivakugan N. (2017). "*Double drain electrokinetic stabilization of dredged mud using stainless steel electrodes and application of surcharge*". KSCE Journal. Published

Malekzadeh M. and Sivakugan N. (2017). "*Effect of polyaniline coated galvanized steel electrodes on electrokinetic sedimentation of dredged mud slurries*". Canadian Geotechnical Journal. Published

Malekzadeh M. and Sivakugan N. "*Effect of electrode placement on electrokinetic settlement*". Environmental geotechnics. Revised paper sent.

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List of symbols

A: are of the specimen
Cc: compression index
CR: compression ratio
Cr: recompression index
DDIC: double drain intermittent current
DM-AL: dredged mud aluminium
DM-CA: dredged mud coated anode
DM-GS: dredged mud galvanized steel
E: electric field intensity
e: Void ratio
e: void ratio
EC_{25}: electric conductivity on temperature factor
EC_t: electric conductivity on temperature factor
EO: electroosmosis
f_t: temperature factor
G_s: Specific gravity
I: Amps (electric current)
I: hydraulic gradient
j: current density
k: Permeability
k_e: electroosmotic permeability
k_h: hydraulic conductivity
L: distance between electrodes
LL: Liquid limit
P: Power consumption per unit volume
PL: Plastic limit
Q_e: rate of water flow due to electric current application
Q_h: water flow rate
r: sedimentation coefficient
RR: recompression ratio
SDCV: single drain constant voltage
SDIC: single drain intermittent current
Su: undrained shear strength
U: pore pressure

V: Volts (electric potential)

V_s: Settling velocity

W: energy consumption

γ_s: Unit weight of solids

γ_w: Unit weight of water

π: Intermittent ratio

ρ_s: Density of solid

ρ_w: Density of water

σ': effective stress

Ω: electrical resistivity

Chapter 1: Introduction

1.1 Introduction

Land reclamations are often created as a storage place for beneficial use of dredged marine sediments. Dredged marine sediments are ultra-soft soils possessing high fine content and high moisture content with low permeability due to which their self-weight settlement takes a long time to complete. Different methods of soil improvement such as chemical stabilization, prefabricated vertical drains, and vacuum preloading have been used to accelerate the consolidation settlement of the soil. Chemical stabilization using lime, fly ash, slag, and cement admixtures are used to improve the engineering properties of soft soils (Mitchell 1976, Supakij et al. 2004, Ho and Chan 2011).

To add admixtures to the soil, factors such as curing time, temperature, soil type, initial moisture content, mixing method to obtain a homogenous soil need to be considered. Overall, addition of the chemicals to the soil may increase the strength of the soil, however, this does not contribute to the higher settlement of the material as a result of which more storage capacity can be obtained. Therefore, chemical stabilization does not contribute to the increase in rate of settlement. Prefabricated vertical drains increase the rate of settlement by improving the drainage of the soil. However, the prefabricated vertical drains undergo a high deformation due to the high compressibility of soft soils. Vacuum preloading is another method for accelerating the settlement and drainage of soft soils with high water content. The vacuum preloading increases the effective stress of the soil by applying suction. This suction pressure drains and imparts a hydraulic gradient that prevents the generation of excess positive pore-water pressure (Indraratna et al. 2005). However, clogging of the drains during the vacuum preloading is not desirable.

Electrokinetic stabilization is an innovative technique where the electric current is applied to the soil through electrodes where pore water moves from the positive electrode (anode) to the negative electrode (cathode). This method is used for slope stability, excavations, increasing the capacity of piles, mitigating liquefaction potential of silty soils, dewatering sludge (Soderman and Milligan 1961; Chappell and Burton 1975; Burnotte et al. 2004; El Nagger and Routledge 2004; Chen and Jia 2007). However, the use of electrokinetic stabilization for improving the properties of the dredged mud has not been investigated.

The use of electrokinetic stabilization for geotechnical purposes is pioneered by Casagrande (1961). However, the lack of standard design and unknown changes in chemical properties of soils draws the attention of geotechnical engineers away from this method. The accurate analysis of electrokinetic stabilization requires understanding of the process and its effect on changing the properties of the soil.

1.2 Aim and scope of the study

The primary objective of this study is to firstly investigate the effect of electrokinetic stabilization on properties of the dredged mud and to investigate its potential application and the response of dredged mud to the method. Secondly, it is proposed to investigate the upper limit and maximize the efficiency and reduce the cost of the method through understanding the effect of type of electric current application, electrode configuration, electrode type and material and its effect.

The sub-objective of this study comprised of the following:

- Optimizing the efficiency of electrokinetic stabilization of dredged marine sediments based on the response of soil to the method.
- Mitigating the corrosion rate of the metal anode through application of coating materials.
- Investigating the ideal location and distance between electrodes which is unclear in the literature.
- Investigating the effect of the type of electric current application and its effect on efficiency of the electrokinetic stabilization method.
- Studying the effect of different electrode configurations including one-dimensional and two-dimensional electrokinetic stabilization.
- Investigating the effect of electrode material.

1.3 Thesis overview

Chapter 1 explains the limitations in the beneficial use of dredged marine sediments for land reclamation purposes. The current practices and the methods to reduce the timeframes of the soil sedimentation is given. A brief overview of this thesis is also presented.

Chapter 2 emphasizes the recent developments in electrokinetic stabilization and factors affecting the process of electrokinetic stabilization, methods to improve the efficiency of the method, and current electroosmotic consolidation models and their boundary conditions.

Chapter 3 presents information about physical properties of the dredge mud, its mineralogy, and the method of sample preparation for electrokinetic stabilization testings along with the procedure for measuring the physiochemical properties of the dredged mud before and after treatment.

Chapter 4 focuses on how electrode configuration affects the electrokinetic stabilization. Horizontal configuration (one-dimensional and two-dimensional), and vertical configuration (cathode top-anode bottom; cathode bottom-anode top) are investigated. The investigation is carried out through understanding the effect of electrokinetic stabilization on settlement of the soil. The changes of consolidation parameters with depth is also presented in this chapter.

Chapter 5 describes how type of electric current application changes the electrokinetic stabilization of soils. Effect of irregular intermittent current application and the drainage condition is presented in this chapter.

Chapter 6 investigates the effect of electrode material. Different type of materials copper, stainless steel, galvanized steel, and polyaniline galvanized steel are tested. To reduce the corrosion rate of the anode polyaniline coating is applied to the anodes, and the changes in efficiency of the electrokinetic stabilization is shown.

Chapter 7 shows the change of physiochemical properties of the soil such as pH, electric conductivity, soil salinity, and liquid limit after electrokinetic stabilization for and their interpretation.

Chapter 8 presents conclusions of this study along with further recommendations for future research in this area.

Chapter 2: Literature Review

2.1 Introduction

The need for soil stabilization is rising due to an increase in global population and limitation of appropriate lands for construction purposes. Geotechnical properties of soils provide an indication of their suitability for construction purposes. Soils with poor geotechnical properties (low compressive and shear strengths, low bearing capacity, etc.) require stabilization. Failure to do so results in extensive damages to future structures, which would be so costly to repair or to mitigate the impacts.

Limitation of appropriate lands coupled with the need for disposal sites for industrial wastes necessitate the development of methods to improve soils. For beneficial use of slurries such as dredged mud and mine tailings, the first approach is to reduce its water content until it gains enough strength of 1 kPa, to be considered as a soil (Azam et al. 2007). Then soil stabilization is an option to improve the soil furthermore. For this purpose, a range of different methods of soil stabilization have been developed for soft soil conditions such as:

- soil densification,
- physical and chemical stabilization,
- modification with inclusions, and
- hydraulic modification.

Soil densification through compaction is one of the most common method of soil improvement in field. Densification through compaction can be shallow or deep depending on the method and the equipment. Shallow compaction affects the top surface layer of the soil and deep compaction affects the soil in deeper levels. This method of soil modification cannot be applied to a soft soil with high moisture content, which is in the form of a slurry.

Chemical stabilization is through in-situ deep mixing of chemicals such as cement, lime, fly ash, or steel slag with the soil for strengthening purposes. However, with this method, curing time is an important factor to consider which in turn renders it rather time-consuming to achieve the appropriate strength. The homogenous mixing of the chemicals in practice is another drawback of this technique.

Modification with inclusions is using geosynthetic fibres for soil reinforcement. This method improves the strength properties of soils and reduces the shrinkage properties in case of expansive soils. Geosynthetic fibre is used in combination with chemical stabilization to increase its effectiveness. However, it is difficult to distribute these fibres evenly in practice.

Hydraulic modification of the soil is through changing the flow of water. This involves drainage, dewatering, and seepage or groundwater flow. Slurries such as dredged mud and mine tailings have very high water content. Settlement of these slurries is time consuming and can be accelerated using a number of techniques, most notably, by hydraulic modifications such as prefabricated vertical drains or vacuum preloading. Any of these techniques consolidates soils either by removing water or air from the system. Application of surcharge is often done simultaneously with the application of vertical drains to improve the efficiency of the technique. Vacuum preloading consolidates soil by removing air and water. Although, it is a faster method than the conventional vertical preloading, failure due to insufficient undrained bearing capacity is a common concern of this technique. An innovative method of soil stabilization known as electrokinetic stabilization with which, consolidation is facilitated by application of direct electric current to the soil.

Electrokinetic stabilization improves the geotechnical properties of the soils including shear strength, compressibility, and permeability. However, due to the lack of understanding and proper design criteria, this method requires extensive research before becoming viable as another method of soil stabilization for applications such as improvement of dredged marine sediments and if shown successful, to determine an efficient design model.

This thesis is focused on an investigation of the suitability of electrokinetic stabilization for improving the settlement and geotechnical properties of the dredged marine sediments. In this chapter, an overview of literature and current developments including the background, design parameters, and factors influencing the electrokinetic stabilization presented.

2.2 Electrokinetics

Electrokinetic stabilization is an application of electrical current to the soil through the electrodes. Electrokinetic stabilization includes a combination of following processes:

- electro-osmosis,
- electrophoresis,
- electrolysis, and
- electro-migration

which collectively change the structure of the soil.

Electro-osmosis is the transport of water from anode to the cathode. This is due to the influence of electric field on dipole water molecules that results in movement of capillary water. Electrophoresis is the movement of charged particles. Electrolysis is the decomposition of the pore water at electrodes. The electrolysis of water occurs due to the redox reactions (oxidation-reduction reactions), given as follows:

$$2H_2O - 4e^- = 4H^+ + O_2 \text{ (Anode)} \qquad (2.1)$$

$$2H_2O + 2e^- = 2OH^- + H_2 \text{ (Cathode)} \qquad (2.2)$$

These reactions result in generation of oxygen and hydrogen gas around the anode and the cathode, respectively (Table 2.2). The oxidation reaction results in reduction of pH and soil plasticity near the anode. Reduction reaction increases the soil pH near the cathode due to the dissolution of hydrogen ions.

Electro-migration is movement of ions due to the induced electric potential, resulting in movement of solute such as salt during the electrokinetic process. These electrokinetic phenomena affect the soil. The practical outcomes of the electrokinetic components are presented in Table 2.1.

Table 2.1 Collection of direct and coupled flow phenomena (After Mitchell 1993; Yeung and Datla 1995; Horseman et al. 1996; Heister et al. 2004)

Flow	**Equation**	Gradient X			
		Hydraulic	**Temperature**	**Electrical**	**Chemical**
Fluid (q_h)	$q_h = k_h \frac{\Delta H}{L} A$	Hydraulic conduction (*Darcy's law*)	Thermo-osmosis	Electroosmosis	Chemical-osmosis
Heat (q_t)	$q_t = k_t \frac{\Delta T}{L} A$	Isothermal heat transfer	Thermal conduction (*Fourier's law*)	Peltier effect	Dufour effect
Current (I)	$I = \sigma_e \frac{\Delta V}{L} A$	Streaming potential	Thermoelectricity (Seebeck effect)	Electric conduction (*ohm's law*)	Diffusion and membrane potentials
Ion (J_D)	$J_D = nD \frac{\Delta c}{L} A$	Streaming potential	Thermal diffusion of electrolyte (Soret effect)	Electrophoresis	Diffusion (*Fick's law*)

where $\frac{\Delta H}{L}, \frac{\Delta T}{L}, \frac{\Delta V}{L}, \frac{\Delta c}{L}$ are hydraulic gradient, thermal gradient, electric potential gradient, and ion flux due to which the mentioned flow occurs.
k_h, k_t, σ_e, nD are hydraulic conductivity, thermal conductivity, electrical conductivity, and diffusion. A is the cross-sectional area of the sample.

During electrokinetic stabilization water, electric current, heat and ions flow through the soil. These flows are due to hydraulic, temperature, electric or chemical gradient that are the result of electrokinetic phenomena. During electrokinetic stabilization, these flow in the soil couple and change the properties of the soil (Table 2.2).

Table 2.2 Practical effects of electrokinetic phenomena (Jones et al. 2006)

Electrokinetic phenomenon	**Effects**
Electroosmosis	Water flow, Pore pressure change, Volume change
Electrophoresis	Particle movement, particle sedimentation
Electromigration	movement of dissolved substance (like salt) – migration of ions
Electrolysis of water	Oxygen evolution, Hydrogen evolution, pH changes

2.3 Background

Electro-osmosis was first reported by Reuss (1809). He was the first to observe the flow of water from the anode to the cathode by application of electrical current to the saturated clay. Later, Quincke (1861) improved the understanding by describing the flow potential. After Reuss' work, Perrin (1904) and Smoluchowski (1921) established Helmholtz-Smoluchowski (H-S) equation, which shows the electroosmotic parameters and their interrelationships.

The first successful application of electroosmosis in geotechnical applications was trialled by Casagrande (1949). The studies in the literature start mainly from electroosmosis which is the flow of pore water from anode to the cathode. To enhance the application of electrokinetic stabilization on different soil types, this method has been studied intensively during the last 80 years. However, due to the lack of a suitable standard design approach, the application of electrokinetic stabilization requires a laboratory simulation. The historical development of the electrokinetic applications is given in Table 2.3.

Table 2.3 Historical development of electrokinetic treatment

Year	Researcher	Observations and studies
1809	Reuss	First researcher that observed electroosmosis by application of direct current to mixture of clay and water
1846	Napier	Recognized the distinction between electroosmosis and electrophoresis
1861	Quincke	Studies the flow and streaming potential
1879	Helmholtz	Provided analytical model for electroosmosis
1904	Perrin	Derivation of electrokinetic velocity
1921	Smoluchowski	
1949	Casagrande	Studied electrokinetic phenomena in porous media like soils and performed the first practical studies
1960	Russian researchers	Electromigration of metals
1961	Soderman and Milligan	Increasing bearing capacity of piles with electrokinetic stabilization
1963	Veder	Electrokinetics of bentonite slurry wall
1975	Chappel and Burton	Stabilization of slopes and excavations
1980	Banerjee and Mitchell	Determination of electroosmotic coefficient of consolidation
1986	Dutch researchers	Successful application of electrokinetic stabilization (soil remediation)

1980 - 1998	Researchers around the world	Successful application of electrokinetic treatment for decontamination purposes
1996	Shang and Dunlap	Using electrokinetic stabilization to increase soil strength
1997	Shang	Reversing the polarity to increase the homogeneity of the soil after electrokinetic stabilization
1998	Shang	Developed 2D electroosmotic consolidation
2001	Micic et al.	Application of intermittent current to improve the electrokinetic stabilization
2004	Pugh and Jones	Patent for innovative electrodes known as EKGs (electrokinetic geosynthetics)
2005	Asavadorndeja and Glawe	Anode depolarization
2005- Now	Yang et al. (2005), Kaniraj and et al. (2011), Fourie and Jones (Reuss, 1809)(2010), Lee et al. (2013), and other researchers.	Investigating and analyzing the effect of electrokinetic stabilization on different type of soils and developing methods to reduce the limitation of the method such as power consumption.

2.4 Advantages and limitations of electrokinetic stabilization

Electrokinetic stabilization is an environmentally friendly and promising method to dewater and consolidate slurries and soils with low permeability. A brief explanation on the advantages and limitations of the electrokinetic stabilization method is given in Figure 2.1. Especially in the case of underwater structures where application of other methods is not possible due to the high water content of the soil, electrokinetic stabilization has potential application. However, due to the lack of design criteria, there is a need for further research to maximize the efficiency and effectiveness of the method.

2.5 Electrokinetic stabilization design

Despite the extensive research on electrokinetic stabilization, there is a lack of design criteria in the literature. The lack of suitable design criteria is due to the factors influencing the electrokinetic stabilization method. These factors change during electrokinetic stabilization and result in changes of soil structure. The energy consumption of the method changes depending on the changes of electrokinetic parameters such as physiochemical changes in the soil and electrical parameters. The effect of these parameters on electrokinetic stabilization is discussed in next section.

Advantage

- It can be applied without disturbance to the adjacent areas, and can be applied to the constructed lands to enhance the soil beneath foundations
- It can treat wide range of soils especially very effective for treatment of clayey soils, due to their negative surface charge and low hydraulic conductivity.
- It has multiple objectives of consolidation, strengthening and decontamination.

Limitatio

- A reduction in electrical current density which is due to the activation, resistance and concentration polarization (Acar and Alshawabkeh 1993, Alshawabkeh and Acar 1996; Acar et al. 1995; Sah and Chen 1998).
- Generation of bubbles of O_2 and H_2 around electrodes, which are the result of oxidation and reduction reactions near anode and cathode, result in the loss of soil-electrode contact (Bergado et al. 2003).
- An increase of soil resistivity to the same applied voltage and the need to increase the voltage that leads to a higher power consumption (Mohamedelhassan and Shang 2001).
- Unknown electrochemical reactions.
- Lack of standard design.

Figure 2.1 Advantages and limitations of the electrokinetic stabilization

2.6 Factors affecting electrokinetic applications in Soils

The physio-chemical properties of soil change due to the electrochemical reaction during electrokinetic stabilization. Factors influencing the electrokinetic process are divided into two main groups. First group is related to the initial soil condition and second group is set-up design parameters. Figure 2.2 shows a brief explanation on parameters influencing the electrokinetic stabilization.

Water content

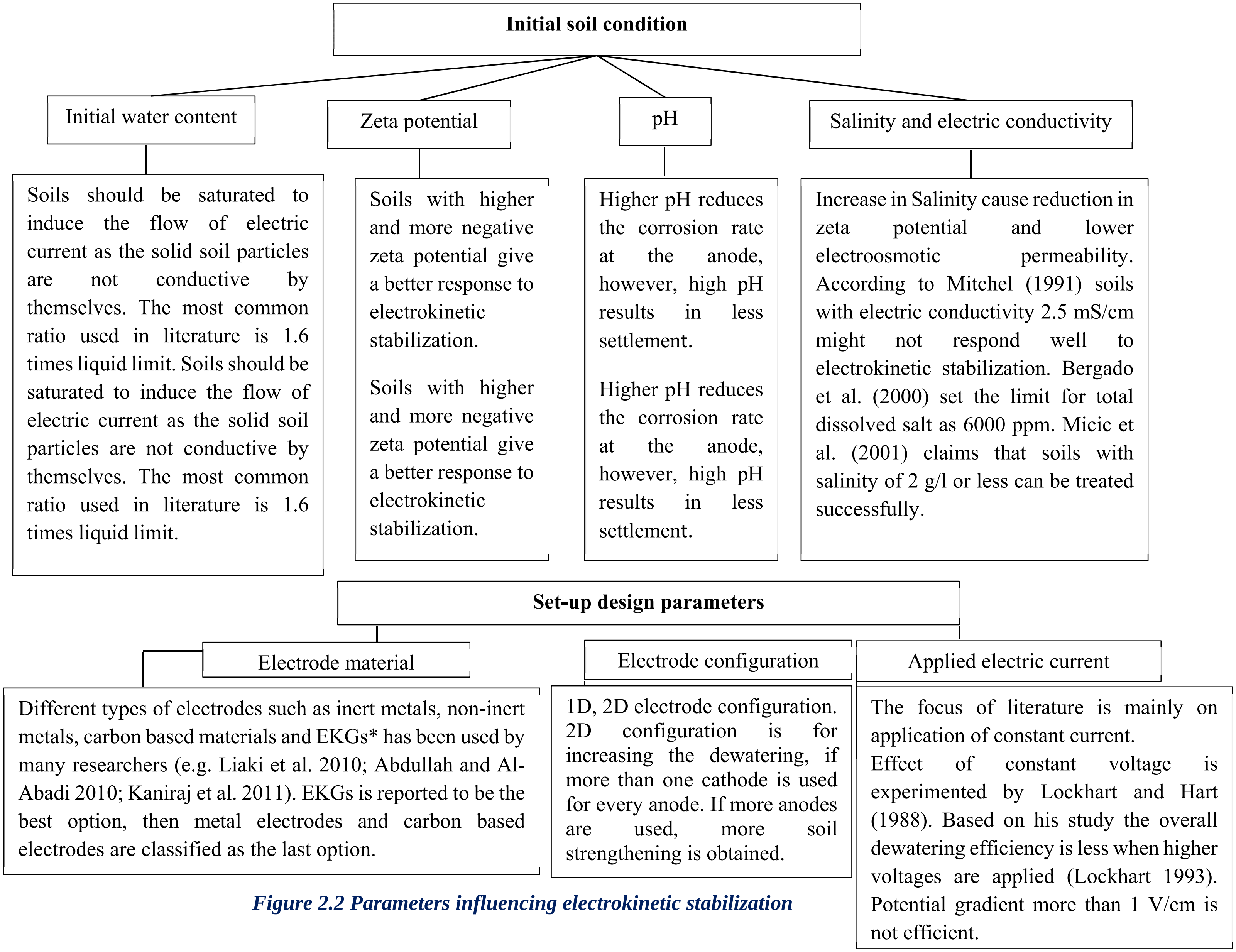
The initial water content affects the soil porosity, void ratio and electrical resistivity of the soil. Fourie et al. (2007) reported 83% water content reduction after application of electroosmosis dewatering of mine tailings with initial gravimetric water content of 257%. Water content in peat and clayey soils with an average initial value of 472% and 355% was reduced significantly using electroosmotic consolidation (Kaniraj et al. 2011). This is a significant improvement. Depending on the properties and type of soil, successful application of electrokinetic stabilization with different initial water contents is reported in the literature (e.g. Kaniraj et al. 2011; Liaki et al. 2010; Chien et al. 2011; Jayasekera and Hall 2007). In general, 1.6 times of the soil liquid limit was found as the most common ratio (Jeyakanthan et al. 2011).

During electroosmosis, as the water content of the soil reduces, desiccation cracks appear. These cracks reduce the efficiency of the electroosmosis. It is necessary to know at which value of water content soil starts to crack. For dredged mud the water content at which it starts to shrink during self-weight sedimentation, which is known as desiccation limit, is estimated at 1.2 times its plastic limit (Stark et al. 2005). This water content should be taken into consideration to determine the initial moisture content that is appropriate for electrokinetic stabilization. Therefore, dredged mud with water content less than desiccation limit is inappropriate for electrokinetic stabilization even for purpose of soil strengthening.

pH and zeta potential

The next factor is pH, which is defined as the ability of the soil to react with chemical admixtures, because some reactions can occur only at a specific pH value. Soil's ability to withstand pH fluctuations is expressed as soil buffering capacity. Soils with high buffering capacity often have high clay and organic content (Burton 2010). However, the alteration of soil buffering capacity, as well as pH, can also be done by adding base or acid. Soils with high buffer capacity are preferable for electrokinetic stabilization, since they are able to withstand the pH fluctuations, which normally occur during the process. Table 2.4 illustrates the initial pH value of different soils that electrokinetic stabilization is performed on.

The acidity or alkalinity of the soil is based on the stability of the ions at different pH values. For instance, metal cations are stable under acidic environment, while anions are stable under alkaline condition (Hamed et al. 1991). Thus, the control of pH is important since it can affect the movement of ions. During electrokinetic stabilization, an acidic environment (high pH value) near anode is generated due to the existence of H^+ ion and oxygen gas and an alkaline environment is generated near cathode due to the existence of OH^- ions and hydrogen as a result of electrolysis of water.



Soils should be saturated to induce the flow of electric current as the solid soil particles are not conductive by themselves. The most common ratio used in literature is 1.6 times liquid limit. Soils should be saturated to induce the flow of electric current as the solid soil particles are not conductive by themselves. The most common ratio used in literature is 1.6 times liquid limit.

Soils with higher and more negative zeta potential give a better response to electrokinetic stabilization.

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Higher pH reduces the corrosion rate at the anode, however, high pH results in less settlement.

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Increase in Salinity cause reduction in zeta potential and lower electroosmotic permeability. According to Mitchel (1991) soils with electric conductivity 2.5 mS/cm might not respond well to electrokinetic stabilization. Bergado et al. (2000) set the limit for total dissolved salt as 6000 ppm. Micic et al. (2001) claims that soils with salinity of 2 g/l or less can be treated successfully.

Different types of electrodes such as inert metals, non-inert metals, carbon based materials and EKGs* has been used by many researchers (e.g. Liaki et al. 2010; Abdullah and Al-Abadi 2010; Kaniraj et al. 2011). EKGs is reported to be the best option, then metal electrodes and carbon based electrodes are classified as the last option.

1D, 2D electrode configuration. 2D configuration is for increasing the dewatering, if more than one cathode is used for every anode. If more anodes are used, more soil strengthening is obtained.

The focus of literature is mainly on application of constant current.
Effect of constant voltage is experimented by Lockhart and Hart (1988). Based on his study the overall dewatering efficiency is less when higher voltages are applied (Lockhart 1993). Potential gradient more than 1 V/cm is not efficient.

Figure 2.2 Parameters influencing electrokinetic stabilization

Changes in pH affect the particle stability, solubility, dispersion, precipitation and chemical reactions in soil. The tendency of hydroxyls to dissolve in water is strongly affected by pH. When pH of the clay increases or reduces sharply, soil compositions such as iron, aluminium, sodium disperse and later precipitate as hydroxides or salt. Liaki et al. (2010) showed that if pH of kaolinite reduces below 5, the aluminium ions migrate and cause soil strengthening. On the other hand, the formation of stabilizing agent occurs under alkaline conditions. Pozzolanic reaction occurs at alkalinity and the cementing agent results in an increase of soil strength and changes of Atterberg limits. Jayasekera and Hall (2007) observed an increase in liquid limit and plastic limit near the cathode (alkaline environment) and reduction near the anode (acidic environment).

Zeta potential is the electric potential in a double diffuse layer. Diffuse Double layer (DDL) is a charged layer around the wet clay particle (Figure 2.3). Since pH and zeta potential have a direct relationship, the changes in pH cause changes in zeta potential and electrical conductivity. Acar et al. (1989) and Hamed et al. (1991) observed that the reduction of pH results in reduction of zeta potential and hydraulic conductivity, which in turn slows down the flow of fluid through the soil mass. In electrokinetic stabilisation, pH changes in each part of the soil mass depends on the conductivity of the presented ions. Sharp changes of pH and existence of insoluble hydroxyls during electrokinetic stabilization cause a drop in the electric potential in the soil (e.g Hamed et al. 1991; Liaki et al. 2010).

Table 2.4 Review of the literature base on initial pH value

Author	**Type of the soil**	**Initial pH**
Shang (1996)	Brown clay, Grey clay	7.4, 7.2
Hamir et al. (2001)	Kaolin grade E	5.0 ± 0.5
Reddy et al. (2006)	Dredged sediment	7.0
Fourie et al. (2007)	Sand tailing	6.4
Jayasekera and Hall (2007)	Silt loam – heavy clay	4.5
Rittirong et al. (2008)	London Ontario clay	7.5
Kamarudin et al. (2008)	Residual soil	5.3
Kalumba et al. (2009)	Soft clay	8.2
Loch et al. (2010)	Na-Bentonite clay	7.5
Kim et al. (2011)	Dredged sediment	7.7

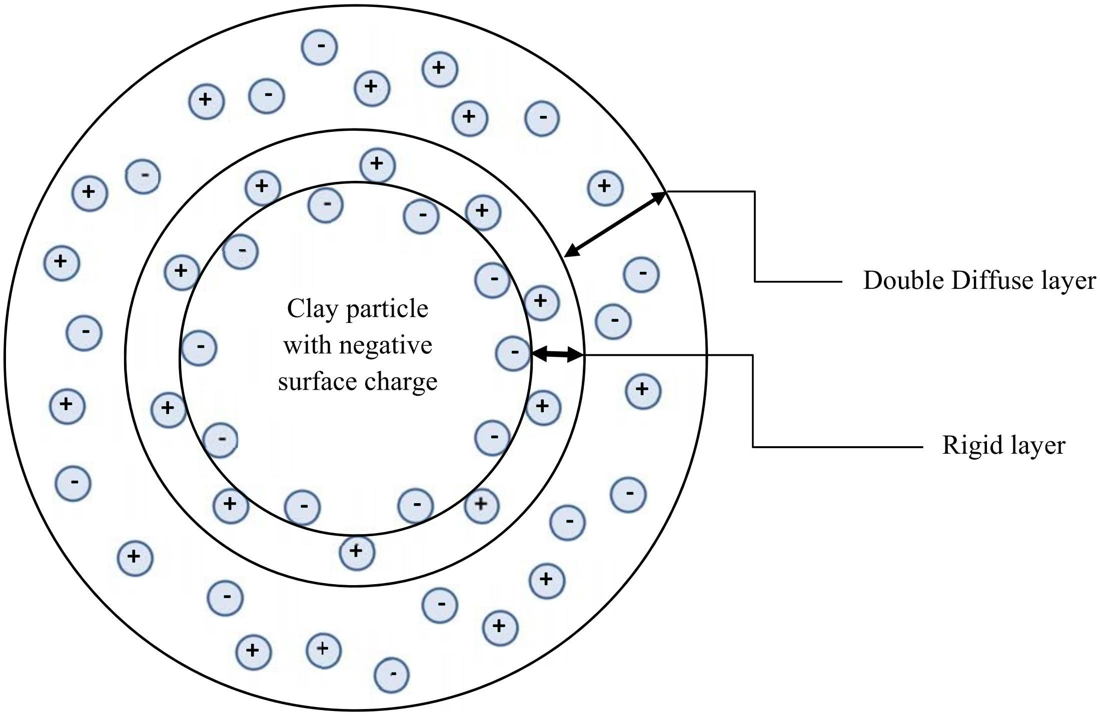


Figure 2.3 Double layer on negatively charged clay particle

Level of soil salinity

Soil salinity affects the electroosmotic flow by affecting its zeta potential (Mitchel and Soga 2005). Soils with higher zeta potential have higher electroosmotic permeability. When soil salinity increases, the zeta potential reduces due to the reduction of double layer thickness. Therefore, electrokinetic stabilization is unlikely to be successful in soils with very high salinity. Hence, it is important to determine the salinity of the soil prior to the electrokinetic application.

The level of soil salinity is estimated by either electrical conductivity (S or mS), direct measurement of salt content (ppm), or measurement of the mass of the salt crystals. There are many controversies on the specific limit for soil salinity that result in optimum electrokinetic stabilization. According to Bergado et al. (2000) soils with salinity higher than 6000 ppm are not responsive to electrokinetic stabilization. Mitchel (1991) suggests that soils with electrical conductivity above 0.003 S/cm are responsive to electrokinetic stabilization. Jones and Glendinning (2006) reported that electroosmotic stabilization can be effective and economical if soil electrical conductivity is between 0.050 S/cm – 50 S/cm. However, depending on the type of the soil, lower initial electrical conductivity might also be applicable if methods such as addition of chemical admixtures and salt solution are used. Micic et al. (2001) suggest that soil with salinity of 0.003 S/cm or less, result in successful application of electrokinetic stabilization. On the contrary, Mohammedelhassan and Shang (2002) observed successful application of electrokinetic stabilization of soils with 0.013 S/cm Nacl. Micic et al. (2001) has experimented with electrokinetic application on marine sediments with 0.050 S/cm of Nacl.

Electrical resistivity and conductivity

Soil electrical conductivity σ (measured in milli-Siemens/cm or Siemens/m) is the ability of the soil to transfer electrical current. The unit Siemen is defined as Ω^{-1} or Ampere per volt. Soil resistivity, which is the soil's ability to resist electrical current, has an inverse relationship with soil electrical conductivity. Soil resistivity is measured in Ω·m or Ω·cm. Electrical resistivity of soils can be affected by many factors such as temperature, water content, soil porosity, pore fluid resistivity, the soil composition, soil salinity, particle and pore size and shape (Yan et al. 2012). Soils with very low water content are not able to conduct enough electrical current. A critical water content above which soil demonstrates electrical conductivity is 15% (Sverko, 1999).

Electrical resistivity is varied by soils due to the existing minerals, chemical and electrical properties such as dielectric constant and zeta potential. For instance, surface soils and clay soils have low resistivity and high conductivity; this might be attributed to the existence of carbon in surface soils and negative surface charges in clays. Electrical conductivity of the soil can be expressed in terms of the soil electrical resistivity by the following equation or it can also be estimated from the plasticity index of the soil.

$$\sigma = \frac{1}{R}\frac{L}{A} \tag{2.3}$$

where σ (Siemens) is the electrical conductivity, R (Ω) is electrical resistivity, L (m) is length and A (m^2) is the cross sectional area of the sample.

During electrokinetic stabilization, the ionic concentration changes due to electromigration. Therefore, electrical conductivity of the soil varies based on the ionic strength. As a result, different zones within the soil may have different values of electrical conductivity. This change in local electric conductivity results in variations in electric potential. The initial electric conductivity shows the initial ionic concentration in the soil. Therefore, it is important to know the electrical conductivity of the soil prior to electrokinetic stabilization. Table 2.5 shows different values of initial electrical conductivity that are reported in the literature.

Table 2.5 Electrical conductivity of the soils reported by researchers

Author	**Soil Type**	**Electrical conductivity (S/cm)**
Shang (1997)	Grey clay	0.000289
Hamir et al. (2001)	Kaolin	0.025
Micic et al. (2001)	Yulchon clay	0.012
Glendinning et al. (2005)	Clay	0.006
Jayasekera and Hall (2007)	Silt loam	0.002
Jayasekera and Hall (2007)	Heavy clay	0.003
Kalumba et al. (2009)	Tunnel Slurry	0.23
Kim et al. (2011)	Sediments	0.000842
Fourie et al. (2007)	Sand tailing	0.00051
Rittirong et al. (2008)	London Ontario clay	0.000222
Loch et al. (2010)	Clay	0.001

Electrode material

The material constituting the electrodes affect the electrokinetic stabilization. Different types of electrode material such as inert metals, non-inert metals, and carbon based electrodes are used for electrokinetic stabilization of soils (e.g. Liaki et al. 2010; Abdullah and Al-Abadi 2010; Kaniraj et al. 2011). When a metal electrode is used, the anode corrodes due to electrolysis. The electrolysis and corrosion of the anode occur due to the following reactions:

$$M + H_2O = MO + 2H^+ + 2e^- \qquad (2.4)$$

where M is the metal element and MO is metal oxide.

For instance, if iron (Fe), copper (Cu) or carbon (C) electrodes are used, the following reactions occur near anode which cause the corrosion of electrodes and result in different chemical reactions within the soil.

$$Fe + H_2O = FeO + 2H^+ + 2e^- \qquad (2.5)$$

$$Cu + H_2O = CuO + 2H^+ + 2e^- \qquad (2.6)$$

$$C + H_2O = CO_2 + 4H^+ + 4e^- \qquad (2.7)$$

This can be added to the oxidation reaction. The following equation is used to investigate the amount of corrosion at the anode.

$$Degree\ of\ corrosion\ (\%) = \frac{M_0 - M_f}{M_0} \qquad (2.8)$$

where M_0 is the initial mass of the electrode, and M_f is the final mass of the electrode after corrosion.

The material selection is challenging. Gold, silver and platinum are non-corrosive, but costly. Carbon is cheap, but it has extensive power consumption due to low conductivity (Mohamedelhassan and Shang, 2001). Although iron electrodes increase the flow of water up to twice the graphite electrodes (Segall and Brull, 1992), the precipitation of metal oxides increases the power consumption and, hence reduces the efficiency. Besides, the corrosion of steel and mild steel electrodes also decreases the effectiveness of soil stabilization (Lefebvre and Burnotte, 2002; Jayasekera and Hall, 2007).

Among metal electrodes, copper and stainless steel are known as the best options. In the case of using copper electrodes, the benefits are their low cost and availability, the oxygen consumption around electrodes, and the conductivity of copper oxide which reduces the voltage loss at the anode; however, a significant loss of power at the cathode was observed by Mohammedelhassan and Shang (2001). Stainless steel is more corrosion resistant and causes soil hardening by introducing iron to the soil as electrodes degrade (Liaki et al. 2010). But, it is not yet obvious that this reported soil strengthening, is due to the stainless steel degradation or reduction of pH below 5 due to which Al^{3+} dissolves from kaolinite. Stainless steel is corrosion resistant but generates chromate into the soil which is a source of contamination depending on the produced amount. According to Lockhart (1983) during soil dewatering, the type of the metal electrodes does not have an influence on the required amount of energy to achieve the targeted solid content.

An innovative material known as electrokinetic geosynthetics (EKGs) which is comprised of a conductive polymer was first developed in 1990 by researchers at the University of Newcastle in UK. Some of the other benefits of EKGs are their non-susceptibility to electrochemical reactions, providing filtration during drainage, and acting as a membrane. However, EKGs are not yet commercially available, and the connection between EKGs and the DC supply is not safe and sometimes results in disintegration of EKGs components which is not mentioned in the literature.

Electrode configuration

The configuration of electrodes affects the efficiency of the electrokinetic stabilization. There are two types of electrode configuration, one known as one-dimensional and the other as two-dimensional. A one-dimensional configuration is when for every anode one cathode is installed. The other type of electrode configuration is two-dimensional configurations in which there is more than one anode for a cathode. When this configuration is used, the acidic soil near the anode is extended to larger area due to the electrolysis. This is desirable when cementation near the cathode does not happen due to the presence of organic materials (Asavadorndeja and Glawe 2005). Depending on the type of chemicals in the soil, high pH develops near the cathode which causes soil cementation and increase the strength properties of the soil. However, if no cementation occurs, the increase in soil strength occurs mainly around the anode. In that case, the two dimensional electrode configuration is preferable.

2.7 Methods to improve electrokinetic stabilization

During electrokinetic stabilization due to the redox reaction, the environment near the anode becomes acidic which increases the corrosion rate of the anode. To reduce this effect on the anode, an alkaline chemical such as lime can be added from the anode to the soil. This method is referred as anode depolarization and improves the efficiency of the electrokinetic stabilization by reducing the corrosion rate of the anode. Another limitation of electrokinetic stabilization is the non-homogeneity of the soil sample between the anode and the cathode. This can be alleviated by reversing the polarity, referred to as polarity reversal. Also, the application of intermittent current has been proven to reduce the corrosion rate of the anode and consumption of energy during electrokinetic stabilization. Figure 2.4 gives a brief description on these methods to improve the limitations of the electrokinetic stabilization.

Polarity reversal

During electrokinetic stabilization, as water flows toward the cathode the soil near the anode starts to dry out and cracks may appear. This interrupts the electric current flow through the soil. For this reason, Shang et al. (1997) suggest polarity reversal. Polarity reversal and intermittent current reduce the corrosion of the anode, increase electroosmotic flow, and resulted in an increase of 570% in shear strength of the soil (Shang et al. 1997).

Due to the spatial changes in ionic concentration and fluctuation of pH, the treated soil is non-homogenous and the strength near the anode is higher than near cathode due to the generation of negative pore pressure near the anode. The polarity reversal however improves the homogeneity of the treatment throughout the soil. Reversing the polarity in specific time intervals is much more effective than polarity reversal at the end of the electrokinetic stabilization. Because the soil has not yet lost its conductivity and the anode has not yet corroded completely, the polarity reversal works better when applied in time intervals. When metal electrodes are used, the polarity reversal is an option to reduce the effect of corrosion. The settlement rate of the soil decreases during polarity reversal (Bjerrum et al. 1967); however, the polarity reversal does not affect the amount of draining water (Ou et al. 2009); and higher energy is consumed during polarity reversal than in unidirectional current flow (Luo et al. 2005).

Methods of improving electrokinetic stabilization of soils

Polarity reversal

- Shang et al. (1997) first performed this method where the efficiency of electroosmosis was improved due to the reduction of electrochemical reactions that occur because of changes in pH.
- Asavadorndeja and Glawe (2005) which shows that reversing the polarity can improve the efficiency by transporting hydrogen ions from cathode to anode performed a comparative study between normal and reversed polarity electrokinetic stabilization. He has reported an increase of shear strength by 570%.
- The polarity reversal can improve the distribution of the treatment throughout the soil. Therefore, it would be a good option to improve the evenness of the treatment by applying polarity reversal in time intervals or after completion of the electrokinetic stabilization.
- Other problems with this method are that the settlement rate of the soil decreases during polarity reversal (Bjerrum et al. 1967); the polarity reversal does not affect the amount of draining water (Ou et al. 2009); higher energy is consumed during polarity reversal than unidirectional method (Luo et al. 2005).

Anode depolarisation

- During electrokinetic stabilization, the generation of oxygen bubbles reduces the soil-electrode contact and the pH near anode. The acidic environment that is generated due to the drop of pH accelerates the corrosion rate of the anode, and decreases the precipitation of the pore fluid near the anode.
- The mobility of the hydrogen ions is much faster than hydroxides, that's why most part of the soil is acidic, and therefore the precipitation can only be limited near the cathode. To reduce this effect, the anode depolarization technique, which is firstly introduced, by Asavadorndeja and Glawe (2005) can be used.
- The strength of the soil can be increased in three cases where cations can be replaced, mineralization can occur and the pore fluid can be precipitates. The precipitations of the pore fluid can only occur when the pH of the soil is above 7 or only in alkaline environment. Therefore, it is desirable to keep the pH of the soil above 7. By addition of alkaline solution through the anode, the power consumption during electrokinetic can be reduced and the electric current distribution throughout the soil can be regulated.
- By addition of alkaline solution through the anode, the power consumption during electrokinetic can be reduces and the electric current distribution throughout the soil can be regulated.

Application of intermittent

- This technique is proposed by Sprute and Kelsh (1975, 1980) which is the application of intermittent current. Intermittent current is an interruption of direct current within specific time intervals which can be regular or irregular. This method can reduce the rate of corrosion at anode and the overal power consumption without effecting the efficiency.
- Regular application of intermittent current is popular in the literature. It is shown that the application of intermittent current reduces the corrosion rate of the anode and the power consumption (Micic et al. 2001; Glendinning et al. 2008).
- Irregular intermittent current application is rarely reported in the literature.

- This technique is proposed by Sprute and Kelsh (1975, 1980) which is the application of intermittent current. Intermittent current is an interruption of direct current within specific time intervals which can be regular or irregular. This method can reduce the rate of corrosion at anode and the overal power consumption without effecting the efficiency.

Figure 2.4 Methods to improve electrokinetic stabilization

Intermittent current

A common type of current used in the literature for soil stabilization is constant direct current. However, intermittent current appears to improve the electrokientic stabilization by reducing the corrosion rate at the anode (Sprute and Kelsh 1975, 1980; Shang et al. 1996). Intermittent current is an interruption of direct current within specific time intervals which can be regular or irregular. Micic et al. (2001) studied the effect of intermittent current on strengthening marine sediments and reported a reduction of power consumption by application of direct current applied for 2 minutes and turning off for 2 minutes. An increase of 185% in shear strength of the soil at the vicinity of the anode shows that the application of the intemittent current leads to better strengthening effects in comparison with application of constant electric current (Micic et al. 2001).

When intemittent current is applied, the energy consumption is based on intermittent ratio which is determined as the ratio of the duration that electric current is applied t_{on} (h) over total treatment time t_{total} (h).

$$\tau = \frac{t_{on}}{t_{total}} \tag{2.9}$$

Energy consumption can be found from the following equation:

$$W = Pt_{total} \tag{2.10}$$

where W is the energy consumption (kWh/m^3) and

$$P = \tau E_j \tag{2.11}$$

where P is power consumption per unit volume of soil (W/m^3) which depends on electric field intensity ($E = -\frac{dV}{dl}$) with unit of V/m and current density of ($j = \frac{I}{A}$) with unit of A/m^2. The intermittent ratio (τ).

2.5 General laboratory designed electrokinetic models

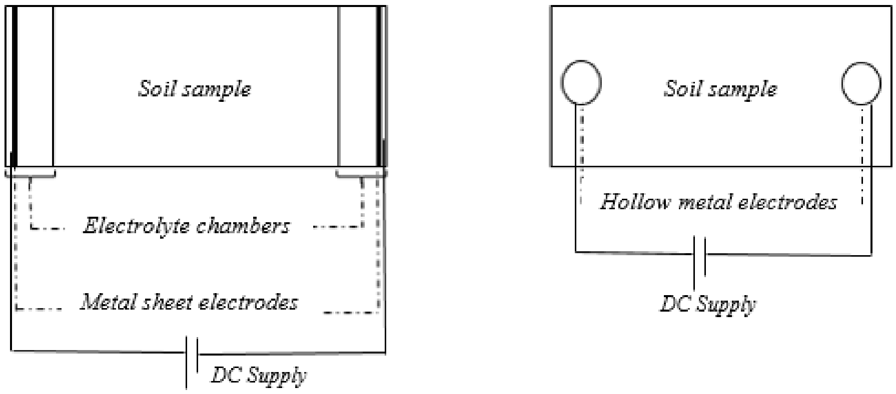
Electrokinetic stabilization is not a conventional and standard method in geotechnical engineering and therefore does not have standard testing equipment or procedures. Researchers are required to develop their own instrument setups. The experimental set-ups presented in literature are classified as three models (Figure 2.5).

The first model is a plan view of the set-up and comprised of three parts: the electrokinetic cell, the soil, and the anode and cathode compartments that are referred as electrolyte chambers. The anode and cathode compartments can be designed as separate parts in the electrokinetic cell or can be as two hollow electrodes that are perforated from which the electrolyte solution is to be removed (Figure 2.5). The scheme with an electrolyte chamber is more popular in case of soil decontamination and using hollow metals as electrodes is a small-scale geotechnical simulation of electrokinetic field stabilization.

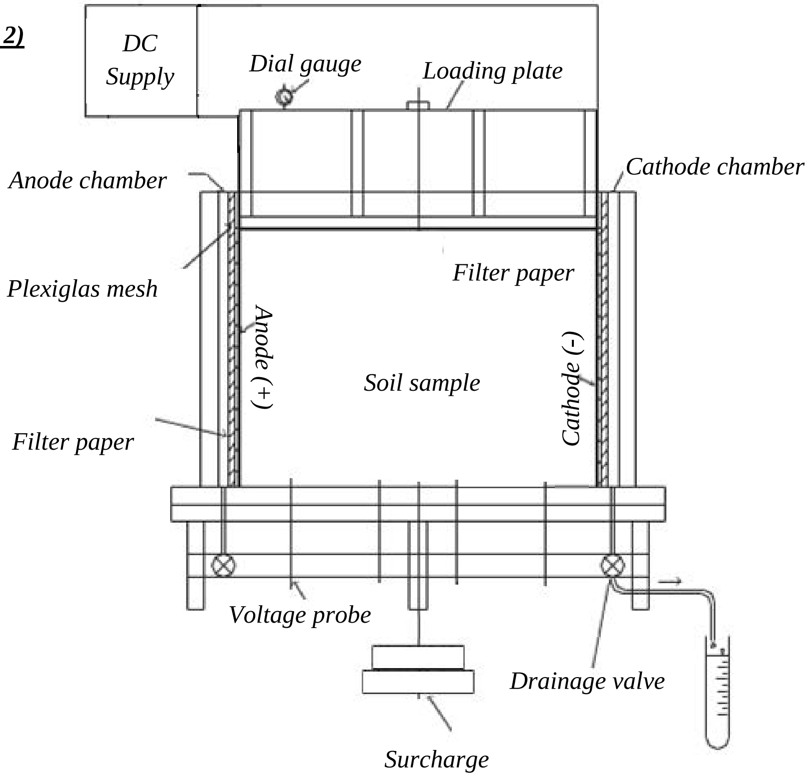
The second model is based on modification of triaxial or odeometer equipment. The concept of this model is same as model 1. This model has electrode chambers with a drainage at the cathode chamber. In this model, a surcharge can be applied to the soil using a loading plate. Application of surcharge improves the electrokinetic method. However, not only the use of this model of set-up is limited to laboratory scale experiments, this model is not applicable in case of soil slurry.

The third model is commonly used to dewater and stabilize slurries. This model is comprised of an electrokinetic cell with a settlement column that is connected to a plain Perspex sheet at the bottom. The rim of the settlement column is to be screwed to the plain Perspex sheet. The plain Perspex sheet has an opening in the centre to pass the wire from the electrode out of the system. The electrodes are to be placed at the bottom and top of the soil sediments with a filter paper in between. The process starts when the electrodes are connected to the direct current supply.

(Model 1)



(Model 2)



(Model 3)

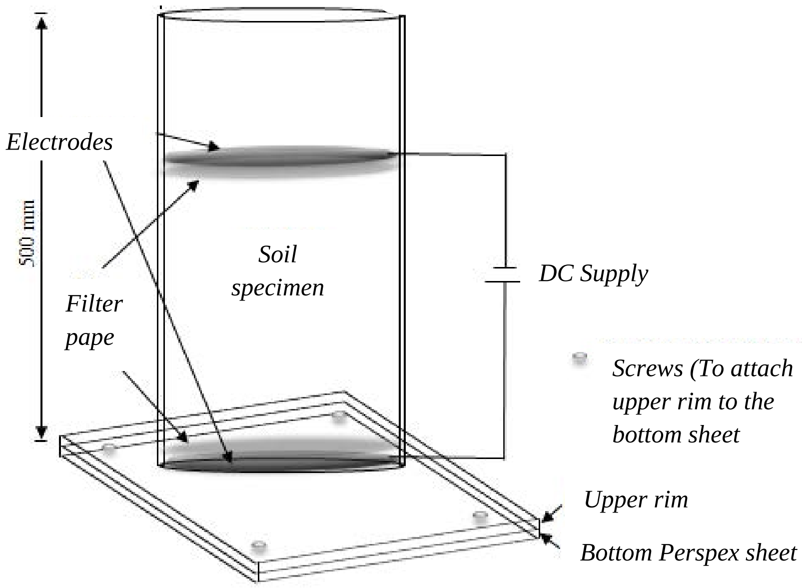


Figure 2.5 Electrokinetic stabilization models presented in the literature

2.8 Theoretical framework for electrokinetic consolidation of soils

Numerous studies on electrokinetic stabilization either in-situ or in the laboratory have been performed (e.g. Gray 1970; Ozkan et al. 1999; Alshawabkeh and Sheahan 2002; Ou et al. 2009) with the ultimate conclusion that this method is one of the most innovative and cost-effective methods for treatment of different types of soils (especially clay and silty soils). However, there is still much to be investigated to optimize the effectiveness and efficiency of this treatment. Esrig (1968) has defined different boundary conditions based on the water flow through electrodes. For instance, if there is no water to flow from the anode (i.e. anode closed) the volume change by the electroosmosis consolidation method is equal to the volume of the draining water. Table 2.6 shows these boundary conditions and pore water pressure for possible cases of electroosmotic consolidation.

Electroosmotic permeability and electroosmotic flow adhere to the principle of Darcy's hydraulic law. The difference is that the electric gradient replaces the hydraulic gradient ($\frac{\Delta H}{\Delta L}$)

$$Q_h = k_h \, i_h \, A = k_h \, \frac{\Delta H}{\Delta L} \, A \qquad (2.12)$$

where Q_h (m^3/s) is the quantity of water flow induced by hydraulic gradient in m^3, A (m^2) is the cross sectional area of the specimen through which the flow takes place (cm^2), $\frac{\Delta H}{\Delta L}$ is hydraulic gradient where ΔH *(m)* is the hydraulic head and ΔL *(m)* is the length of the soil sample. Therefore, the electroosmotic theory of consolidation as proposed by Casagrande (1952) based on Darcy's law is:

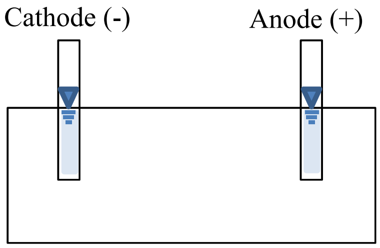
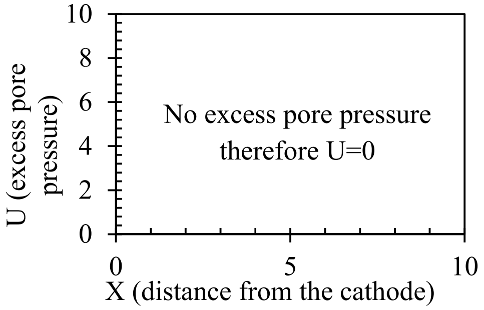
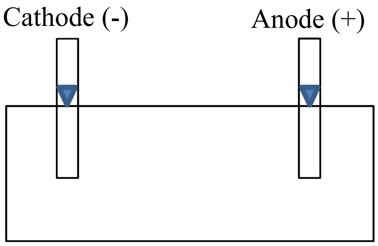
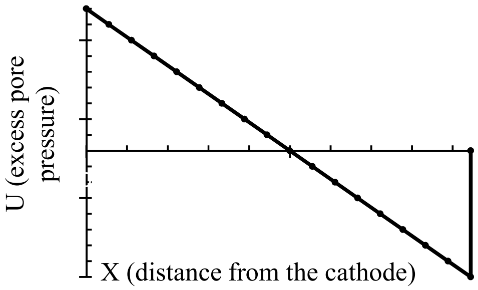
$$Q_e = k_e \, i_e \, A = k_e \, \frac{\Delta V}{\Delta L} \, A \qquad (2.13)$$

where Q_e (m^3/sV) is the quantity of water in m^3 which moves through an area of A (m^2) under an applied gradient of $i_e = V/L$ (volt/m) to a soil with electroosmotic permeability of k_e (m^2/V.s). The parameter, which governs the flow of water under an electric current, is electroosmotic permeability k_e, similar to k_h in conventional consolidation theory. According to Shang (1997), if both the anode and the cathode are open, then flow veloctiy can be determined by the following equation:

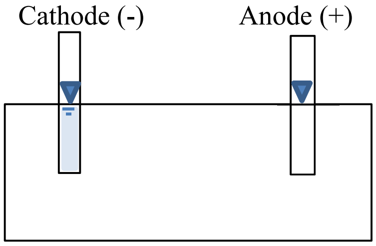
$$Q_e = k_e \, E \qquad (2.14)$$

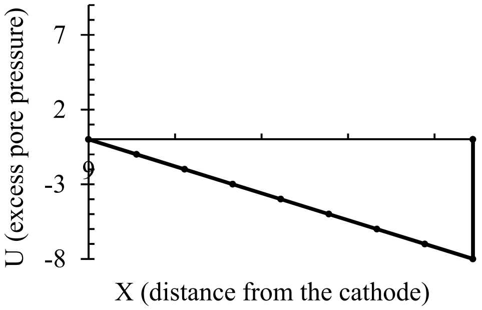
E (V/m) is the electric field intensity that is the electrical potential difference *(V)* over the distance d (m) and is the strength of the electric field. In fact, it is the force on a unit positive charge at a specific point.

Table 2.6 Boundary conditions and pore water pressure (Modified from Esrig 1968)

Condition	**Pore pressure distribution**
Open cathode-open anode:  	
Closed cathode - closed anode:  	 $U = 0.5\frac{k_e}{k_h} E_0 \gamma_w$ E_0 is applied electric potential k_e is electroosmotic permeability k_h is hydraulic conductivity γ_w is unit weight of water

Open cathode-closed anode:

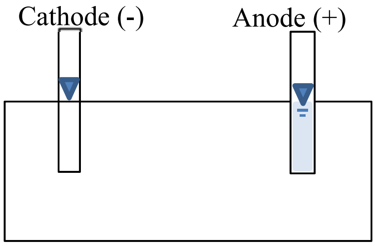


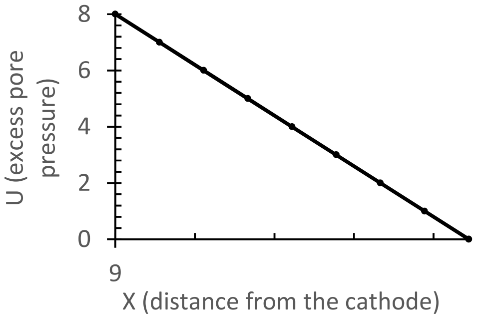


$$U = -\frac{k_e}{k_h} E_0 \gamma_w$$

E_0 is applied electric potential
k_e is electroosmotic permeability
k_h is hydraulic conductivity
γ_w is unit weight of water

Closed cathode-open anode:





$$U = -\frac{k_e}{k_h} E_0 \gamma_w$$

E_0 is applied electric potential
k_e is electroosmotic permeability
k_h is hydraulic conductivity
γ_w is unit weight of water

Theoretical framework for electrokinetic consolidation of soils

The electroosmotic consolidation theory is generated on the basis of consolidation theory, which is based on the quantification of water flow through the soil mass. The water flow in electroosmosis depends on the hydraulic conductivity (k_h) and electroosmotic permeability (k_e) of the soil. The flow velocity V_s (m/s) based on these two parameters is formulated by Schaad and Haefeli (1947). Following Schaad and Haefeli (1947) and Esrig (1968), Lewis and Humpheson (1974) formulated a two-dimensional flow based on two-dimensional application of electrical field (Figure 2.7).

All of the mentioned equations are derived in the following assumption: 1) the soil is saturated and homogeneous, 2) a constant electrical field with respect to time is applied, 3) there would be no electrochemical reactions, 4) there would be no movement of soil particles, 5) soil has uniform and constant physical property, and 6) all ranges of applied voltage is effective (Mitchel and Saga 2005). The electroosmotic formulations are mainly one-dimensional or two-dimensional with the similar concept.

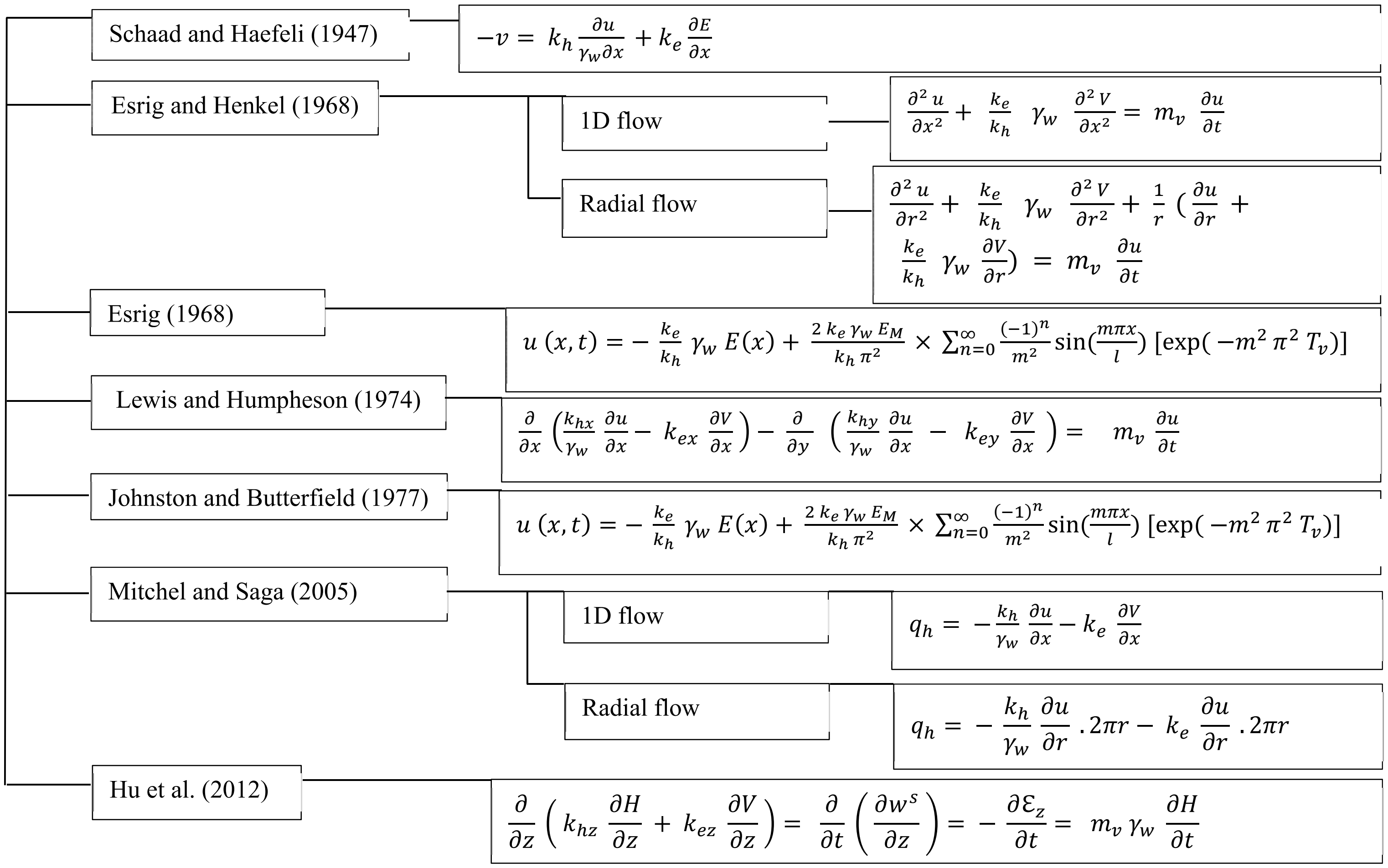


Figure 2.7 Theoretical framework of electrokinetic stabilization

2.10 Summary

An overview of theoretical and experimental studies on electrokinetic stabilization has been presented in this chapter. The review shows the effect of different factors on the efficiency of electrokinetic consolidation. Understanding the effect of these factors on electrokinetic consolidation process helps to achieve optimal design criteria. Different methods have been reported in the literature to overcome the current limitations of electrokinetic stabilisation. However, further enhancement to the method should be adapted in the line of developing a standard design criteria and to make the method more accessible to geotechnical engineers.

Loss of soil-electrode contact, which is the result of oxidation and reduction reactions near the anode and cathode, interrupts the flow of electric current through the soil. This effect is mainly observed when metal electrodes are used. Electrokinetic geosynthetics (EKGs) seems to solve this problem. However, EKGs are not yet commercially available and the connection between the EKGs and power supply is not clearly defined in the literature, which seems to be a problem that needs further investigation before making any decision on using EKGs. Therefore, due to the low cost and availability of the metal electrodes, it is still desirable to use metal electrodes for laboratory and field simulations. There are very few studies on the effect of electrode material on electrokinetic stabilization of dredged mud in the literature. Therefore, the effect of electrode material needs to be further investigated.

After some time, the electric current applied to the soil drops due to an increase in soil resistivity, when the same voltage is applied. At this point, the applied voltage should be increased in order to maintain the electric current, which leads to higher power consumption. However, this is applicable when the electric current is intended to remain constant. To keep the electric current constant during the process, a stable direct current power supply required which is expensive. Effect of commonly available low cost power supplies is important to be investigated as it reduces the overall cost of the project. Very few studies investigated the effect of constant voltage and the literature is mainly focused on the constant electric current application. The effect of adopting a constant voltage (electric potential) needs to be further investigated.

Electrode configuration is another parameter that affects the efficiency of the electrokinetic stabilization. One-dimensional (using one cathode for each anode) and two-dimensional (using more than one cathode for each anode) electrode configurations are presented in the literature. One-dimensional electrode configuration is the most commonly used configuration for stabilizing and strengthening soils, and it appears that a two-dimensional electrode configuration is rarely used. Very few studies have investigated the effect of electrode configuration on the electrokinetic stabilization of dredged marine sediments for land reclamation purposes. Therefore, in this study different electrode configuration are used to determine the best laboratory set-up to stabilize dredged marine sediments.

The electrokinetic stabilization set-up using the settlement column is presented in the literature. However, whether placing the anode on the top or at the bottom to maximize efficiency is not obvious. Further, a clear comparison based on soil settlement and its effect on electrokinetic stabilization is unavailable. Therefore, there is a need to investigate which electrode placement provides better results which is further investigated in this study.

As explained earlier in this chapter, methods such as application of intermittent current, polarity reversal and anode depolarization are potential methods to improve the drawbacks of the electrokinetic stabilization method. Application of intermittent current is reported to reduce the corrosion of the anode and improve the efficiency of the electrokinetic stabilization. However, this is true for application of regular intermittent current, which is mainly investigated in the literature. Investigations on effect of irregular application of electric potential on electrokinetic settlement, variation of electric current and its effect on overall efficiency of the electrokinetic stabilization needs to be investigated.

All the theoretical models proposed in the literature for estimating the electrokinetic consolidation of soils are mainly known as Esrig (1968), Johnston and Butterfield (1977), Hu et al. (2012) models. The proposed model by Esrig is based on constant parameters such as electric potential and soil properties. However, in practice this model is far from reality since during electroosmotic stabilization many parameters are changing which results in improvement of the soil. In order to improve the Esrig model, Johnston and Butterfield (1977) proposed a model based on the changes of electric potential. But still both models were based on constant soil properties, thus further investigation is required to consider the changes of soil properties during electrokinetic stabilization. For this purpose, Hu et al. (2012) presented a model based on the changes of soil properties. However, the effects of physiochemical changes during electroosmotic consolidation are not investigated and this needs to be further examined.

In general, this chapter has reviewed the applicability and effectiveness of variety of methods and has discussed the limitations of electrokinetic stabilization as well as the different aspects of the method that needs further investigation.

Chapter 3: Materials and preparations

3.1 General

In this chapter, the properties of the soil and the method of sample preparation used throughout this study are discussed in detail.

3.1.1 Material: soil

Samples of dredged material used in this study are obtained from the land reclamation area in port of Brisbane, Queensland, Australia. When the sediments are dredged, they are often poured into the containment paddocks to go through self-weight sedimentation. When the dredged sediments are initially pumped into the paddocks, they have a very high water content ranging from 350% to 450%. The water content of the dredged marine sediments reduces to 250% to 300% due to air and sun drying. The dredged mud used in this study is taken from paddock C1 (Figure 3.1). This is due to two reasons, one is the moisture content of the sample at this paddock which is reduced to 250% and the other is its location since it is located at the centre of the area which is the ideal location of soil sampling as it is less disturbed by its surrounding.

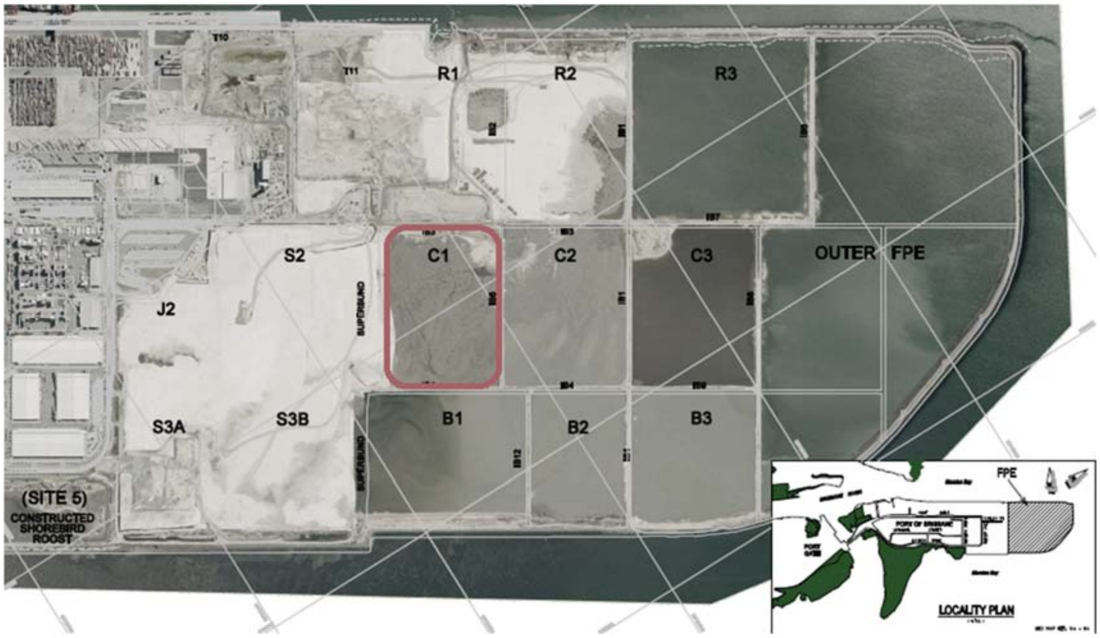


Figure 3.1 Plan view of port of Brisbane showing the location from which the samples were taken

The mineralogy study of the dredged mud that is performed by Advanced Analytical Centre (AAC) at James Cook University is demonstrated in Table 3.1. The behaviour of the soil depends on the type of mineral present in the soil.

Table 3.1 Mineralogy of the dredged mud obtained from port of Brisbane (modified from Ganesalingam 2013)

Name of the minerals	**% weight**	**Importance** **	**Characteristics**
Quartz - (SiO_2)*	31	Mostly sand and silt	Retention of Na, k, Ca, Mg, Fe(II), and Silica, alkaline parent rock
Illite/ Muscovite - $K_2[Si_6Al_2]Al_4O_{20}(OH)_4$*	21	Abundant mineral in clay as a result of weathering	
Kaolin - $[Si_4]Al_4O_{10}(OH)_8\cdot nH_2O$ (n=0*** or 4)*	25		Low pH, Removal of Na, K, Ca, Mg, Fe (II) and Silica can be by leaching in fresh water
Amphibole - (Ca, Na, K)2,3(Mg, Fe, Al)5(OH)2	2	Easily weathered and oxidized	Low water and humus content, limited leaching environment
Sodium Plagioclase - $NaAlSi_3O_8$*	-	Abundant mineral in not leached soils	
Sodium Calcium Plagioclase - $(Na, Ca)Al(Si, Al)_3O_8$*	2		
Potassium feldspar - $KAlSi_3O_8$*	11		
Calcite - ($CaCo_3$)	-	Carbonate	
Halite - (NaCl) – (g/l)	35*****	Salt	-
Pyrite - FeS_2	5	Sulfide mineral – (Fool's gold)	-
Expansive Clay - $(Na, Ca)0.33(Al, Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$*	2	very soft phyllosilicate	-
Organic Content (%)	0.4 - 1	-	-
*silicate groups, have soluble Na^+, Mg^{2+}, K^+, Ca^{2+}, Mn^{2+}, Fe^{2+}, and metal cations Co^{2+}, Cu^{2+}, and Zn^{2+}. ** Sposito (2008) *** n is the number of moles of hydration between layers **** Laventure and Warkentin (1965)/ (Average organic content of the marine clays) ***** Quigley (1980)			

The presence of metal elements in the soil especially contaminants affect its behaviour by interacting with its minerals and raise environmental issues. Pyrite (FeS_2) is one of the commonly found minerals from sulphides group. Pyrite is one of the unstable minerals that weather into sulphuric acid due to oxidation process and forms acid sulphate soils (Karathanasis, 1982). Pyrite has a very large surface area, and it reacts immediately in presence of air. Illite has a specific area of 65 to 100 m^2/g with flaky particles. Dredged mud consist of

21% Illite. Silicate is the most abundant element on earth. Dredged mud is mainly consisting of Quartz and feldspars.

The ICP-AES (Inductively coupled plasma atomic emission spectroscopy that is used to detect the existence of trace metals) and ICP-MS (Inductively coupled plasma mass spectrometry is used to detect trace of metals at low concentration of one part in 10^{15} part per quadrillion) are conducted by Advanced Analytical Centre (AAC) at James Cook University. The metal elements and their concentration are presented in Table 3.2. According to the limits presented in environmental Australian Capital Territory (EPA 1999) and environmental protection (DEP 2004), the dredged material in this study is not contaminated.

Table 3.2 Metal elements in the dredged mud (Ganesalingam 2013)

Element	**Concentration (mg/kg or ppm)**	**Element**	**Concentration (mg/kg or ppm)**
Ag	< = 0.05	Cu	18.1
Al	3970	Fe	28500
As	7.02	Hg	≤0.5
Ba	51.3	Mn	695
Be	0.9	Mo	1.02
Cd	0.431	Ni	17.2
Co	15.1	Pb	13.7
Cr	18.1	Sb	< = 0.05
Se	< = 1	Ti	0.097
Zn	55.3	-	-

Table 3.3 shows the physical and chemical properties of the dredged mud along with the standard used to determine the related property. According to the Unified soil classification system, the dredged mud is classified as highly plastic sandy clay (CH).

Table 3.3 Physical properties of the dredged mud

Property	**Value**	**Standard**
Liquid limit (%)	92	AS1289.3.9
Plastic limit (%)	35	AS1289.3.2.1
Plasticity index (%)	57	PI = LL-PL

Linear shrinkage (%)	18-19	AS1289.3.4.1.
Sand (%)	20	AS1289 3.6.3
Silt (%)	38	
Clay (%)	42	
Specific Gravity	2.61	AS 1289.3.5.1.
Soil classification (USCS)	CH	Unified soil classification system
pH	8.05-8.13	Refer to section. *ppt = Part per thousand
Electrical conductivity (mS/cm)	4.8	
Salt content (ppt)*	2.9	
Colour	Grey	Visual identification
Activity	0.82-0.88	Activity = $\frac{PI}{\%\ Clay\ (particles < 2\ \mu m)}$
Specific surface area (m^2/g)	130	Farrar and Coleman (1967) equation (± 20%) LL=19+0.56A$_s$ where LL is liquid limit, and A$_s$ is specific surface area in m2/g.

3.2 Methods

3.2.1 Sample preparation

3.2.1.1 Sample preparation for settlement columns

Step 1. setting the moisture content to the initial condition of dredged marine sediments: When dredged marine sediment is stored in the Geotechnical laboratory, its water content reduces to about 60% due to evaporation. Therefore, to replicate the initial condition of the soil received from the port, water is added to the soil to bring up the moisture content to 250% until consistent homogeneous slurry is obtained. The added water is either distilled water as a substitute for freshwater or saltwater that is taken from the seaside foreshore located in the Strand, Townsville. The salinity of the saltwater is measured using mass measurement and the correlation between salinity of the water at port of Brisbane and strand is determined (Figure

3.2). Accordingly, the saltwater from port of Brisbane has same salinity. The 0.0098% error is attributed to the laboratory condition and human error that may occur during the measurement. The correlation is determined by bringing up the salinity of the water to the set values of g/l concentration. For this purpose, 4 beakers are filled with a same specific amount of strand saltwater and 4 beakers are filled with saltwater from port of Brisbane. The concentration of the water is reduced by adding distilled water.

The correlation between the measured values of salinity with the probe in ppt and g/l is determined and shown in figure 3.2. The salinity of the saltwater is monitored using the probe shown in figure 3.3. To monitor the concentration of the saltwater while adding distilled water to reduce the salinity to the desired value, the probe is inserted to the saltwater samples. Once the equivalent salinity in ppt is reached the sample is left aside for salt content measurement using the mass measurement method. The method of mass measurement for determining the salinity of the water involves leaving the saltwater in the oven until completely dried, then the salinity of the saltwater is determined based on the measured mass of the salt crystals in proportion to saltwater mass that is tested.

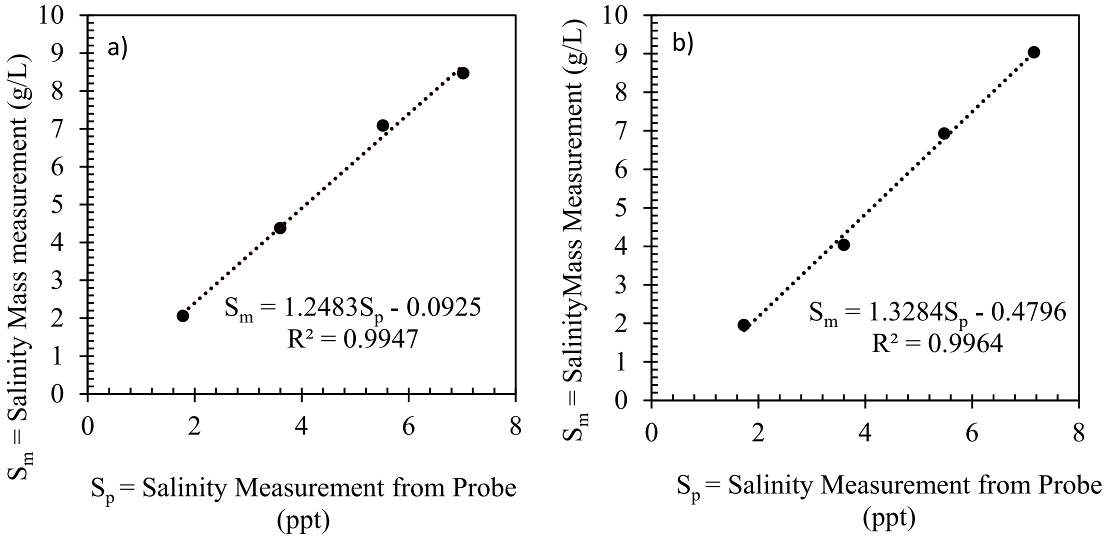


Figure 3.2 Correlation between salinity of salinity obtained with probe and mass measurement a) Port of Brisbane saltwater b) Strand saltwater

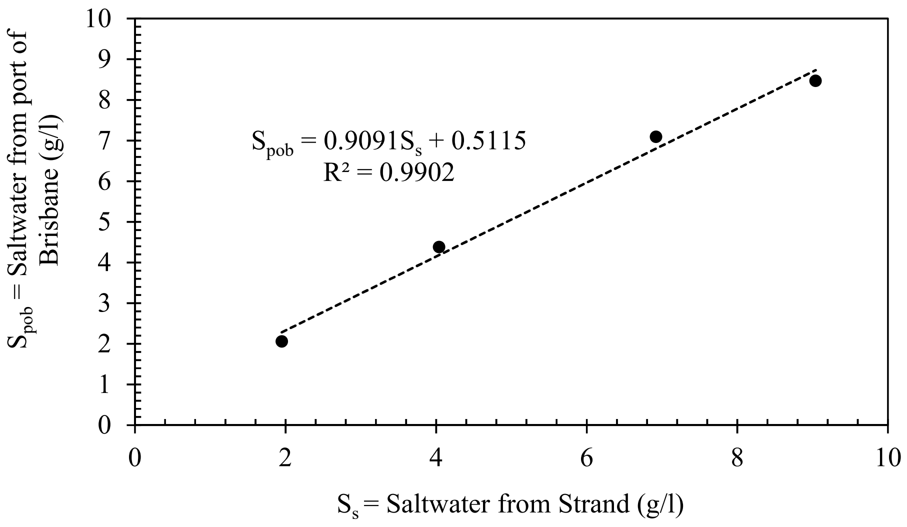


Figure 3.3 Correlation between salinity of the saltwater from port of Brisbane and the salinity of the saltwater from Strand beach

Step 2. Removing stones and shells in the soil: when the water content of the slurry is brought to 250%, the soil mixtures are then passed through 4.25 mm sieve to remove any shell and large stones that interrupt the analysis.

Step 3: Measurement of soil salinity, electric conductivity and pH: when the soil is prepared the salinity of the slurry is determined with the following method:

After mixing the slurry thoroughly, couple of small representative samples are taken from the mixture. The samples are left in the oven to dry completely. The dried samples are then pulverised and passed through 2.36 mm sieve and mixed with water in 1:5 soil-water mass ratio. There are different methods of measurements. In traditional methods, soil samples are dried and ground before being brought up to 1:5 soil water ratio and, then, left for a specific time to settle (Allan and Hodgins 2003). The proposed waiting time before any measurements is 4-16 hours. Walker (2008) suggests a mixing time greater than 30 minutes and a waiting time of 15 minutes prior to any measurements. Rayment and Higginson (1992) proposed a mechanical shake of an hour and waiting time of 20-30 minute prior to measurements.

The ratio of soil and water at which electrical conductivity should be measured is another matter to be considered. The popular soil-water ratio for measurement of electrical conductivity and pH is 1:5 (dry mass) in Australia and 1:1 in America. In this study, 1:5 soil-water ratio is used for sample preparation. Then, the mixture is left on a magnetic stirrer for an hour to mix thoroughly. Since dredged mud sediment settles slowly due to its low permeability, the mixtures are left to settle for 24 hours prior to any measurements. Then, the chemical properties of the mixtures are determined using a microprocessor-based waterproof pH/Conductivity/Temperature tester (Figure 3.4).

The electrical conductivity of the soil varies depending on soil porosity, water content, salinity, degree of saturation, and density. The conductance path is mostly through capillary liquid. The critical temperature at which electrical conductivity should be measured is 25 degrees Celsius. If the instrument does not have ATC (automated temperature correction), the measurements should be converted according to the following equation:

$$EC_{25} = f_t \, EC_t \tag{3.1}$$

where EC_{25} is the electrical conductivity of the soil measured at 25 degrees Celsius, EC_t is the electrical conductivity f_t is the temperature factor which can be determined from the following equation as suggested by Sheet and Hendricks (1995):

$$f_t = 0.4470 + 1.4034 \, e^{-t/26.815} \tag{3.2}$$

Figure 3.4 Waterproof pH/Conductivity/Temperature tester probe with calibration kit

Conclusion

This chapter explains the location where the samples for this study is taken from, the properties of the soil with its mineralogy, and the method of sample preparation to be treated with electrokinetic stabilization. The method of measuring soil salinity is given. The salinity measurement is based on two methods of mass measurement and the probe measurement. The correlation between mass measurement and the probe measurement is determined to ensure that accuracy of the probe and to find a conversion factor between g/l and ppt. In next chapter, the effect of electrode configuration on electrokinetic stabilization is presented.

Chapter 4: Electrode configuration

4.1 Background

The configuration of electrodes has been reviewed in chapter 2. This chapter focuses on how different electrode configurations affect the electrokinetic stabilization of soils. The effectiveness of the process is largely a function of the extent of effective area where the soil changes physio-chemically, as it is these changes that produce electrokinetic stabilization. The physiochemical changes in the soil are due to the oxidation and reduction reactions that occur near the anode and cathode, respectively. The parallel installation of anodes and cathodes is the most common type of electrode configuration presented in the literature. This configuration was initially developed to decontaminate soils, and then was used by Casagrande in 1949 and later by other researchers to stabilize soils. With this configuration, the region where electrochemical reaction occurs is more localized than with other configurations such as a two-dimensional configuration. As noted, it is the physiochemical reactions in the soil that result in cementation and soil strengthening, hence the broader the area affected by physiochemical reactions, the better the soil improvement will be.

A two-dimensional configuration is when more than one electrode of opposite polarity is installed for every electrode. Therefore, a greater area is affected by physiochemical reactions resulting in better stabilization. In a two-dimensional electrode configuration, if the purpose is specifically to improve the dewatering process, it is advisable to have more cathodes than anodes. However, if electrokinetic stabilization is being used specifically to improve the strength of the soil, anodes should be installed more dominantly. Sahib and Vinod (2010) showed that the tetrahedral configuration shape with the cathode at centre increased the shear strength of the soil by 76% and the tetrahedral configuration shape with the anode at the centre resulted in better dewatering by 33 %.

The effect of electrode configuration on performance reported in the literature, is mainly in relation to attempts to decontaminate soils (e.g. Kim et al. 2010; Cameselle et al. 2013; Jeon et al. 2015; Popescu et al. 2016). Some studies investigated the effect of electrode configuration on soil dewatering (Fourie et al. 2007; Rittirong et al. 2008; Sahib and Vinod 2010). However, very few studies investigated the effect of electrode configuration on electrokinetic consolidation and strengthening of dredged marine sediments. The effect of electrode configuration on dewatering and strengthening of dredged marine sediments is specifically the topic of this study and is investigated and explained herein. The aim of this study is to investigate the best electrode configuration to maximize the electrokinetic settlement of the dredged mud.

4.2 Horizontal electrode configuration

4.2.1 One-dimensional and two-dimensional electrokinetic stabilization

A one-dimensional configuration is when the one-dimensional electromagnetic field is applied through identical number of anodes and cathodes that are installed in parallel to each other. In this case, the spacing between the electrodes governs the effectiveness of the treatment as it dictates the effective area that is treated. Figure 4.1a shows the effective area between the electrodes with different spacing in one-dimensional arrays. The spacing between electrodes affects the effectiveness of the electrokinetic stabilization. Shorter spacing results in better soil stabilization. However, a much shorter spacing requires a significantly larger number of installed electrodes. Installation of more electrodes results in higher electric density and as a result higher power consumption.

Two-dimensional electrode configurations increase the effectiveness of electrokinetic stabilization. Figure 4.1b shows the most popular two-dimensional electrokinetic stabilization arrangements. In this configuration, if number of anodes are greater than number of cathodes, the acidic environment created by electrolysis of the anode is extended to a larger effective area. This is desirable if cementation near the cathode does not happen. Cementation near the cathode occurs due to three reasons. The first reason is the accumulation of cations from metal electrodes that migrate from the anode to the cathode forming a cementing agent as a result of cation exchange reactions (Casagrande 1948). Second reason is the amount of organic matters in the soil. Soils with higher organic matter result in better cementation near the cathode (Ou et al. 2015). And the third reason is the level of soil alkalinity near the cathode resulting in cementing reactions, as cementation near the cathode occurs when the soil alkalinity is higher than 8.7. Depending on the soil mineralogy, the rise of pH near the cathode prepares the condition for soil cementation (Asavadorndeja and Glawe 2005). Cementation near the cathode results in an increase of soil strength. The strength of the soil near the anode increases due to the reduction of water content that is caused by electroosmosis. The electrolysis at the anode improves the strength of the soil through cation exchange reaction, which depends on the type of electrode used. The increase of strength near both electrodes results in better soil improvement. However, if the soil near the cathode does not improve, the effective area that is improved can be increased by increasing the number of anodes if the purpose of the treatment is to improve the strength of the soil. Otherwise, for dewatering purposes installation of more cathodes result in better drainage.

The affected and non-affected areas are shown in Figure 4.1 for both one-dimensional and two-dimensional electrokinetic stabilization. The coloured configuration is used in this study. The affected and non-affected areas are influenced by the electric field potential depending on the polarity of the electrodes. The area between two identical electrodes are not influenced by electric field since they repel each other. Only the area between two non-identical electrodes is affected by the electrokinetic stabilization. The electric field lines between two identical and non-identical electrodes are shown in Figure 4.2.

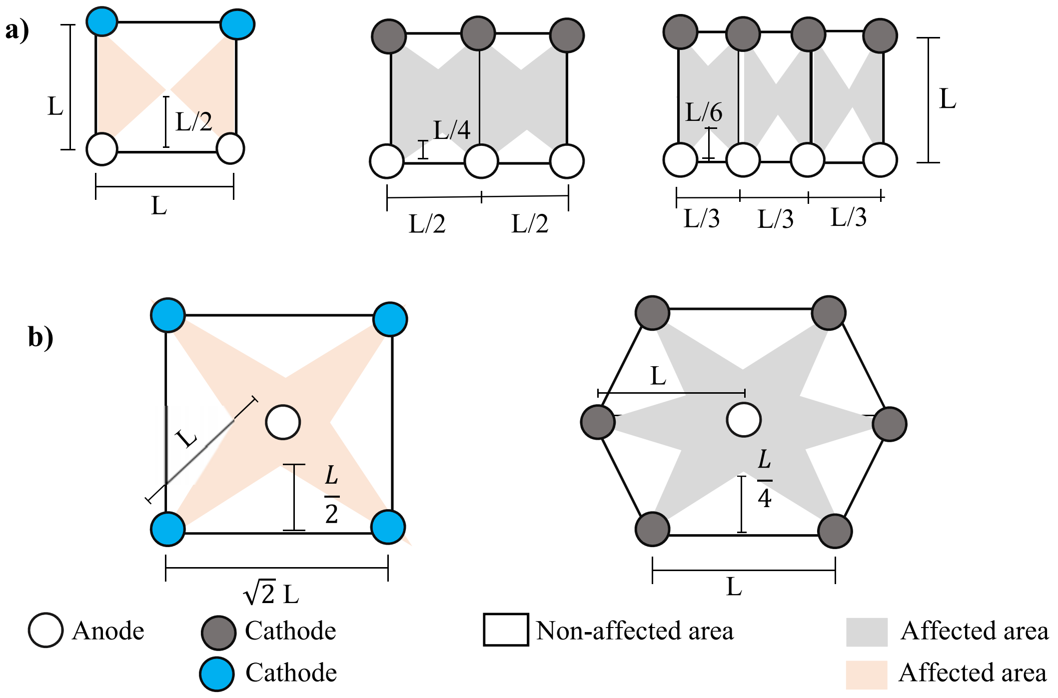


Figure 4.1 a) One-dimensional electrode configuration (2 array electrodes experimented in this study) b) Two-dimensional electrode configuration – 4 cathodes, one anode in the centre is experimented herein (Alshawabkeh et al. 1999b)

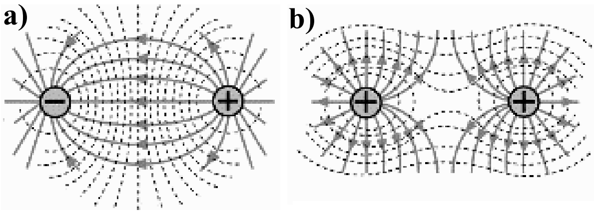


Figure 4.2 a) The electric field between two non-identical electrodes b) The electric field between two-identical electrodes (Ogborn et al. 2000)

In this section one-dimensional electrode configuration is adapted in the laboratory to investigate the effect of this type of configuration on electrokinetic stabilization of the dredged mud through monitoring the changes of consolidation characteristics.

4.3 One-dimensional electrokinetic stabilization trial

4.3.1 One-dimensional electrokinetic set-up

In this study to set-up the one-dimensional electrokinetic stabilization experiments, two hollow galvanized steel electrodes with inner diameter of 19 mm and outer diameter of 22 mm were used. The water was collected from the cathode due to electroosmosis. As explained earlier in chapter 2, electroosmosis is the flow of water from the anode to the cathode. Therefore, the water accumulates in the cathode, from where it can be collected. For this reason, the cathode is perforated and wrapped with a filter paper to avoid the blockage of the perforations. When the electrodes are placed in the Perspex box, the soil slurry that is prepared beforehand (for detailed sample preparation refer to section 3.2) is poured into the Perspex box until the sediment reaches a thickness of 70 mm. When the Perspex box is filled with the slurry, the electrodes are connected to the power supply and a voltage gradient of 30 Volts is applied to the slurry.

Figure 4.3 shows the schematic view of the one-dimensional electrokinetic set-up. This experiment is performed firstly to investigate the response of dredged marine sediments to electrokinetic stabilization and secondly to test the suitability of this electrode configuration. The effect of electrokinetic stabilization using two array electrodes is tested through examining its effect on consolidation properties of dredged marine sediments. To examine the consolidation behaviour of the dredged mud after electrokinetic stabilization, two samples of 38 mm diameter were taken. One sample was taken from the area near the anode and the other sample was taken from the area near the cathode. These samples were then tested in an oedometer.

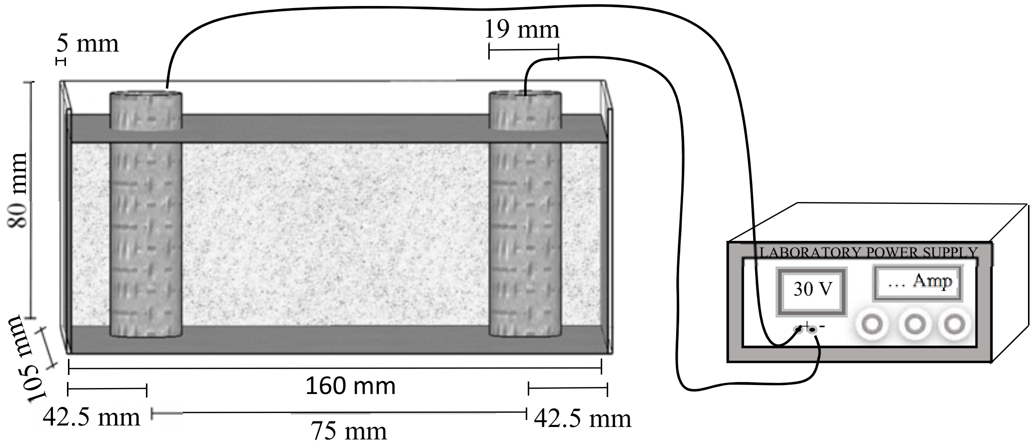


Figure 4.3 Schematic view of one-dimensional electrokinetic stabilization set-up

4.3.2 Compression and rebound index

Compression index or soil compressibility shows how much the soil settles due to consolidation. The degree of soil compressibility can be rated according to the compression index. Mitchell (1993) categorized soils as highly compressible if having a compression index greater than 0.4, moderate to intermediately compressible with compression index between 0.2 to 0.4, and low compressibility if it has a compression index less than 0.2. Table 4.1 shows the values of consolidation characteristics before and after electrokinetic stabilization that is obtained from the void ratio versus effective stress plot (Figure 4.4).

The compressibility of the same untreated dredged mud was determined by Ganesalingam (2011) as 0.693, which categorizes the dredged mud as a highly compressible soil. With the use of electrokinetic treatment, the compressibility of the dredged mud is reduced to 0.446 near the anode, and to 0.386 near the cathode, showing a significant improvement. The compressibility of the dredged mud reduced by up to a maximum 2.1 that of the untreated soil. The rebound index of the treated dredged mud, which is the slope of the rebound curve in void ratio-effective stress plot, near the anode and the cathode is 0.079 which is 88% lower than the rebound index of the untreated soil. Compression ratio which is $C_c/(1+e_0)$ reduced 4 times of the untreated dredged mud showing a reduction in plasticity index of the soil. However, the recompression ratio $C_r/(1+e_0)$ increased showing an increase in proportion of recompression deformation.

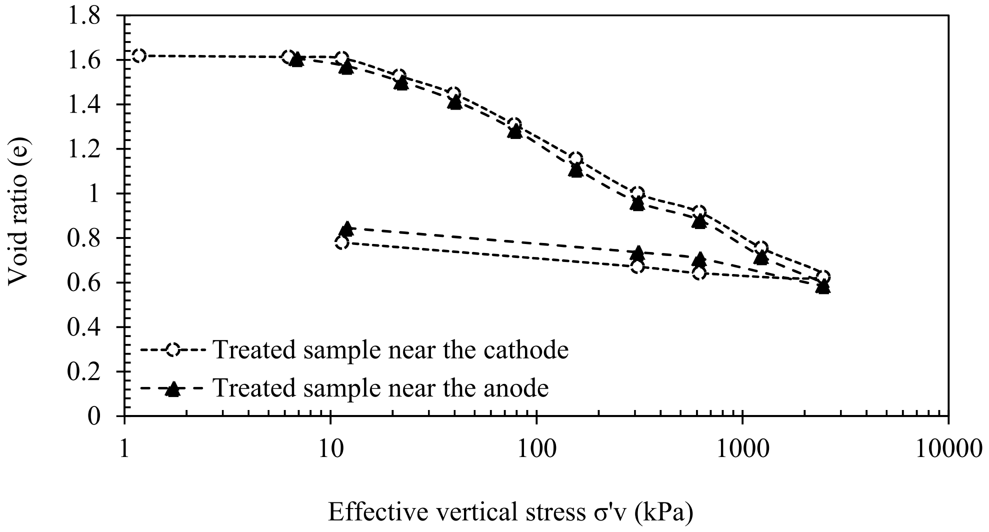


Figure 4.4 Void ratio versus effective stress of the stabilized dredged mud

Table 4.1 Compression index, rebound index, compression and recompression ratio of the treated and untreated dredged mud

	Untreated Dredged mud*	**Electro-kinetically treated dredged mud near the anode**	**Electro-kinetically treated dredged mud near the cathode**
Compression index C_c	0.693	0.446	0.386
Rebound index C_r	0.078	0.079	0.079
Compression ratio CR	0.176	0.030	0.030
Recompression ratio RR	0.019	0.017	0.015

*** Ganesalingam et al. (2011)**

4.3.3 Coefficient of volume compressibility

Figure 4.5 shows the changes of coefficient of volume compressibility with changes of effective stress near the anode and the cathode. The m_v increased for σ'_v <12 kPa and reduced as the effective stress increased, when the soil becomes stiffer. Similar behaviour was observed in untreated samples with lower ranges of coefficient of volume compressibity and this is attributed to the difference between the initial void ratios (Ganesalingam et al. 2011).

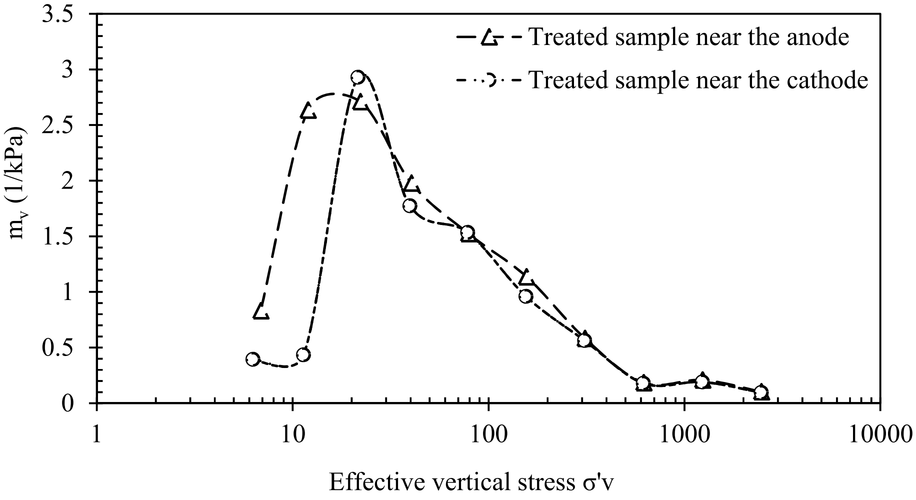


Figure 4.5 Coefficient of volume compressibility versus effective stress

4.4 Two-dimensional electrokinetic stabilization trial

As explained in section 4.2, two-dimensional electrokinetic stabilization is when more than one opposite polarity electrode is installed for a single anode or cathode. The installation of electrodes can be in rectangular, hexagonal, or circular configurations with either the anode or the cathode in the middle. The choice of the middle electrode depends on the purpose of the experiment. If the purpose is to maximize the dewatering, the anode should be placed in the middle and if the purpose is to maximize the soil strength, then the cathode is to be placed in the middle. Herein, the anode is placed in the centre to maximize the dewatering of this dredged marine slurry which has an initial water content of 250%.

4.4.1 Two-dimensional electrokinetic Set-up

Five hollow galvanized steel electrodes were placed in a Perspex box (300 mm × 200 mm × 200 mm), in a rectangular configuration as shown in Figure 4.6. The cathodes were wrapped with filer paper before placing them in the Perspex box to avoid the blockage of perforation. Once the slurry was poured into the Perspex box to a depth of 180 mm, the electrodes were then connected to the DC supply, and an electric potential of 30 V was applied.

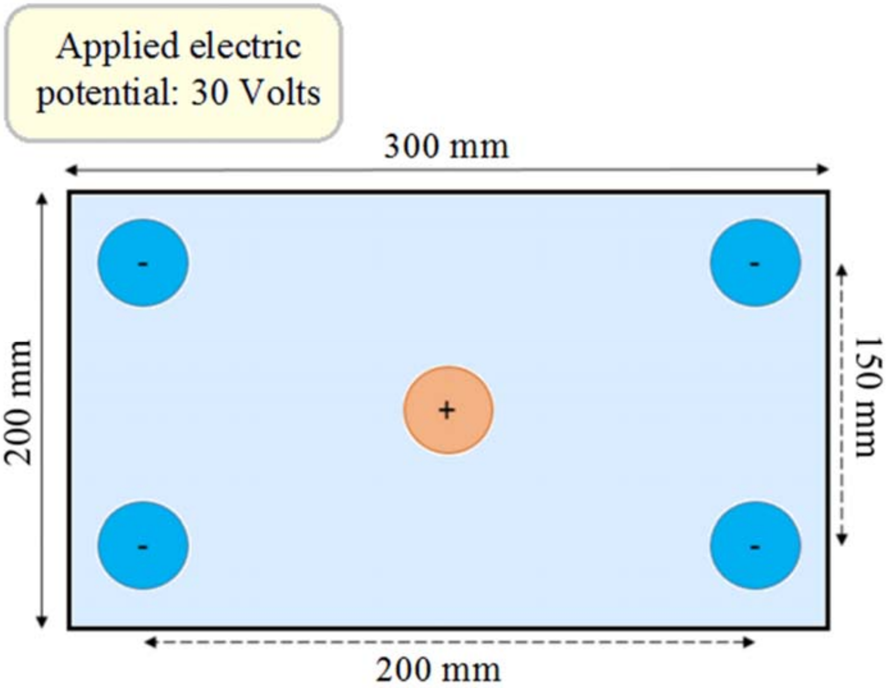


Figure 4.6 Plan view of two-dimensional electrokinetic stabilization set-up

The undrained shear strength of the treated soil which gives an indication on improvement of soil strength properties, is measured using the laboratory vane (Figure 4.7). Vane shear strength of the samples were measured after completion of the test in different locations near the anode and the cathodes where samples were taken to measure the moisture content and chemical properties of the treated dredged mud. Figure 4.8 shows the measured undrained shear strength values and Figure 4.9 shows the water content of the treated dredged mud at the same location where the vane test was performed. It is seen that the shear strength near the cathodes was lower than at the anode, indicating that no significant cementation had occurred. However, the shear strength near the cathode was still much higher than the shear strength of the un-treated slurry due to the reduction of the moisture content.

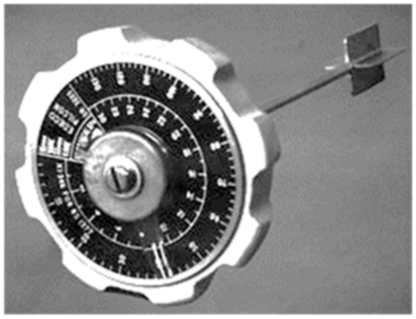


Figure 4.7 The vane shear apparatus

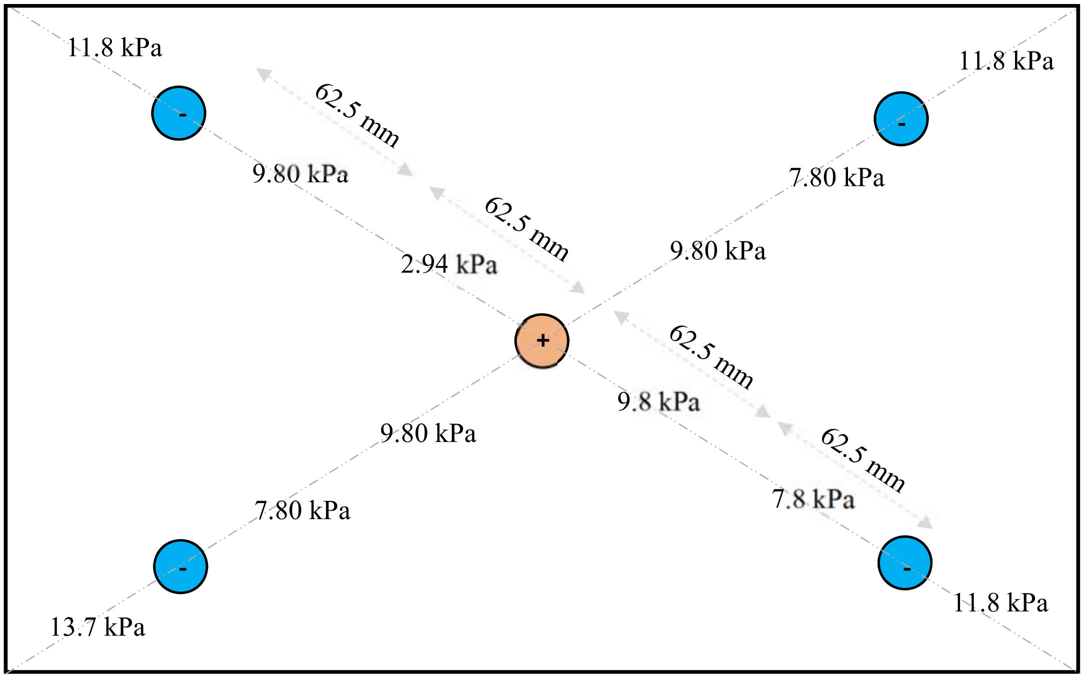


Figure 4.8 Shear strength profile after electrokinetic stabilization

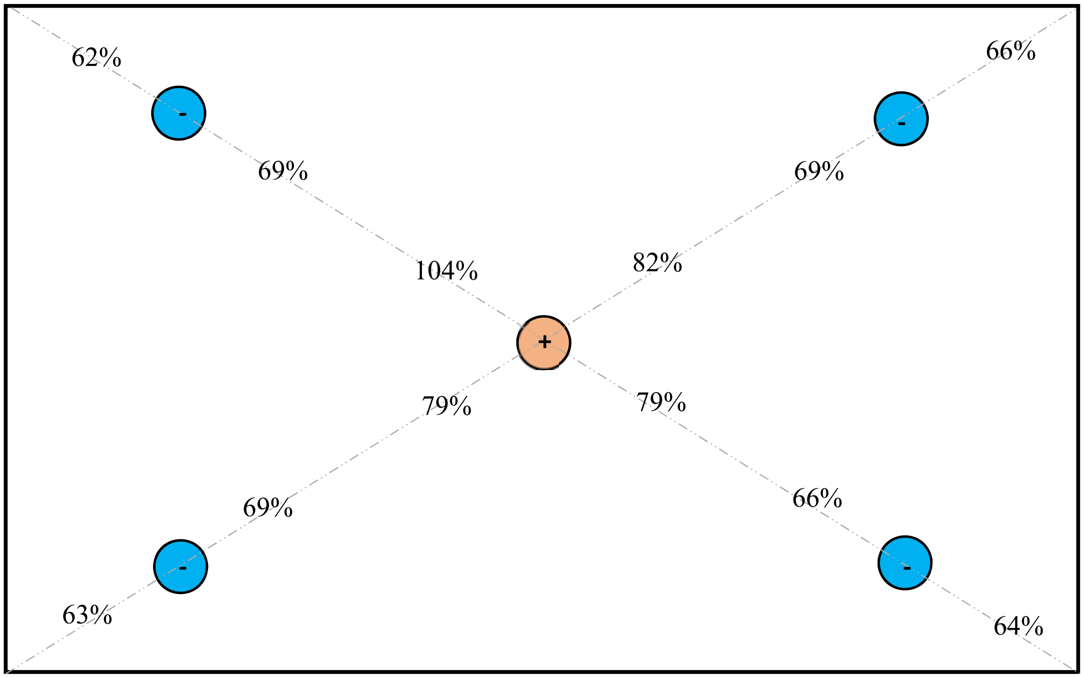


Figure 4.9 Water content profiles after electrokinetic stabilization

Figure 4.10 represents the relationship between the measured shear strength versus water content of the treated dredged mud. The relationship between shear strength and water content with 66% coefficient of correlation (r^2) is given as:

$$S_u = 65.54\, e^{-0.027\, w} \tag{4.1}$$

where S_u is the undrained shear strength (kPa) and w is the water content (%). This correlation can be used to determine the required increase in shear strength with reduction of water content of the treated dredged mud.

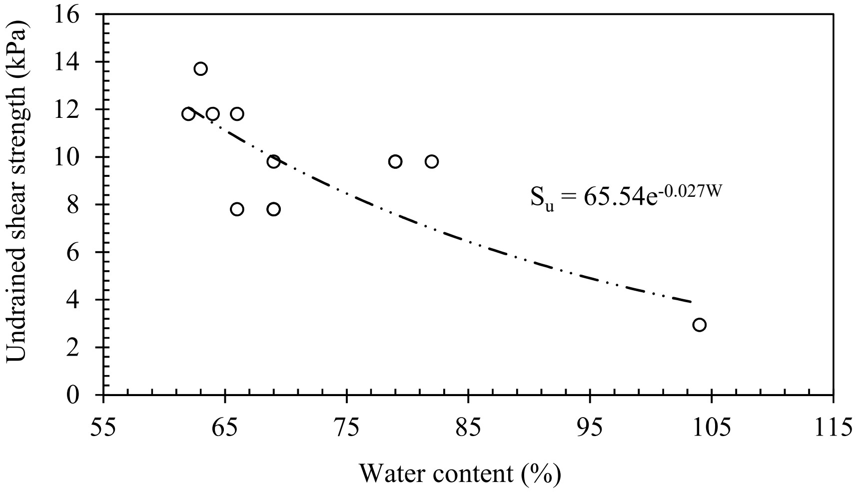


Figure 4.10 The relationship between water content and undrained shear strength

4.5 Vertical electrode configuration, investigation on placement of the anode and cathodes

Based on the one-dimensional and two-dimensional electrokinetic stabilization explained in sections 4.2 to 4.4, electrokinetic stabilization seems applicable and has potential to improve the consolidation and shear strength properties of dredged mud slurries. However, when the water content of the soil is greater than 1.5 its liquid limit, which is 2.7 times liquid limit in this study, the settling profile in horizontal (one-dimensional and two-dimensional) electrokinetic stabilization is not clear (Figure 4.11). This is due to the high surface area that leads to evaporation of the surface water and generation of desiccation cracks specifically near the anode. Therefore, to monitor the settlement of the dredged mud during the electrokinetic stabilization a vertical electrode configuration is implemented.

One of the key attributes of the vertical electrokinetic stabilization model is the placement of electrodes. The placement of electrodes is investigated to determine which method is better in maximizing the amount of settlement. Irrespective of where the anode is placed, the water flows from the anode toward the cathode due to the electroosmosis process. However, if the anode is placed at the bottom, besides electroosmosis, soil particles also move toward the bottom of the column due to electrophoresis. In the next section the effect of electrode placement on the variation of electric current, electrokinetic settlement, and the efficiency of the method based on dewatering and cumulative power consumption are investigated.

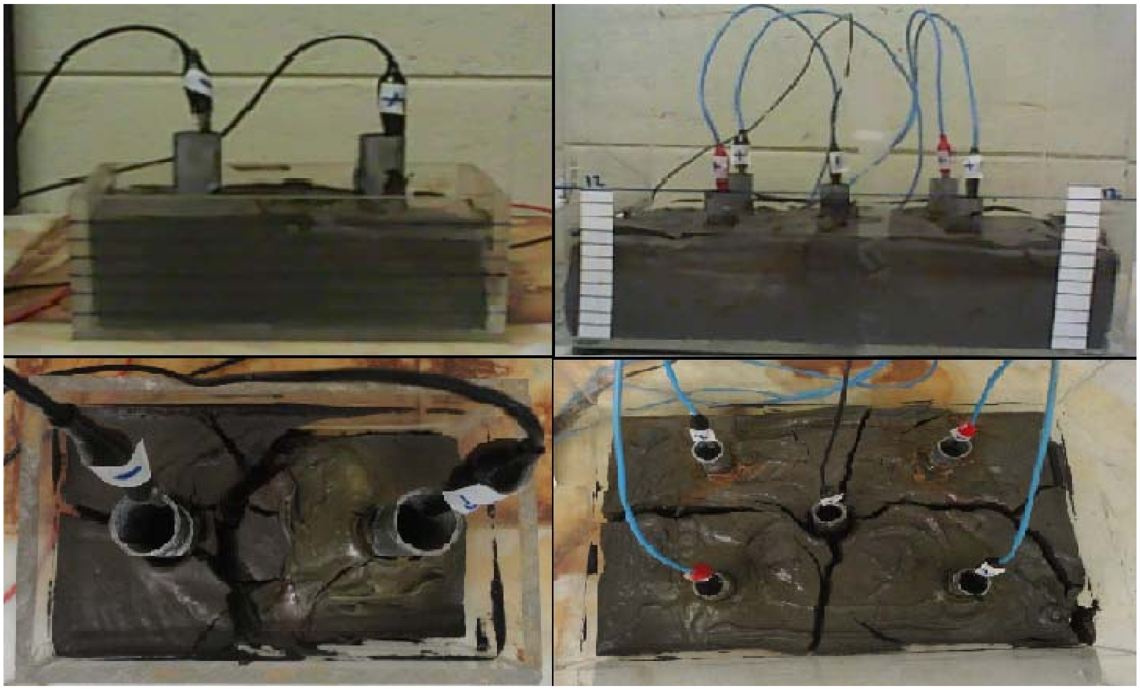


Figure 4.11 Settling profile in one-dimensional and two-dimensional profile and generation of desiccation cracks

4.5.1 Vertical electrode configuration electrokinetic Set-up

Settlement columns made of plexiglass tubes were prepared with a height of 500 mm and internal diameter of 90 mm. The bottom of the column was attached to a plain Perspex glass sheet with a 3 mm diameter hole to admit the anode/cathode connection. Once the electrode, in the form of a circular disc, was placed on the plain Perspex sheet, the space around the 3 mm hole was sealed with silicone to avoid any leakage from the bottom and the four corners were screwed to the rim of the settlement column. Since the bottom of the column is closed, no drainage is allowed from the bottom. Therefore, the path of water flow is toward the top of the sediments providing a single drainage from the top only. When the drainage of water is not allowed from the bottom, the salinity of the entire soil sample can be controlled as the pore water accumulated on the top. However, in double drain condition the pore water dissipated through the top and the bottom resulting in changes of concentration of salt in the treated soil. When the soil has high salt content the electric current varies and this variation of electric current results in an increase in power consumption due to an increase in soil resistivity (Jones et al. 2008).

Figure 4.12 shows the vertical electrokinetic set-up. The electrodes used are made of galvanized steel due to their availability and low cost. The electrodes are in the form of circular galvanized steel sheets where the anode has a thickness of 4 mm and the cathode has a thickness of 2 mm. The cathode is perforated to allow the drainage of water. Once the set-up is ready the slurry that is prepared with initial moisture content of 250% is poured into the columns in one instant (assuming that the lag time between pouring the slurry and starting the application of electric current is zero). A filter paper is located on the top of the dredged mud slurry and the electrode is placed on the top of the filter paper.

According to Hamed and Bhadra (1997) the same amount of dewatering with 80 % less energy consumption is obtained if the constant voltage is applied to the soil in increasing sequential order. Therefore, the electric potential is applied to the dredged mud slurry in two constant increments of 0 to 20 V and 20 to 30 V with gradient of 0.48 V/cm and 0.70 V/cm, respectively.

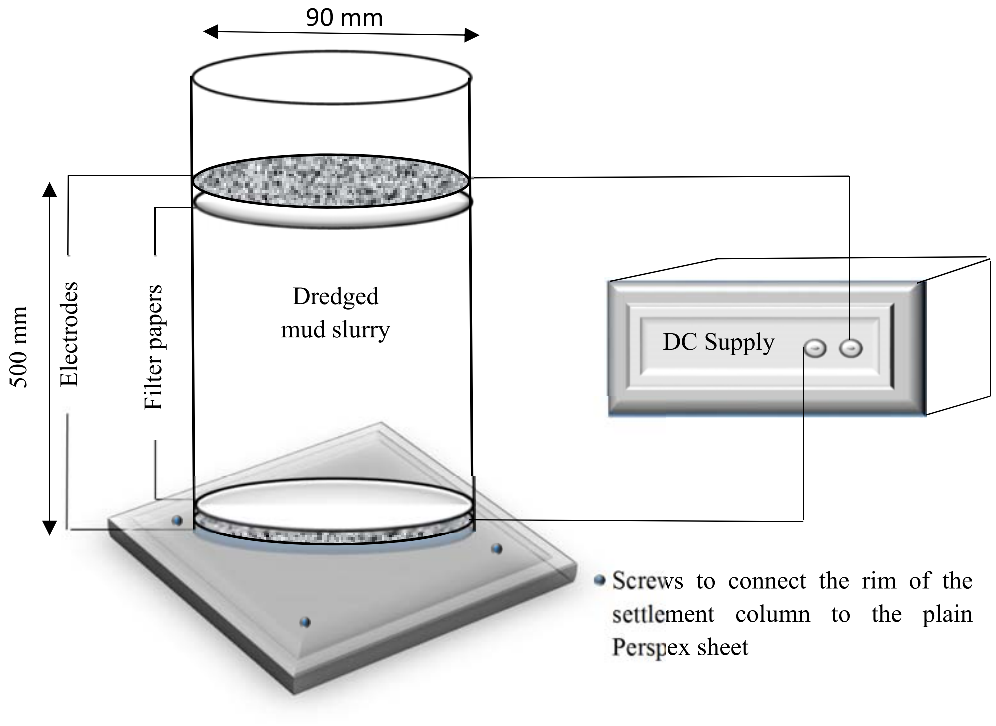


Figure 4.12 Vertical electrokinetic stabilization set up based on settlement column

4.5.2 Electroosmotic settlement

Figure 4.13 shows the changes in interface height (settlement) with time during electrokinetic stabilization. Higher settling rate, better sedimentation and flocculation of the particles were observed when the cathode is placed at the top. It can be seen that, when the anode is placed at the bottom the rate of settlement was much higher than when it is placed at the top. When the anode is at the bottom, the negatively charged particles migrate toward the anode to the bottom of the column due to the electrophoresis (movement of particles) and the pore fluid moves to the cathode due to the electroosmosis (movement of pore fluid). Therefore, more settlement was obtained when the cathode is placed at the top. Whereas, when the cathode is located at the bottom, negatively charged particles moved upward, which decelerated the settlement of the particle and resulted in generation of cracks within the soil.

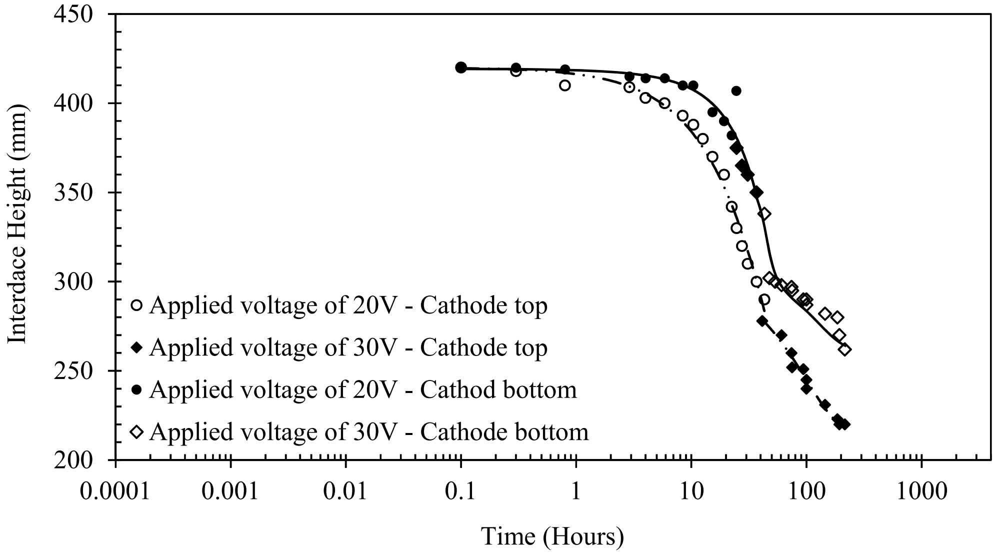


Figure 4.13 Changes of interface height versus log time

When a slurry settles, it normally goes through three stages of sedimentation. First stage is the free settling stage at which particles settle individually. Second stage is hindered settling stage at which particles start to flocculate and settle together. Third stage is consolidation when the flocculated soil particles have sufficient grain contact between them with enough strength that the effective stress with the soil is greater than 1 kPa. These stages are identified from the time versus settlement graph when the trend of the data changes. When the cathode is at the top, the velocity of the hindered settling phase (that is the slope of the second portion of the settlement versus time), is much faster than when the cathode is at the bottom (Figure 4.13). This shows that, the application of electric current to the soil accelerates the settling velocity. Therefore, electrokinetic stabilization is effective in increasing the free and hindered settling velocity of the soils and reducing the time of settlement (Mohamedelhassan and Shang 2001).

4.5.3 Variation of electric current with time

The current at the beginning of the test is a measure of the amount of generated ions in the soil, which presents as salt precipitates or as metal contaminants. Because the mobile ions are constantly electro-migrating toward the electrodes and the excess ions are neutralized by reacting with the soil the electric current reduces with time. H^+ and OH^- ions are generated at the electrodes as a result of redox reactions. Adsorption of these ions into the soil and the slow dissolution and precipitation of minerals and/or salt results in pH changes that lead to a long term and steady supply of charge carriers (Eykholt 1992). A constant voltage of 20 V has been applied to the soil at the beginning of the test. Once the electric current declined and approached zero, the voltage was increased to 30 V (at time t_{30}), on the assumption that the soil resistivity under application of a 20 V electric potential has reached its maximum and no further effect can be observed. However, once the voltage increased to 30 V, no significant changes in electric current was observed. This shows that further increase in voltage gradient did not affect the dredged sediment since it reached its maximum resistivity prior to application of further electric potential.

Figure 4.14 shows the variation of electric current with time for four cases where the cathode was placed at the top and bottom of the column, with the voltage applied being 20 V and then stepped up to 30 V. The variation in electric current with time follows a similar pattern regardless of anode/cathode configuration, however when the cathode was placed at the top, the maximum electric current was slightly higher and the dredged sediment experienced less peak resistivity. When the cathode was placed at the bottom of the settlement column lower electric current was observed when the voltage increases to 30 V. It is expected that as electrical resistivity of the soil increases the electric current reduces (Lo et al. 1991). However, in this study, the electric current of the soil increased and then reduced, implying an initial reduction of soil resistivity. The soil resistivity reduces until the electric current reaches a maximum of 0.55 Ampere.

Rittirong et al. (2008) used electrokinetic stabilization to improve the properties of soft clay soils. According to his study, when a voltage gradient of 25 V is applied, the electric current fluctuates at about 0.1 Ampere. Whereas, application of 45 V results in a reduction of electric current from 0.14 to 0.10 Amps after 6 days. The reduction in electric current is attributed to the voltage drop at the electrode-soil interface and the increase in resistivity of the electrodes. The electric current started to reduce when the resistivity of the anode was increased from 4 to 16 ***Ω***/m after 6 days.

The reduction in electric current within the soil herein is solely attributed to the increase in resistivity of the soil. Since the drainage is from the surface of the sediment, water accumulates on the top. The accumulation of water on the top does not interrupt the flow of electric current through the soil as water is a good conductor of electricity. Higher voltage gradients result in higher soil resistivity and lower electroosmotic efficiency (Kuma 2005). When a voltage gradient is applied, the current flow increases showing an effective electroosmosis, however, at a specific point in time the electric current starts to fall due to the built-up resistance of the soil to the applied electric current (Karunaratne 2011). Lockhart (1983) argues that faster electroosmotic dewatering and higher final solid content with higher pH near the cathode are obtained with higher voltages. High pH results in depletion of water and higher resistance to the electric current flow. Therefore, the reduction of the electric current after 11 hours is attributed to an increase of pH near the cathode.

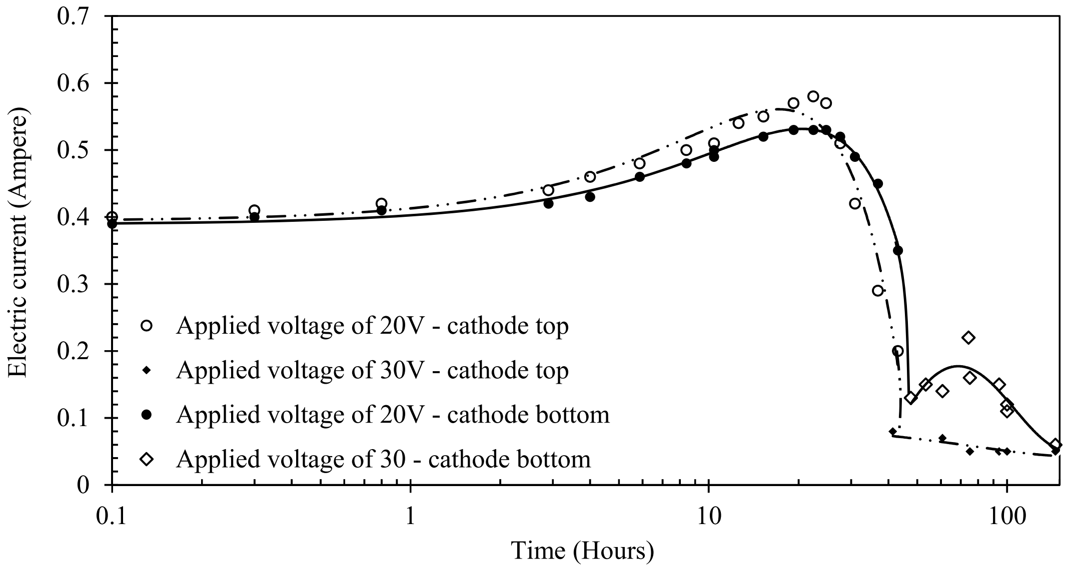


Figure 4.14 Variation of electric current with time

4.5.4 Efficiency of the method

The energy expenditure or power consumption defines the suitability and the efficiency of the method to dewater and consolidate the dredged sediment. Since the amount of energy consumption relates to the cost of electrokinetic stabilization, the efficiency of the method is evaluated against power consumption. The energy consumption is investigated based on measure of soil settlement, amount of dewatering and soil resistivity.

4.5.5 Settlement versus energy consumption

The total cumulative energy consumption when the cathode is at the bottom (C-Bottom) and when it is at the top (C-Top) are calculated as 136 kWh and 113 kWh, respectively. Therefore, it is desirable to place the cathode at the top for lower energy consumption, and higher settlement. High power consumption is often due to cracks in the soil surface and the generation of heat near the electrodes (Gray 1970). Asavadorndeja and Glawe (2005) reported the total cumulative energy expenditure of 120 kWh/m^3 which is close to the energy consumed in this study to stabilize and dewater dredged mud slurries.

4.5.6 Dewatering versus energy consumption

Electroosmotic efficiency is defined as the quantity of water drained per unit of electrical current which is proportional to electroosmotic permeability (Jones et al. 2008). The reduction of water content and increase of shear strength is higher near the anode (Mitchell 1993). More reduction in water content results in higher dewatering efficiency. Dewatering efficiency is based on the amount of water to be removed in comparison with the initial moisture content (W_i) and defined as follow:

$$\text{Dewatering efficiency} = (W_i - W_f)/\, W_i \qquad (4.2)$$

When water is drained and soil porosity reduces, the thickness of the electric double layer reduces such that it overlaps with that of the adjacent particle. The reduction in thickness of the double layer results in a reduction of zeta potential. The lower the zeta potential, the lower the hydraulic conductivity meaning that by application of the same voltage further settlement cannot be achieved. Therefore, higher voltages must be applied in order to further improve the dewatering. For this reason, the electric potential in the experiment were increased to 30 V after which a further reduction in water content is observed.

Due to the electromigration of the ions, most of the cations presented in the soil can be removed from the water that can be collected from the top where the cathode is located. Whereas, if the cathode is placed at the bottom, the contaminants in the form of cations are trapped in the sediment as there is no drainage at the bottom. Figure 4.15 shows that negatively charged ions (anions) and negatively charged particles settle while migrating toward the anode, and cations move toward the cathode in the direction of the water flow.

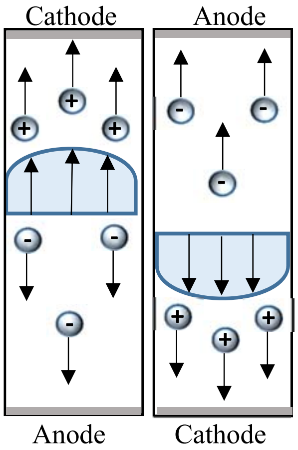


Figure 4.15 Electroosmotic and electrophoretic settlement of the dredged marine slurry

Figure 4.16 shows the amount of dewatering versus cumulative power consumption for both cases of anode-top-cathode-bottom and anode-bottom-cathode-top that was treated for duration of 9 days. Higher dewatering when the cathode was at the top is due to the complimentary benefits in the direction of electrophoresis and electroosmosis that occurred at the same time. However, when the cathode was at the bottom, the particles moved toward the anode. This slows down the process of sedimentation. The dewatering efficiency was calculated as 67% and 48% for the case where the cathode was placed at the top and where the cathode was placed at the bottom, respectively. Therefore, considering dewatering efficiency, it is more efficient to place the anode at the bottom and the cathode at the top.

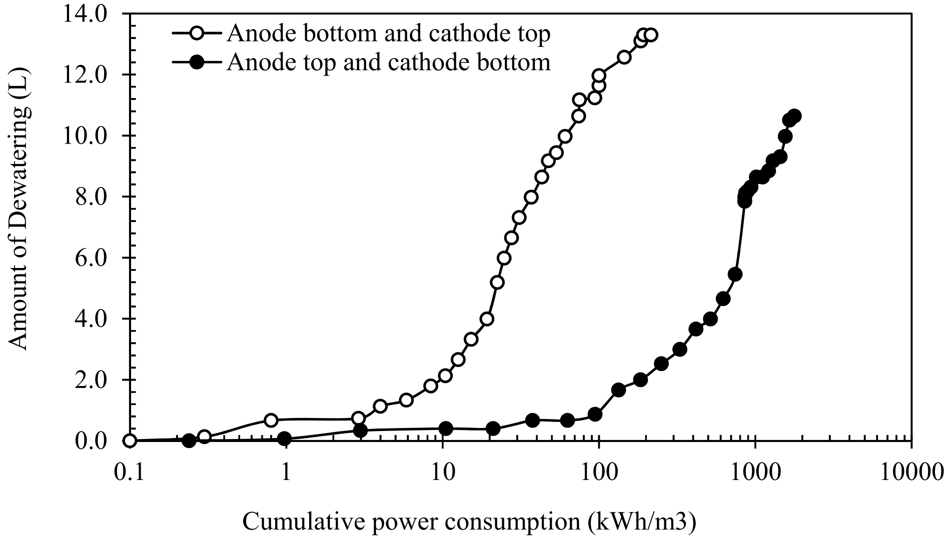


Figure 4.16 Amount of dewatering with time during electrophoresis and electroosmotic settlement

4.5.7 Resistivity versus energy consumption

According to Acar et al. (1995) energy expenditure depends on the soil electrical conductivity, and the interface resistivity which is inversely proportional to the conductive areas between electrodes and soil (Zhuang and Wang 2007). As the soil electrical conductivity increases the energy required increases (Mohamedelhassan and Shang 2001).

Kuma (2005) evaluated the efficiency of the electrokinetic stabilization method through several field and laboratory trials. He showed that the efficiency of the method is based on power consumption and soil resistivity. Based on his study, the greater the surface area of the electrode, the lower the electrical resistance of the material, and better the efficiency of the method. The constant applied voltage over electric current varies as the interface height (volume of the treated soil) changes with time. Within a given time (t) and the electrical energy (E), the cumulative energy passing through the system is defined as:

$$E = V^2t/R \tag{4.3}$$

By taking the logarithm of its components, equation (4.3) becomes

$$\ln E = 2 \ln V + \ln t - \ln R \tag{4.4}$$

If the voltage is constant, the cumulative energy consumption solely depends on the changes of electric current with time, which depends on changes of soil resistivity. Based on the field and laboratory studies, he defined a range of resistivity versus cumulative power consumption for which the electroosmotic stabilization can be effective, moderately effective or non-effective. Accordingly, the most effective electroosmotic stabilization is to be achieved if the ranges of electric current is greater than 10 A/m^2 and the ranges of soil resistance is less than 50 kΩ/m^3, and if the ranges of electric current is less than 1 A/m^2 for the ranges of soil resistance greater than 500 kΩ/m^3 the electroosmotic stabilization is not effective. Figure 4.17 shows the effectiveness of electroosmosis when the cathode is placed at the top (C-Top) and the bottom (C-Bottom). This figure compares the two arrangements of electrode placement, electroosmosis is effective for both cases. However, the cumulative energy is marginally lower when the cathode is placed on the top.

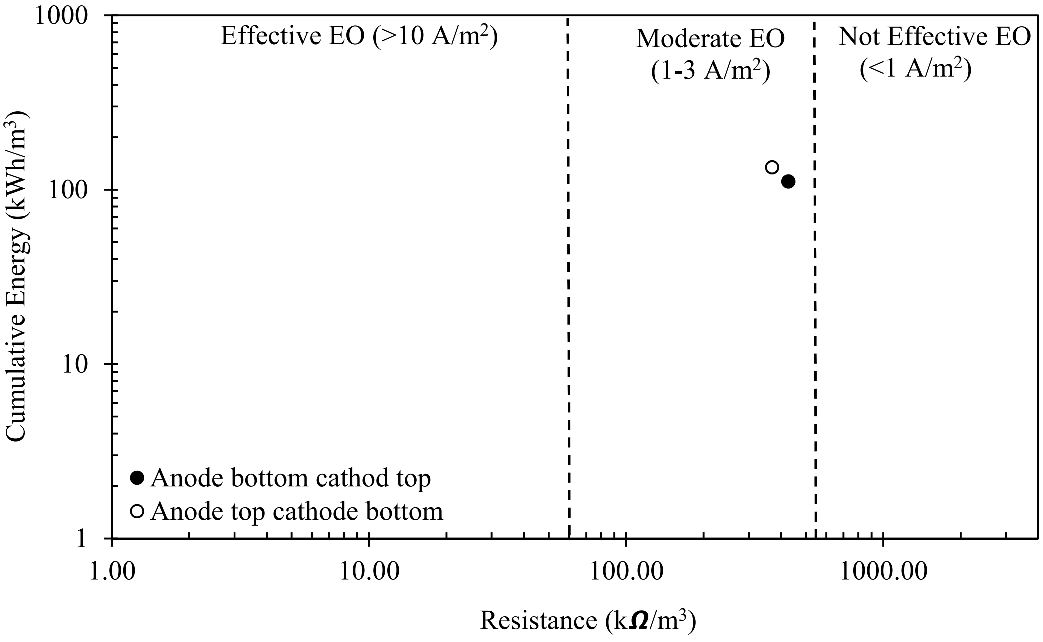


Figure 4.17 Efficiency of electroosmosis

4.6 Effect of electrokinetic stabilization on consolidation parameters with depth

In previous sections the effect of electrode configuration was investigated. It is shown that horizontal electrode configuration where the cathode is placed at the top is the most efficient design set-up to simulate the electrokinetic stabilization of dredged mud in the laboratory. It is also observed that the electrokinetic stabilization reduced the soils compressibility. In this section the effect of electrokinetic stabilization on compressibility of the dredged mud within depth is investigated. For this purpose, a constant electric current of 30 V is applied using horizontal electrode configuration explained in section 4.5.1. After electrokinetic stabilization, the treated sample is tested under oedometer consolidation.

When electrokinetic stabilization is completed, the strength of the treated dredged mud within 7 cm of the cathode is low. To ensure that the shear strength of the treated dredged mud near the cathode is enough for oedometer testing, a surcharge of 5 kPa is added to bring up the undrained shear strength near the cathode to 2 kPa, estimated using the following equation proposed by Skempton & Henkel (1953):

$$\frac{c_u}{\sigma'} = 0.11 + 0.0039(PI) \tag{4.6}$$

where c_u is undrained shear strength, σ' is the effective vertical stress (applied load), and PI is the plasticity index of the untreated dredged mud given in section 3.1.1 as 57%. Applying surcharge of 5 kPa is equivalent to applying 3.3 kg weight to the dredged mud. Since the dredged mud near the cathode is weak, the loading should be applied in stages. Therefore, everyday 0.3 kg is added through 10 days. After 10 days, the bottom rim of the column is opened and samples are taken from the bottom (near the anode which has higher undrained shear strength) to the top (near the cathode with lowest shear strength). Figure 4.18 shows how samples are taken from bottom of the column using an oedometer ring, and Figure 4.19 shows the location of the sampling.

Figure 4.18 Method of taking samples from bottom of the column

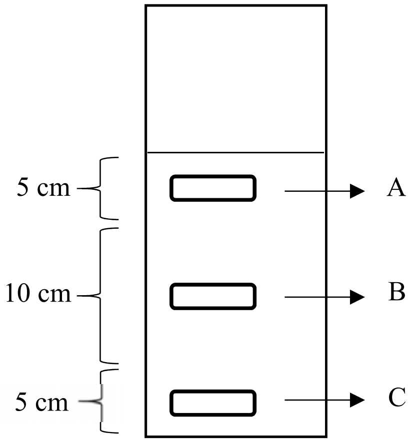


Figure 4.19 Location of the sampling with depth for oedometer testing

4.6.1 Compression index and Rebound index

Figure 4.20 shows the compression curves for treated dredged mud with depth. Sample A is taken from the area closest to the cathode, and sample C is taken from the area closest to the anode.

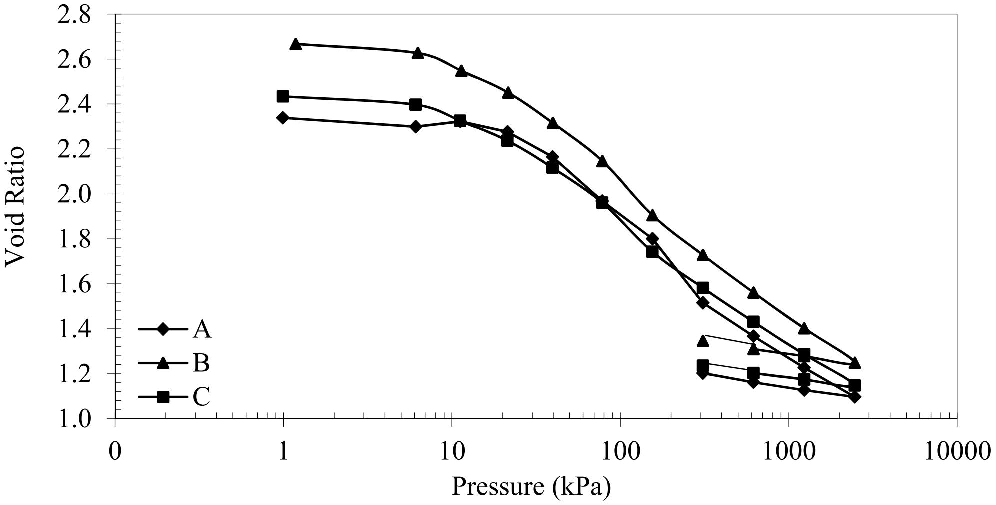


Figure 4.20 Compression curves of the treated dredged mud with depth

The compression index of the treated soil with depth is shown in Table 4.2. As discussed earlier, cementation near the cathode did not happen during stabilization of the dredged mud. Therefore, application of the surcharge increased the shear strength of the treated soil near the cathode and increase the homogeneity of the treated soil sample. According to Mitchell (1993) if the compression index of the soil is less than 0.2, the soil has slight to low compressibity. This shows that the compressibity of the dredged mud has significantly improved with application of electrokinetic stabilization. The compression index and rebound index of the untreated dredged mud discussed in section 4.3.2 given as 0.69 and 0.078, respectively (Ganesalingam 2013). Showing a significant improvement in compressibity of the dredged mud when electrokinetic stabilization is used. The rebound index or recompression index of the treated dredged mud at all depths is equal to 0.163 showing an increase of 108% in comparison with the untreated soil that is 0.078 (Ganesalingam 2013). The soil compressibility of the treated dredged mud increased with depth.

Table 4.2 Compression index of the treated dredged mud with depth

Sample number	**Compression index untreated dredged mud**	**Treated dredged mud**	**% reduction in compression index**
A	0.69	0.57	21%
B	0.69	0.56	23%
C	0.69	0.52	32%

4.6.2 Pre-consolidation pressure

The preconsolidation pressure reduced from 25 kPa to 20 kPa from near the cathode to near the anode (Table 4.3). The value of the pre-consolidation pressure is determined using Casagrande graphical method. Pre-consolidation pressure is the maximum overburden pressure that is experienced by the soil in the past. The surcharge of 5 kPa is applied from the cathode. These values show that layer B and C is unaffected by the applied surcharge.

Table 4.3 Preconsolidation pressure of the treated dredged mud with depth

Sample number	σ'_p **(kPa)**
A	25
B	20
C	20

4.7 Summary

In this chapter the effect of different electrode configurations is presented and discussed. One-dimensional and two-dimensional electrokinetic stabilization was used to investigate the potential application of electrokinetic stabilization to improve the properties of the dredged mud slurries. The experimental study on effect of one-dimensional electrode configuration showed that electrokinetic consolidation reduced the compression index of the dredged mud by 2.1 times and reduced the coefficient of volume compressibity, thus making the sediment stiffer. The recompression index is also reduced up to 88 % of the compression index of untreated dredged mud.

Generally, it was observed that the consolidation properties of the dredged mud improved by one-dimensional electrokinetic stabilization. However, when one-dimensional electrokinetic stabilization is used, the spacing between electrodes is an important design factor to be considered. The lower the spacing between electrodes, the better the effectiveness of the method. However, this results in higher power consumption. For more effective electrokinetic stabilization two-dimensional electrode configuration can be used. Two-dimensional electrokinetic stabilization improved the undrained shear strength of the dredged mud by reducing its water content especially near the anode. The water content and shear strength of the soil near the cathode did not improve as much as near the anode. This lowers the shear strength near the cathode, indicating the absence of organic matters which shows that no cementation had occurred.

Two-dimensional and one-dimensional electrokinetic stabilization can be used for the already existing lands and for natural soils with low hydraulic conductivity. More soil improvement can be obtained using two-dimensional electrokinetic stabilization. The installation of electrodes in the case of one and two-dimensional electrokinetic stabilization is not easy as the slurry does not have enough strength to hold the electrodes in place especially in land reclamation areas. In addition, the pull-out of the electrodes after electrokinetic stabilization affects the strength properties of the treated dredged mud. Therefore, the vertical electrode configuration was chosen to be used to investigate the electrokinetic stabilization parameters. However, the placement of electrodes was investigated to determine which electrode placement results in maximum dewatering and soil settlement. For this purpose, laboratory models where cathode placed at the top and at the bottom of the settlement column were evaluated based on the resulting efficiency, power consumption, amount of dewatering, soil settlement, and soil resistivity.

Based on the result of the study, when 20 V electric potential is applied, the electric current increased till soil resistivity reached the maximum. The maximum soil resistivity is less, when the cathode is placed on the top. By applying additional electric potential, up to 30 V, further variations in electric current was not significant and electric current remained constant, showing that the soil has reached its maximum resistivity by applying an electric potential of 20 V. The dewatering efficiency improved from 48% (when cathode is placed at the bottom) to 67% (when cathode is located at the top) with less power consumption. Therefore, based on this experimental study, it is better to place the cathode on top to get maximum settlement and dewatering. This electrode configuration will be used throughout this thesis to investigate the effects of other design parameters on electrokinetic stabilization of the dredged mud sediments.

When cathode is placed on the top, the soil at deeper levels (near the anode) has more strength due to the reduction of water content as a result of electroosmosis and electrolysis of the anode. Therefore, the area near the cathode was improved by application of surcharge to increase the homogeneity of the treated dredged mud. It is shown that the compression index of the soil increased by 32%.

Chapter 5: Type of electric current application

5.1 General

In previous chapter the effect of electrode configuration was presented. It was concluded that the vertical electrode configuration is the most feasible and efficient laboratory configuration to obtain maximum settlement of the dredged mud and highest storage capacity. After determining the best electrode configuration for analysing the dewatering and settlement of the dredged mud slurries. The application of electric potential needs to be investigated to determine the voltage to be applied to the slurry during the electrokinetic stabilization.

Application of constant current is commonly used in the literature to stabilize soils. However, the electric current at which maximum settlement is to be achieved is not clear or standardized. In this study, different electric potential is applied for two main reasons 1) the application of constant current requires a constant electric power source, which is expensive and is counted as an additional cost to the project 2) to determine the optimum electric current at which maximum electrokinetic settlement can be obtained. For these purposes, an easily available laboratory power supply is used. This power supply works based on Ohms law:

$$V = IR \tag{5.1}$$

where if the voltage is kept constant the electric current (I) changes as the resistivity (R) of the soil changes. For different applied constant voltages, the variation of electric current with time which shows the resistivity behaviour of the soil is presented in this chapter.

Intermittent current is one of the methods that is reported in the literature to reduce the power consumption and therefore the cost of the project. Intermittent current is the application of electric current in on and off cycles, which can be regular or irregular. The regular application of intermittent current reported to reduce the corrosion of the anode beside power consumption (e.g. Micic et al. 2001). The regularity and irregularity of the intermittent current application can be determined from the intermittent current ratio. The intermittent current ratio is the ratio of the duration when electric current is applied to the soil over the total duration of the electrokinetic stabilization which includes the duration at which electric current is disrupted.

$$\tau = \frac{t_{on}}{t_{on} + t_{off}} \tag{5.2}$$

where t_{on} is the time during which the power is on (hours) and t_{off} is the time duration the power is off (hours). If the intermittent ratio is 0.5 then regular intermittent current is applied. If it is greater or less than 0.5 it means the application of intermittent current is irregular.

Buckland et al. (2000) showed that the constant application of electric current results in better sedimentation than regular intermittent current application with 50% intermittent ratio. However, there is a lack of research on the effect of irregular application of intermittent current, with intermittent ratio greater than 50%. Therefore, in this study application of constant electric current and irregular intermittent current of 70% intermittent ratio are investigated to determine if application of intermittent current with higher intermittent ratios would improve the efficiency of electrokinetic stabilization.

5.2 Effect of constant electric potential

Application of constant electric current for electrokinetic stabilization of soils is reported in the literature. If the electric current is kept constant, the electric potential changes as the resistivity of the soil increases. Same pattern is observed if the voltage is kept constant. In order to apply a constant electric current a special current source is required to limit the increase of electric current to the desired constant value. In that case, to bring up the electric current to the desired constant current, the voltage needs to be increased. This increases the timeframe of the electrokinetic stabilization as well as the cost needs to be invested for the direct current source. This process can be accelerated by applying a constant voltage (electric potential).

In this chapter, the effect of applied constant electric potential on settlement of the dredged mud slurry is investigated. For this purpose, electric potentials of different values are applied to determine how field intensity affects the electrokinetic dewatering and consolidation of the dredged mud. Series of electrokinetic set-up was prepared and the dredged mud slurry with initial moisture content of 250% is poured into the settlement columns. A constant electric potential of 2.5 V, 5 V, 10 V, 15 V, and 30 V is applied to dredged mud slurries to monitor the changes of electrokinetic sedimentation with different applied voltages. The maximum allowable electric potential (under safety regulations) that can be applied to the soil in the laboratory is 30 V. The effect of application of 20 V is given in chapter 4. To test the effect of low and higher ranges of voltage, the interval of 2.5 V is chosen for low voltages of 0-5 V and interval of 5V is chosen for 5-15 V.

It is concluded from previous chapter that electrokinetic settlement is maximized if vertical electrode configuration with the cathode on top is used. Therefore, the set-up used in this thesis is the set-up presented in chapter 4, section 4.5.

5.2.1 Variation of electric current with time

The variation of electric current with time, for the applied constant voltages, is shown in Figure 5.1. It is shown that in the first 40 hrs, the current in high voltage tests is significantly varied, especially for 30V test ($I_{max}/I_{min} \approx 5.5$). Meanwhile, the current in low voltage tests remains the same, showing the insignificant effect of electric potential on soil resistivity at low voltages up to 5V. The increase of electric current to the maximum in early stages of the process shows that the soil resistivity reduces initially and then increases after 40 hours.

The changes of electric current with time follows a similar pattern regardless of the voltage if the electric potential is greater than 2.5 V. Beside soil resistivity, the variation of electric current with time depends on the ionic concentration and movement of ions in the soil (Chou et al. 2004). When the electric current is at its highest value, the ionic concentration is at its maximum level. When the ions start to move and the concentration of ions reduces, the electric current reduces. The electric current reduces until the number of free ions are equal to the dissolved ions when the electric current remains constant.

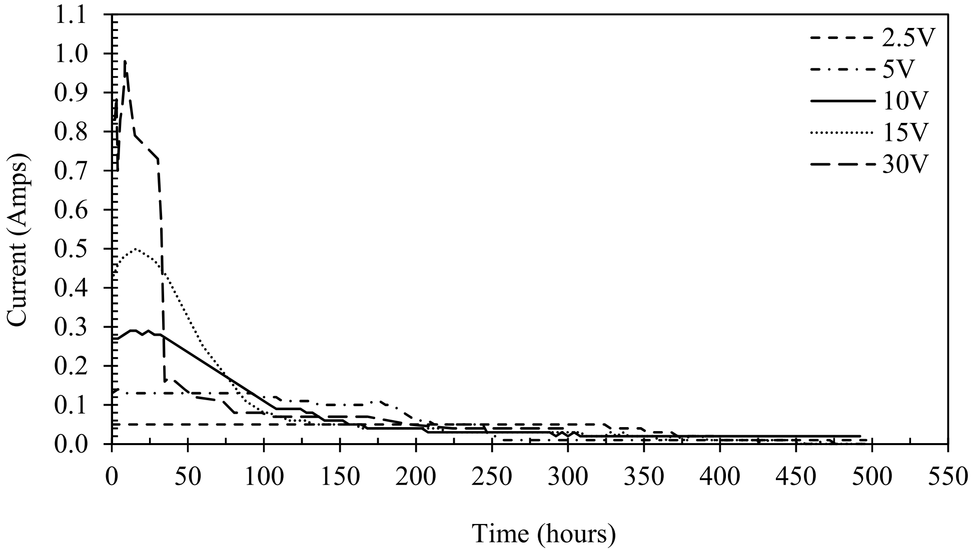


Figure 5.1 Variation of electric current with time for different voltages

5.2.2 Electrokinetic sedimentation

The settlement of the dredged mud slurry with time during electrokinetic stabilization is shown in Figure 5.2. The free settling of the dredged mud finishes sooner when 30 V electric potential is applied, this is due to an increase in settling velocity of the soil. Electric potential has a direct relationship with settlement of the dredged mud. Therefore, the settlement of the dredged mud is higher if the applied electric potential is greater. When low electric potential of 2.5 V is applied, the settlement of the dredged mud is not completed within the timeframe of 20 days. However, when electric potential of 30 V is applied, the final settlement of the soil is maximum and the free settling and hindered settling of the dredged mud is completed within 20 days. Only when 2.5 V electric potential is applied, the settlement curve is not completed within 20 days.

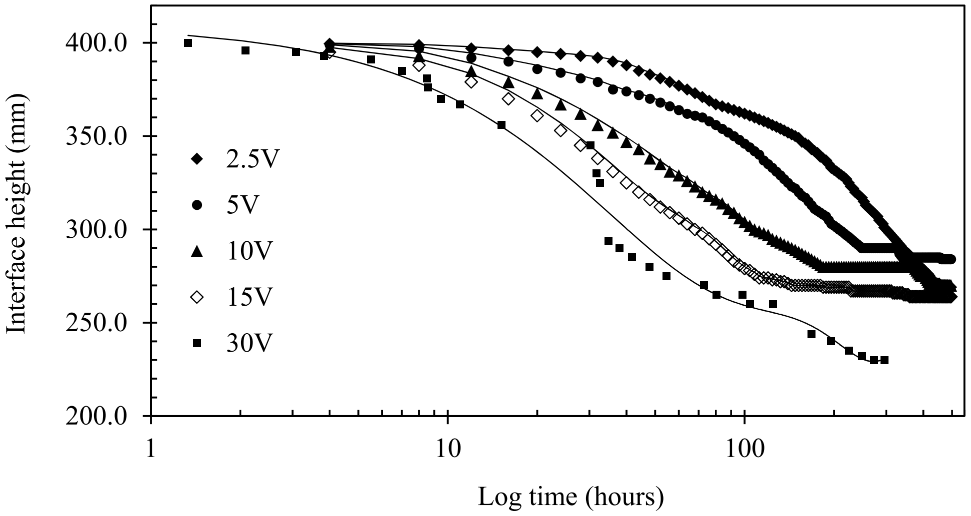


Figure 5.2 Electrokinetic surface settlement of the dredged mud with application of different electric potential

5.2.3 Power consumption

The power consumption of the method depends on the electric current and the applied voltage. Higher electric current leads to higher power consumption of the electrokinetic stabilization. The Power consumption of the method is determined using the formula given in section 4.5. Cumulative energy consumption is the summation of the energy consumption at each time interval that is calculated with the measured electric current at that time interval.

$$W = \frac{u_0}{V} \int_0^t I(t)dt \qquad (5.3)$$

Where u_0 is the applied voltage, $I(t)$ is the electric current as a function of time, and V is the volume of the treated soil.

Table 5.1 Power consumption versus applied voltage for application of constant voltages

V (Volts)	**I_{max} Maximum electric current (Amps)**	**Duration (hrs)**	**Cumulative energy consumption (kWh)**
2.5	0.05	436	0.05
5.0	0.14	248	0.17
10	0.29	184	0.53
15	0.50	120	0.90
30	0.98	295	7.71

5.3 Effect of Irregular intermittent current application

5.3.1 Intermittent current electrokinetic Set-up

Figure 5.3 shows the intermittent current set-up. The vertical configuration where cathode is placed on top of the dredged mud slurry is used throughout this study. To investigate the effect of intermittent current, a timer is attached to the plug of the power supply to stop the electric current flow to the DC supply according to the program that is given to the timer. The timer is programmed to be turned on and off for intervals of 3 hours for 3 days. After 3 days, a 24 hours break is given to the system and the timer is reprogrammed for the next 3 days. To simulate the double drain and single drain sedimentation, a plain and a perforated sheet is screwed at the bottom to the rim of the settlement column.

5.3.2 Variation of electric current

Figure 5.4 shows the variation of electric current with time during electrokinetic stabilization for when electric current is applied to the soil. It is shown that when irregular intermittent electric current is applied, the electrical resistivity of the soil did not change within the first 4 hours. However, the electrical resistivity of the soil reduced, between 4 to 20 hours after which it started to increase. Two jumps are shown in the data, these jumps in electric current is due to the 24 hours in which the electric current is turned off. When constant electric current is applied, the resistivity of the soil started to increase from the beginning of the experiment until

80 hours after which it stayed constant. To analyse the electric resistivity of the soil the points at which electric current was zero is eliminated from the plot to be able to compare the trends of changes of electric current with time.

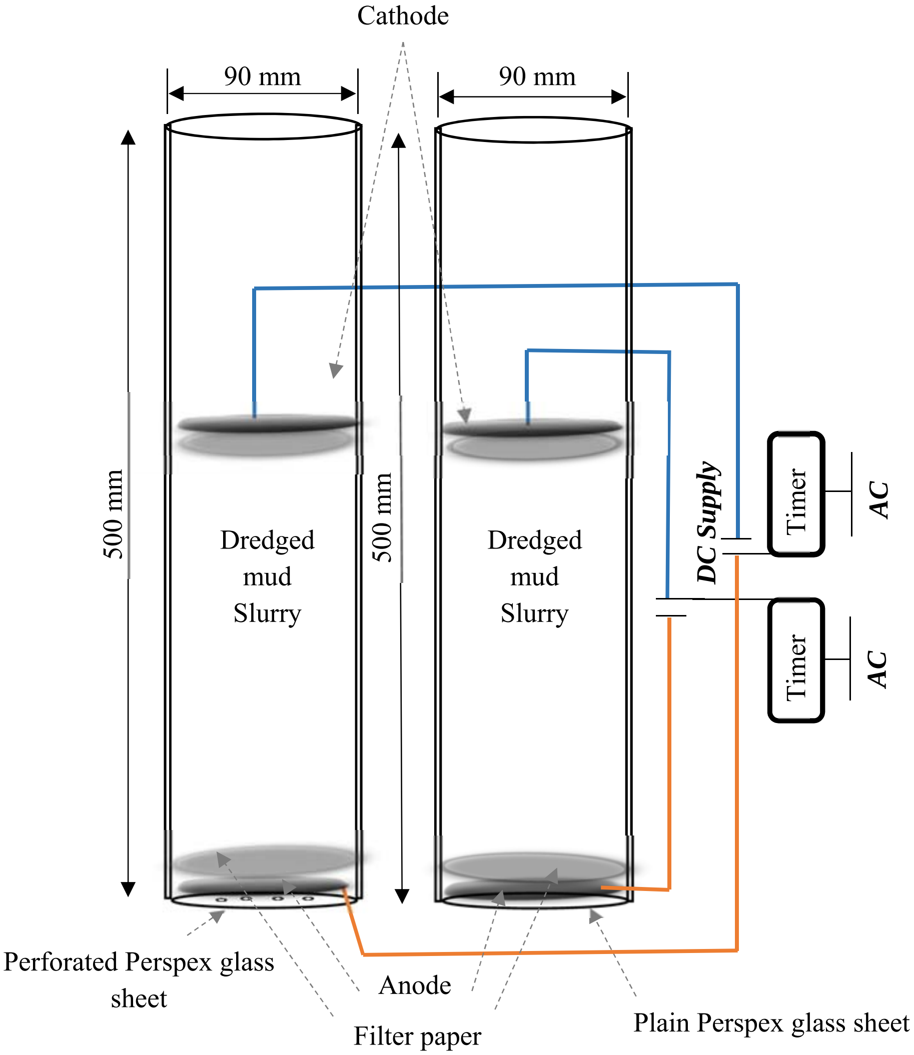


Figure 5.3 Set-up used to investigate the effect of intermittent current

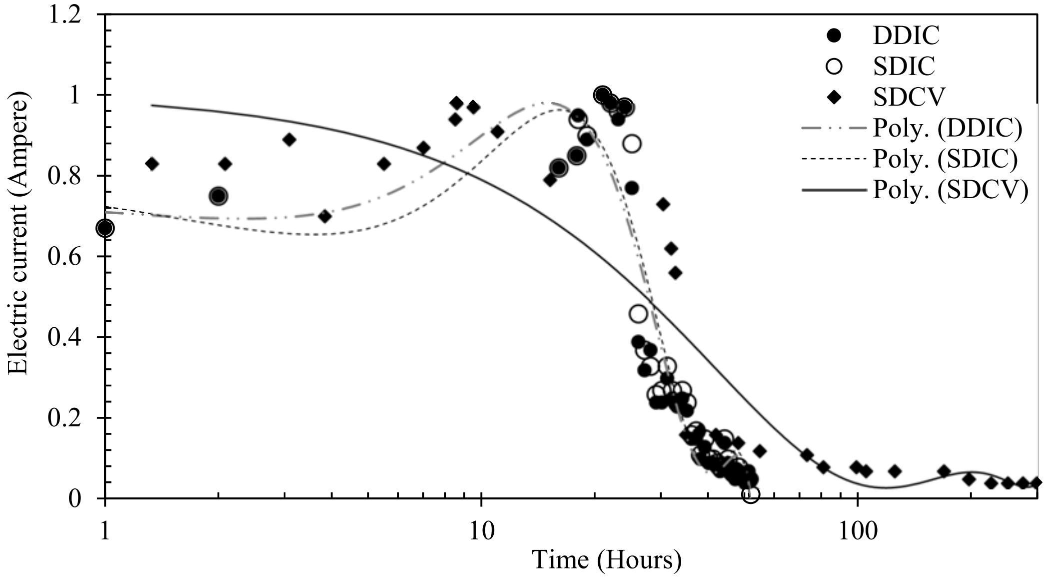


Figure 5.4 Variation of electric current with time for double drained intermittent current (DDIC), single drained intermittent current (SDIC), and single drained constant voltage (SDCV)

5.3.3 Effect of Intermittent current application on soil sedimentation

The effect of providing drainage at the bottom of the column during electrokinetic sedimentation of the dredged mud is investigated along with the application of irregular intermittent current. It was observed that, the dissipation of pore pressure in the case of double drain condition is different to single drain in Terzaghi's theory of consolidation. However, in electrokinetic settlement the dissipation of pore water pressure in double drain condition was similar to the single drain behaviour. The similarity of the draining condition is due to the cementation near the anode that blocks the flow of water in double drain condition. Therefore, although a perforated sheet is provided at the bottom, the water did not drain out due to electroosmosis.

Figure 5.5 shows the changes of settlement with time. Intermittent current was applied to a singly drained (SDIC) and doubly drained sediments (DDIC). These two cases are compared to the single drained sediment when constant voltage is applied (SDCV). It is shown that the application of 70% irregular intermittent current did not change the sedimentation behaviour of dredged mud in comparison with application of constant voltage. Therefore, the time at which free settling and hindered settling of the dredged mud is completed was same for all cases. However, the final settlement of the dredged mud increased up to 4% when intermittent current is applied in comparison with constant voltage. The settlement of the soil did not change if the water is allowed to flow from the bottom where simulating the double drain condition. Therefore, the electrokinetic settlement of both single and double drained sediments are almost identical.

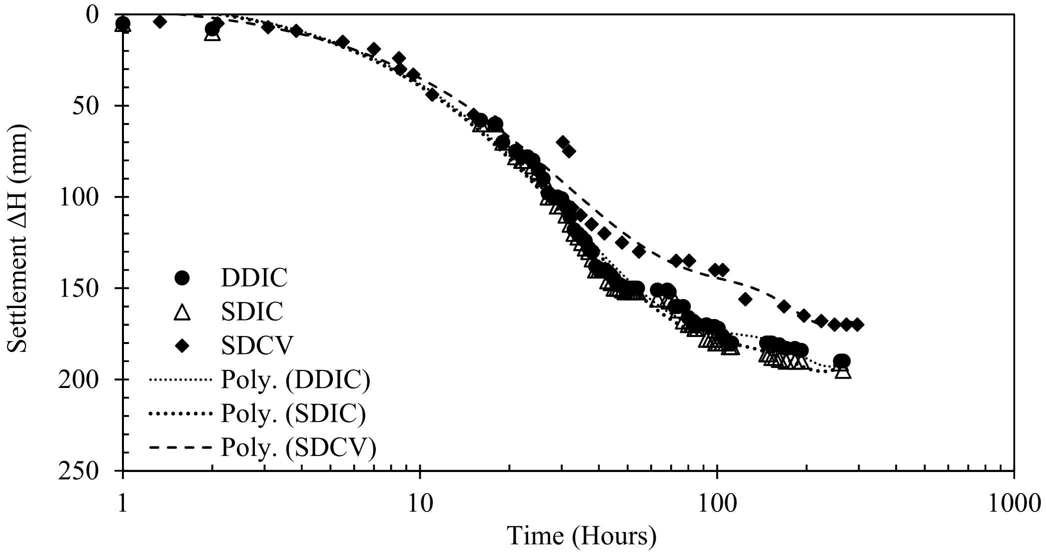


Figure 5.5 Settlement versus time

5.3.4 Electroosmotic permeability

The electroosmotic permeability ($m^2/V.S$) of soils is determined based on Darcy's law from the following equation given by Jones et al. (2011):

$$k_e = \frac{Q_e}{i_e * A} \tag{5.4}$$

where Q_e (m^3/s) is the volume of the dewatered water per unit time in seconds, i_e is the gradient, and A (m^2) is the cross-sectional area. The distance between electrodes is changing as soil settles since the cathode that is located on the top of the sediments moves downward toward the anode.

Figure 5.6 shows the relationship between electroosmotic conductivity and void ratio. It is shown that the electroosmotic permeability of the dredged mud increased with application of 70% intermittent current.

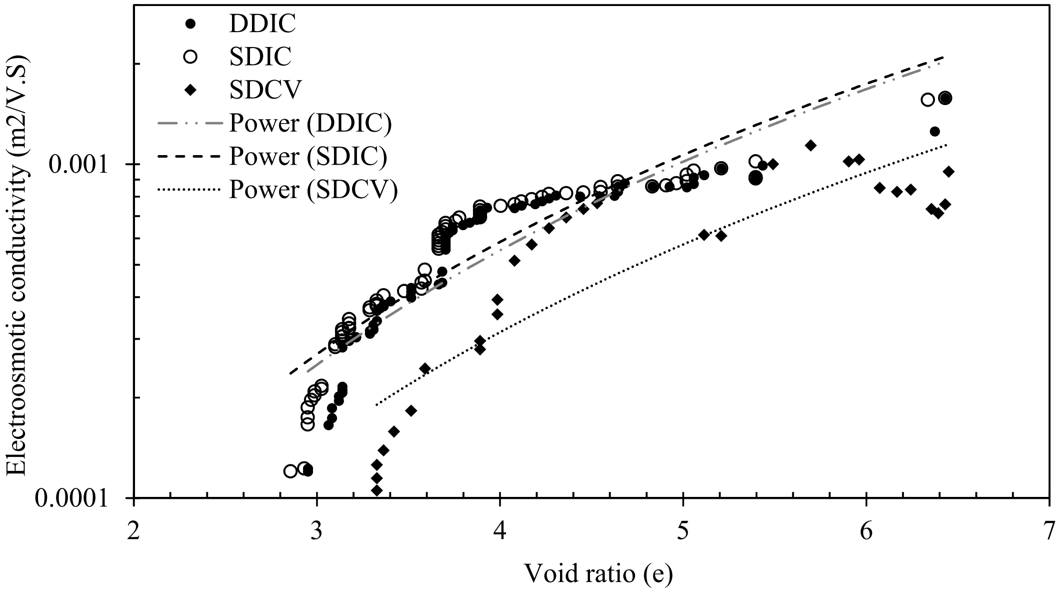


Figure 5.6 Electroosmotic conductivity versus void ratio relationships

5.3.5 Effect of drainage and intermittent current on efficiency of the method

Table 5.2 compares soil resistivity, power consumption, and the amount of dewatered water after electrokinetic stabilization of the dredged mud to determine the most efficient case. In case of the double drain condition the resistivity of the soil is much higher than the other two cases. This is attributed to the loss of water from the base at the beginning of the experiment which resulted in appearance of cracks at earlier stages of the experiment in comparison with other tests. Depending on the place of the sedimentation, dredged mud experiences desiccation even under self-weight sedimentation, and this occurs as soon as 30 days (Lee et al. 2013). With electrokinetic stabilization, the desiccation occurs sooner if the soil is properly drained out from the bottom or the top; and this interrupts the flow of electric current through the soil. Therefore, it is better to keep the water on the top to reduce the desiccation cracks throughout the soil which interrupts the flow of electric current within the soil specimen and increases the soil resistivity.

Earlier the effect of intermittent current on settlement is discussed, showing that the application of intermittent current increased the settlement of the dredged mud by 4% in comparison with application of constant voltage. When irregular intermittent electric current is applied the energy consumption is reduced to half of the application of constant voltage. If drainage is not provided at the bottom of the column, the final resistivity of the soil is lower, this is due to the larger dry area near the anode that increased the soil resistivity in case of double drain condition.

Table 5.2 Effect of intermittent current on soil resistivity and power consumption

Test ID	Final soil Resistivity (kΩ)	Cumulative power consumption (kWh)	Volume of the dewatered water (m^3)
SDCV	0.986	7.71	0.000133
SDIC	0.602	3.70	0.000149
DDIC	2.990	3.71	0.000153

5.4 Summary

In this chapter, the effect of constant electric potential and its magnitude on electrokinetic settlement of the dredged mud is investigated along with the application of intermittent current and the effect of providing drainage. Following conclusions are drawn.

It is shown that the coefficient of electroosmotic permeability increased as the applied electric potential increased which led to a better soil sedimentation. However, increase in magnitude of the electric potential resulted in higher power consumption. When 30 V electric potential is applied to the soil, a significant increase in settlement was observed in comparison with application of lower voltages. Therefore, application of irregular intermittent current with 70% intermittent ratio studied and it is shown that intermitted current application resulted in higher settlement in comparison with application of constant electric potential of 30 V. Higher settlements were obtained while the energy consumption reduced to half. The power consumed by application of intermittent current for both double and single drained condition is almost the same.

When the drainage is provided from the bottom, the settlement or the process of electrokinetic consolidation did not significantly change in comparison with single drain condition, except increasing the generation of cracks in the soil specimen resulting in higher final resistivity. Therefore, intermittent current application using an impervious base and application of 70% irregular intermittent current is suggested to reduce the cost of the project.

Chapter 6: Effect of electrode material

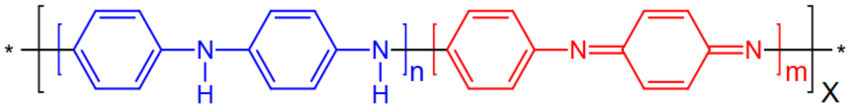
6.1 General

The effect of electrode configuration and voltage gradient were discussed in previous chapters. The vertical configuration where the cathode is placed on the top is the most efficient configuration. The application of constant electric current is shown to be effective in increasing the settlement of the dredged mud slurry. As explained in chapter 5, higher electric current results in better sedimentation. Application of constant 30 V electric potential showed a significant improvement in soil settlement, therefore, to determine the effect of electrode material on optimum settlement of the dredged mud, 30 V electric potential is applied and the suitability of the electrode material is evaluated based on the corrosion rate and the improvement of the soil after electrokinetic stabilization.

In this chapter, the effect of electrode material is investigated and discussed. Different types of electrode material are used in the literature for electrokinetic stabilization of soils. However, a study on the effect of the different electrode materials on electrokinetic sedimentation is missing. For this purpose, the effect of electrode material on electrokinetic stabilization of dredged mud using aluminium, stainless steel, copper, and galvanized steel are investigated. The advantage, limitation, and the conductivity of these materials are given in Table 6.1.

Table 6.1 Electrode materials used in this study to dewater and consolidate dredged marine sediments

Electrode Type	**Advantageous**	**Limitation**	**Conductivity (S/m)**
Copper	Lower wear rate, High resistant to DC current	Take longer to deburr a Copper electrode than to manufacture it. In addition to its high wear rate, it causes soil contamination and not environmentally friendly. Loss of voltage near cathode due to the high production of hydrogen gas. High Power loss at cathode	$62*10^6$
Aluminium	High resistant to DC current, Light and Easy to shape, good conductor of electricity	Reacts with hydrogen ion (produce Aluminium-hydroxide) and cause compositional changes in the soil. Not environmentally friendly and a source of contamination.	$37*10^6$
Steel, Mild steel, steel tubes	good conductor of electricity	High rate of Corrosion in presence of salinized soils is its main problem.	$16*10^6$

Stainless steel	Easy to clean, Highly scratch resistance, Last long (high corrosion resistance)	Difficult to fabricate, not as malleable as other metals.	$137*10^6$
Polyaniline coated electrodes: Polyaniline is a carbon based coating that increases the corrosion resistance of the metals.	Chemical composition of the polyaniline: 		

6.1.1 Copper

During the electrokinetic stabilization, copper anodes are corroded significantly (Figure 6.1), due to oxidation with anions in discharged water, salinity of the soil and the tendency of copper to react and create copper oxide. Figure 6.1 shows the corroded anode after electrokinetic stabilization. An attempt to remove the anode resulted in breakage and disintegration of the anode.

Figure 6.1 The copper anode corroded such that it consumed and disintegrated completely

6.1.2 Aluminium mesh electrodes

When aluminium electrodes were used to stabilize the dredged mud, the anode and the cathode both corroded (Figure 6.2). The corrosion of anode is due to the electrolysis and the disintegration of cathode is attributed to the alkalinity of the adjacent area. The corrosion of the electrodes reduced the efficiency of the electrokinetic settlement. The dewatering of 37% did not make the slurry a workable material. Despite the reported studies in the literature on positive effects of aluminium electrodes on electrokinetic stabilization of soil (e.g. Liu et al. 2012), aluminium mesh is found non-effective in improving the properties of the dredged mud.

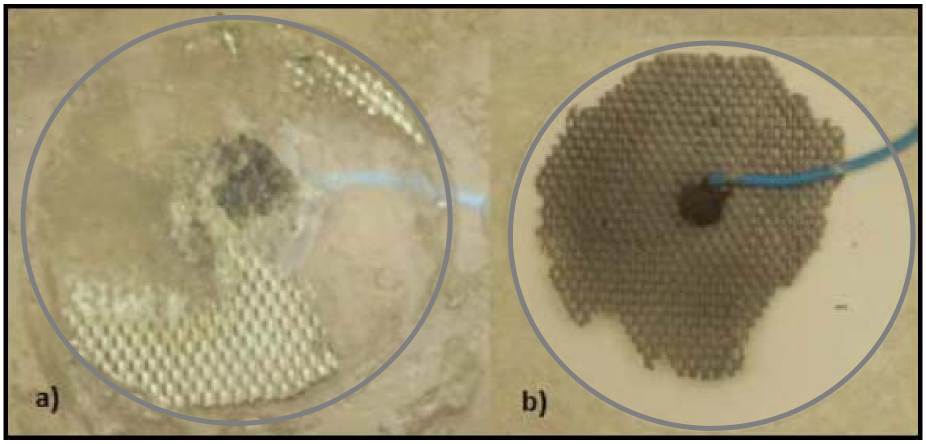


Figure 6.2 Corrosion of the aluminium anode (a) and aluminium cathode (b) after electrokinetic stabilization

6.1.3 Stainless steel electrodes

When stainless steel electrodes are used, the variation of electric current with time was more scattered than other metal electrodes (Figure 6.3). The electrical conductivity of the dredged mud near the cathode was approximately twice that of the untreated soil, which is the result of electromigration and production of hydroxides that increases the concentration of ions near the cathode. The dewatering and settlement of the dredged mud was successfully accomplished using stainless steel electrodes. However, scattered variation of electric current, and the related environmental concerns related to the generation of chromate, associated with the electrolysis of stainless steel coating, eliminates this metal from the electrode material options.

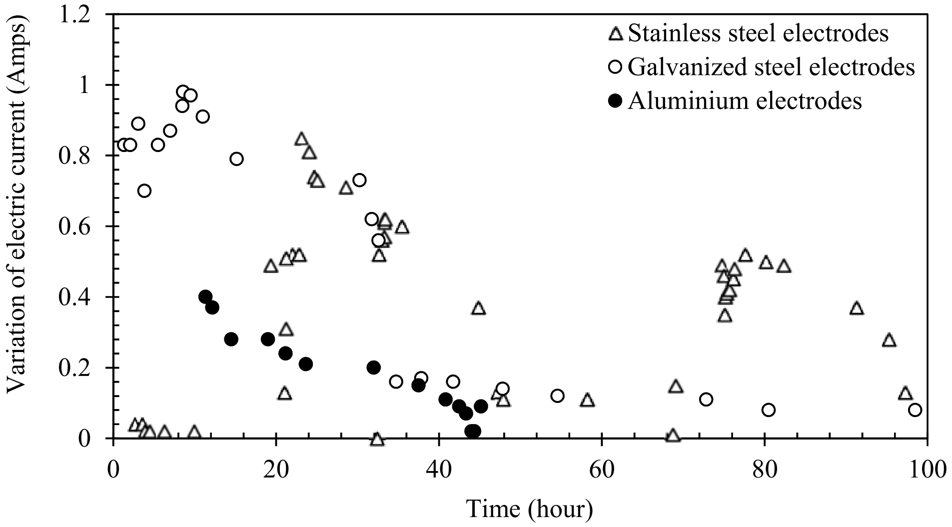


Figure 6.3 Variation of electric current with time

6.2 Galvanized steel and Polyaniline coated galvanized steel

As explained in section 6.1, corrosion of the anode is one of the criteria for choosing a proper anode. Aluminium mesh, copper and stainless steel electrodes were corroded during electrokinetic stabilization due to the reduction of pH near the anode. Another criterion for choosing a proper electrode is what enters the soil, for example stainless steel, copper, and aluminium are all source of contamination and not environmentally friendly. If these metals are used as the anode, care should be taken to control soil contamination by considering soil decontamination at the same time as soil stabilization. Steel that is coated with a layer of zinc oxide to reduce its corrosion rate is galvanized steel. Zinc is an element that is environmentally friendly and often used as a fertilizer for agricultural purposes. For this reason and due to its consistent electric current variations, galvanized steel is chosen as electrode material in this study.

Galvanized steel sheet with diameter of 900 mm and thickness of 3 mm is cut into circular plates (Figure 6.4) to be used as electrodes. Cathodes are perforated to allow the passage of water providing a drainage from the top and anodes are coated with polyaniline to investigate its effect on electrokinetic stabilization of the dredged mud. Polyaniline coating is a widely used conductive polymer that increases the aqueous corrosion resistance of metals (Santos et al. 1998). Polyaniline is obtained by electrochemical oxidation and polymerization of aniline (Skotheim and Reynolds 2007) which has unique properties such as low cost monomer, electrochemical activity, stability, optical activity (Gvozdenovic et al. 2012). Since, polyaniline is effective in reducing the corrosion, especially in acidic environment (MacDiarmid and Ahmad 1997), it was selected as a coating material.

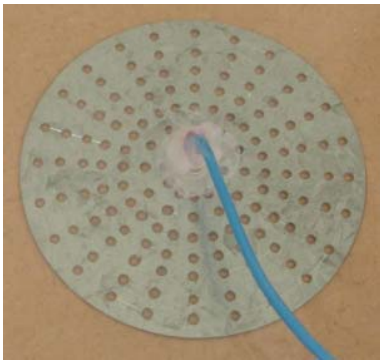


Figure 6.4 Circular galvanized steel

6.2.1 Variation of current density with time

The constant electric potential of 30 V or 5 V were applied to the dredged mud. When the electric potential was applied, the electric current was monitored for all cases until the tests were completed. Because electric current varied similarly in 30V coated and 30V non-coated tests, the fitting curves coincide at t_{opt} (Figure 6.5). Referring to the figure, when 5 V electric potential was applied to the soil through the coated anode, the pattern of changes in electric current with time was similar to when 30 V was applied through the coated anodes. This shows that the polyaniline coating increased the efficiency of the method by reducing the soil resistivity. However, this only happened when low voltage of 5 V was applied.

In case where electric potential of 30 V was applied through the coated anode, the soil resistivity was higher than the case of non-coated anode. This shows that the polyaniline coating was disintegrated at voltage of 30 V, resulting in higher resistivity and power consumption in comparison with non-coated anode. The disintegration of the polyaniline at voltage of 30 V will later be discussed in more detail through changes of physiochemical properties in next chapter.

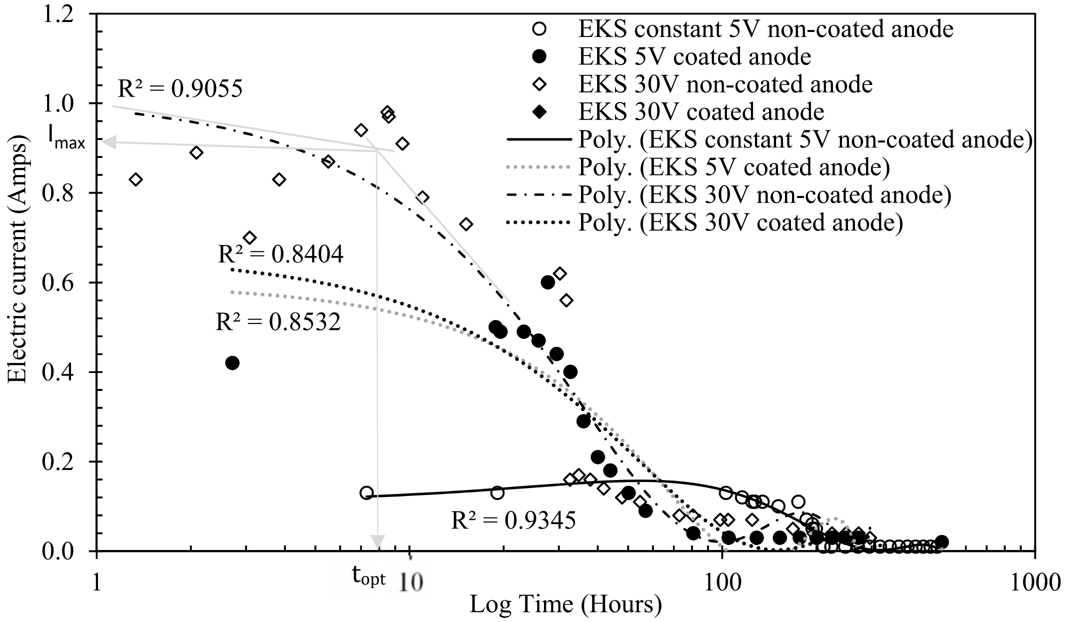


Figure 6.5 Variation of electric current with time during electrokinetic stabilization of dredged mud slurry

As electric current and resistivity of the soil change with time and as soil particles settle, the density of the soil changes, and as a result the settling velocity varies. The variation of settling velocity with changes of electric current is given in Figure 6.6. The settling velocity of the soil is shown to be at its maximum when the electric current is the maximum. The detailed explanation on how settling velocity is obtained is given in section 6.2.3. The polynomial regressions to the measured settling velocities with respect to changes of electric current with application of 5 V and 30 V electric potential through coated and non-coated electrodes, are defined as:

When 30 V electric potential is applied through coated anode:

$$V_s = -32.45\, I^2 + 19.28\, I + 0.53 \tag{6.1}$$

When 5 V electric potential is applied through coated anode

$$V_s = -31.55\, I^2 + 18.56\, I + 0.564 \tag{6.2}$$

When 30 V electric potential is applied through non-coated anode

$$V_s = -27.14\, I^2 + 5.22\, I + 0.29 \tag{6.3}$$

When 30 V electric potential is applied through non-coated anode

$$V_s = -4.09\, I^2 + 5.79\, I + 1.07 \tag{6.4}$$

where V_s is the settling velocity in mm/hr and I is the electric current in Amps. These regression equations are valid for electric current ranging from 0 to 1 amp showing that the electric current of the soil does not exceed 1 amp when 30 V electric potential is applied. The settling velocity based on electric current gives an information about soil resistivity. Since soil resistivity is a function of chemical changes in the soil, therefore it is necessary to investigate the relationship between settling velocity based on application of electric current. The maximum settling velocity is obtained at electric current of 0.3 amps in case of coated anode, and 0.6 amps in case of 30 V non-coated electrode, and less than 0.1 amps for when 5 V electric potential is applied.

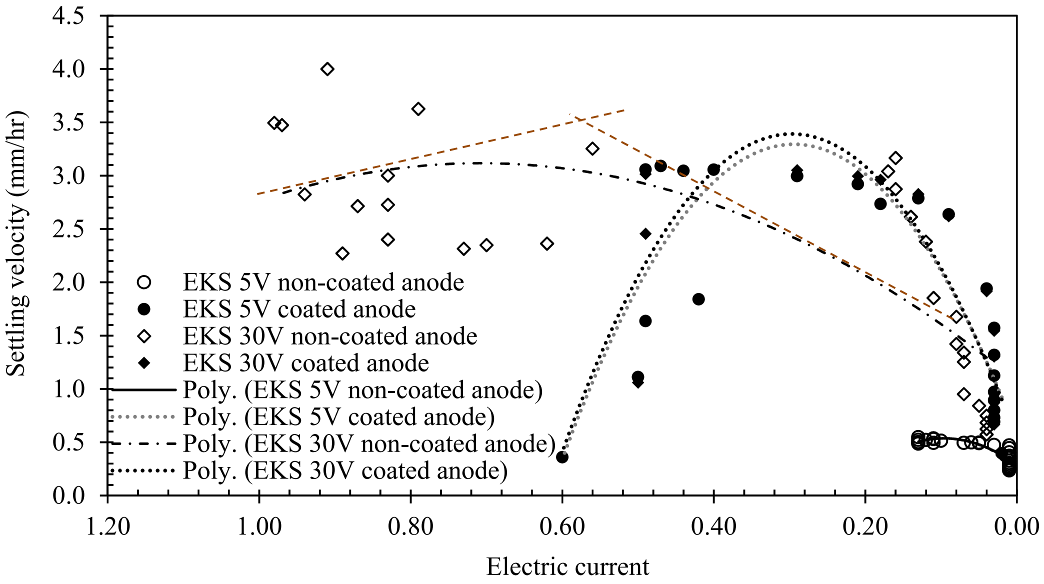


Figure 6.6 Variation of electric current with settling velocity during electrokinetic stabilization of dredged mud slurry

The maximum electric current at optimum time and maximum electric current at maximum settling velocity that is obtained for each case is given in Table 6.2. When 30 V is applied through the non-coated anode, the maximum electric current is reached as soon as 8 hours. Whereas, if the anode is not coated, the maximum electric current with applying the same voltage is reached in 18 hours. When electric potential of 5 V is applied through the coated anode, same amount of time is required to reach the maximum electric current. This shows that polyaniline coating improved the electrokinetic stabilization of the dredged mud if 5 V electric potential is applied and resulted in lower power consumption and higher electrokinetic efficiency.

Settling velocity is based on the hydraulic and electroosmotic permeability of the soil. Therefore, the relationship between electric current and settling velocity given in this section shows that the highest hydraulic and electroosmotic permeability was achieved at electric current of 0.3 amps when anodes are coated. Whereas, the ultimate current for non-coated anodes is twice the coated anode for application of 30 V electric potential and less than half for application of 5 V electric potential. Therefore, application of constant $I_{v(max)}$ is suggested electric current to obtain the maximum possible settlement. Use of $I_{v(max)}$ as the design electric current result in lowest power consumption and maximum settlement.

Table 6.2 Optimum time at which maximum electric current occurs

Electrode condition (anode)	V (volts)	Optimum time t_{opt} (Hours)	I_{max} Maximum electric current (Amps)	$IV_{s\ (max)}$ Electric current at maximum V_s (Amps)
Non-coated	5.00	90	0.20	<0.1
Coated	5.00	18	0.52	0.3
Non-coated	30.00	8	0.92	0.6
Coated	30.00	18	0.56	0.3

6.2.2 Electrokinetic sedimentation

The changes of interface height with time is shown in Figure 6.7. It is shown that if 5 V electric potential is applied through coated anode the sedimentation behaviour of the soil is similar to when 30 V constant electric potential is applied. Application of 30 V electric potential through coated anode did not significantly change the final settlement of the soil, and only 11% increase in final settlement of the dredged mud is observed. This is due to the disintegration of the polyaniline coating at higher voltage of 30 V, and is attributed to the unknown chemical reactions resulting from the interaction between polyaniline coating and dredged mud particles, or changes in resistivity of the anode by applying the polyaniline coating. However, when 5 V electric potential is applied through polyaniline coated anode, the final settlement of the dredged mud increased to 73% of the final settlement of the dredged mud in case of non-coated anode.

The logarithmic regression that is the best fit of the experimental data shows the settlement of the dredged mud at any time during electrokinetic stabilization given as:

When 5 V electric potential is applied through coated anode:

$$S = -47.38ln(t) + 472.84 \tag{6.5}$$

When 5 V electric potential is applied through non-coated anode

$$S = -31.521ln(t) + 475.03 \tag{6.6}$$

When 30 V electric potential is applied through coated anode

$$S = -45.1ln(t) - 463.69 \tag{6.7}$$

When 30 V electric potential is applied through non-coated anode

$$S = -38.37ln(t) - 438.61 \tag{6.8}$$

where S is the settlement of the soil with time and t is the time interval in hours. These correlations are true for the dredged mud with the presented initial state and under the given laboratory condition.

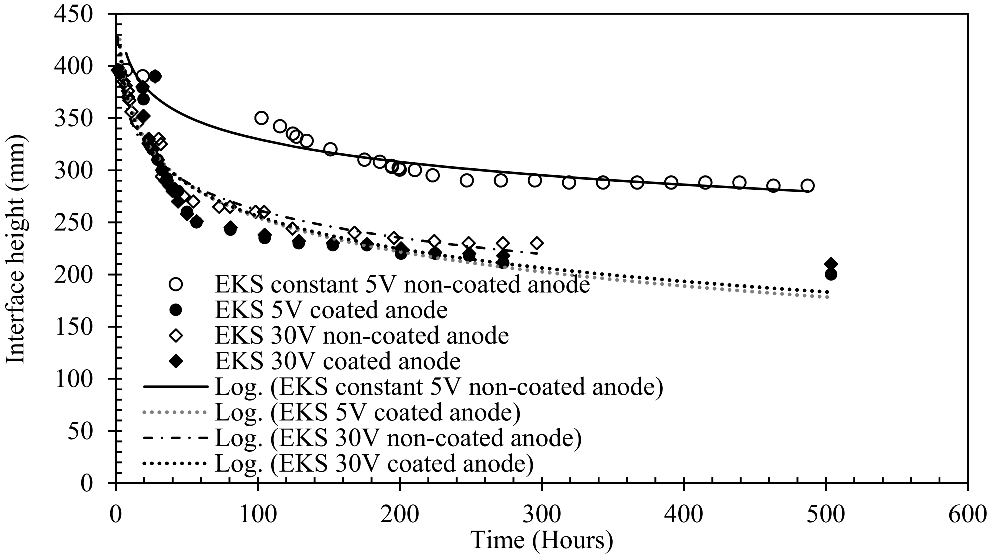


Figure 6.7 Changes of settlement versus time

6.2.3 Electrokinetic sedimentation coefficient

The electrokinetic sedimentation coefficient is the slope of the porosity and settling velocity of the slurries. The sedimentation coefficient is related to the process of hindered settling prior to consolidation and it is similar to the coefficient of consolidation during the process of consolidation. When slurry settles, concentration of solids increases with time. As a result, the porosity and the settling velocity of the particles reduces (Mohamedelhassan and Shang 2001). According to Zaki and Richardson (1954) the velocity of suspension V (m/s) depends on porosity (n) and coefficient of sedimentation (r):

$$r = \log_n(\frac{U}{V})$$

where U is the particle settling velocity (m/s):

$$U = \frac{g(\rho_s - \rho_f)\, d^2}{18\, \mu}$$

where g is gravitational acceleration (m/s^2), ρ_s and ρ_f are density of solid and fluid respectively (kg/m^3), d is diameter of particles (m), and μ is the viscosity of fluid (N.s/m^2). The coefficient of sedimentation can be determined from the plot of settling velocity and porosity. In this study the settling velocity and the porosity is determined using following equations:

$$n = \left(\frac{e}{1 + e}\right) \times 100$$

where e is the void ratio, and n is the porosity in percent. The settling velocity (mm/hr) of the slurry based on changes of interface height is determined from:

$$V_s = \frac{\Delta H}{\Delta t}$$

where ΔH is the changes of interface height in (mm) within time interval of Δt (hr).

The variation of coefficient of sedimentation versus porosity is shown in Figure 6.8. The settling velocity increases as porosity increases up to 81% after which it reduces. The experiment starts initially with porosity of 86% which gradually reduces as sediment settles. In case of 5 V non-coated anode, the settling velocity did not change significantly. However, in case of 30 V non-coated, the settling velocity increases to a peak of 84% after which, it reduces progressively to a final porosity of 77%. Both cases of coated anodes follow a similar pattern. In both cases, the settling velocity starts at a relatively slow rate and increases progressively up to a maximum velocity, at porosity of 82%, then it reduces gradually reaching a final porosity of 74%.

The sedimentation coefficient increases when properties such as clay content of the soil increases (Shang 1997). The polyaniline contributes to changes in the properties of the dredged mud through unknown chemical reactions which result in better electrokinetic settlement and efficiency. The coefficient of electrokinetic sedimentation is calculated from the left hand side of the slope of the settling velocity versus porosity. The left side of the graph is related to the initial peak of the electric current, and first half of the settlement before consolidation, and the right hand side of the graph is considered as consolidation stage. Therefore, the coefficient of sedimentation is determined using the left hand side of the settling velocity versus porosity plot. The coefficient of sedimentation is 0.46 mm/hr, 0.98 mm/hr, 0.11 mm/hr, and 0.14 mm/hr for 5 V non-coated anode, 30 V non-coated anode, 5 V coated anode, and 30 V coated anode, respectively.

This shows that for coated anodes, the increase in voltage does not significantly change the settling velocity of the dredged mud. The electrokinetic sedimentation depends on the intrinsic properties of the clay and current density. The results reported in this study are in agreement with the findings of Shang (1997).

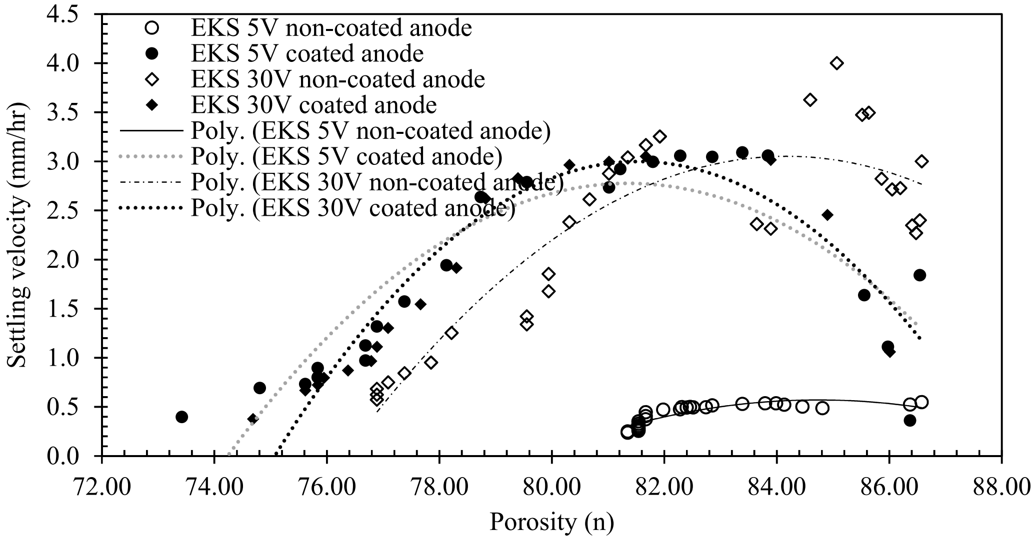


Figure 6.8 Variation of settling velocity with porosity

6.2.4 Electroosmotic permeability parameters

The soil settling velocity (given in section 6.2.1) is based on electroosmotic permeability of the soil. And the effectiveness of the electrokinetic dewatering depends on electroosmotic permeability k_e. Electroosmotic permeability is measured using the equation given by Mitchell (1993):

$$q_{eo} = k_e A \frac{j}{\sigma} \tag{6.9}$$

where q_{eo} is the flow rate of water (m^3/s), k_e is electroosmotic permeability $m^2/$ (s.V), A is cross-sectional area between electrodes, j is current density in A/m^2, and σ is the electrical conductivity of the dredged mud slurry (S/m).

As dredged mud slurry settles, the electroosmotic flow reduces with time. The flow rate of water (q_{eo}) that is induced by application of electric current is measured using the volume of drained water within the time interval when interface height changes. Figure 6.7 shows the changes of electroosmotic permeability with void ratio. The electroosmotic permeability of the dredged mud reduced with reduction of void ratio. The responses of dredged mud to 30 V electric potential that was applied through coated and non-coated anodes were similar. Therefore, their fitting curves are nearly coincident. According to Malekzadeh and Sivakugan (2016), the electroosmotic permeability parameter which is assumed to be dependent on changes of interface height and index properties of the soil is given as:

$$k_e = C^* e^{D^*} \tag{6.10}$$

where C^* and D^* are electroosmotic permeability parameters and e is void ratio. According to this equation the electroosmotic permeability parameters derived from the performed experiments are as follows:

5 volt non-coated anode: $C^* = 2\times10^{-6}$, $D^* = 2.45$ (6.11)

30 volt non-coated anode: $C^* = 7\times10^{-6}$, $D^* = 2.74$ (6.12)

5 volt coated anode: $C^* = 3\times10^{-5}$, $D^* = 1.77$ (6.13)

30 volt coated anode: $C^* = 7\times10^{-6}$, $D^* = 2.74$ (6.14)

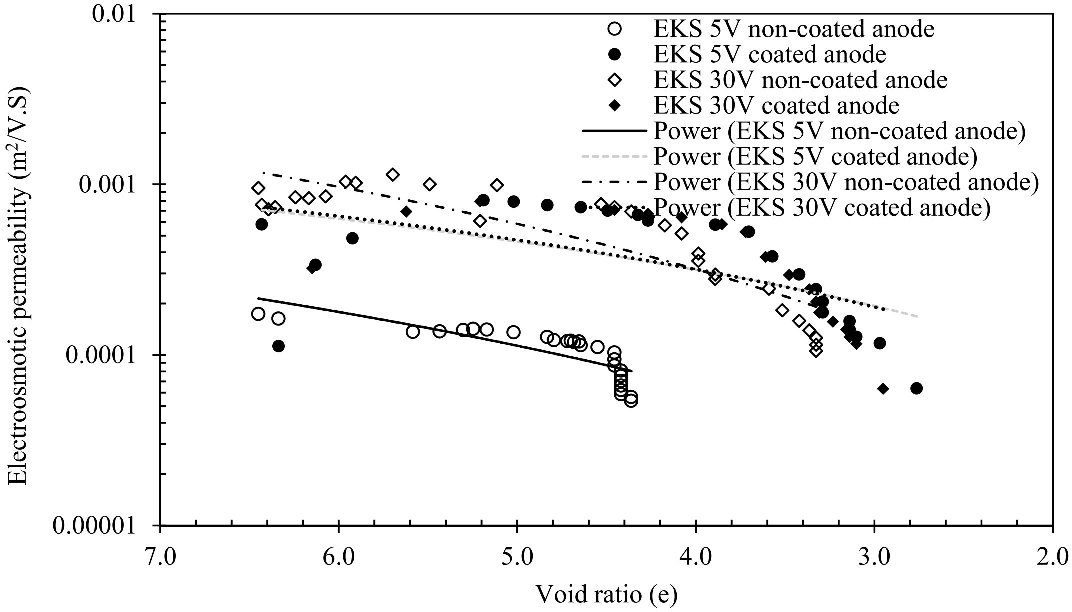


Figure 6.9 Electroosmotic permeability versus void ratio

6.2.5 Power consumption

The power consumption in this study is based on two variables. One is the electric current which changes with changes of soil resistivity and time and the other variable is the distance between electrodes, since the cathode moves downward with as interface height changes. Therefore, the following equation is used to determine the consumption of energy.

$$P = \frac{dI}{dl} \times \frac{V}{A} \times \Delta t \tag{6.14}$$

where P is the power consumption (W.s/m^3) to settle the volume of sediments noted as dl (changes in distance between electrodes), with a constant applied voltage of V (Volts), which generates an electric current difference of dI (Amps) within a time interval of Δt in hours through cross sectional area A (m^2).

The energy consumption for treating 1 cubic meter of dredged mud when constant electric potential of 5 V and 30 V electric potential is applied to the soil through coated and non-coated anodes is shown in Table 6.3. The consumption of energy when a non-coated anode is used with a voltage of 5 V is 1.97 kWh/m^3 which is very low in comparison with the other cases, however, the percent settlement is relatively lower than other cases too. When 5 V electric potential is applied to the dredged mud through the coated anode the power consumption increases 1.8 times the case of non-coated anode. However, the coating increases the settlement up to 9.8 times. The power consumption increase when the anode is coated with polyaniline. This is attributed to the lower conductivity of polyaniline coating in comparison with the non-coated anode. The choice of whether to apply the polyaniline coating needs to be based on the budget and timeline of the project. The coated anode with application of 5 V constant electric potential is suggested as an effective anode for maximum electrokinetic efficiency.

Table 6.3 Power consumption, percent settlement and average electric current

Electrode condition (anode)	Energy consumption per 1 m^3 of dredged mud assuming power consumption has linear relationship with soil volume (kWh/m^3)	V (volts)	% settlement $(\Delta H/H_i)*100$
Non-coated	1.97	5.00	28.75
Coated	19.34	5.00	50.00
Non-coated	71.88	30.00	42.50
Coated	112.73	30.00	47.50

6.3 Summary

In this chapter the effect of electrode material on electrokinetic stabilization of dredged mud is investigated. Different electrode materials such as aluminium, stainless steel, and copper are used as electrodes and it was observed that these metals corrode in short period of time. Therefore, galvanized steel electrode is chosen to be used as the electrode material in this study. However, galvanized steel corrodes in high saline environment. The galvanized steel anode is coated with polyaniline to reduce its rate of corrosion and to investigate its effect on electrokinetic sedimentation of the dredged mud.

Based on the results obtained, polyaniline coated anode increased the settlement of the dredged mud at low voltage of 5 V electric potential while increased the electrokinetic sedimentation coefficient from 0.46 to 0.98. Comparison between the changes of resistivity when coated electrodes are used shows that resistivity reduced when 5 V electric potential is applied, whereas it increased when 30 V electric potential is applied. The increase of resistivity during 30 V electric potential is due to the disintegration of polyaniline coating.

When 5 V electric potential is applied through the coated anode, although the power consumption is higher than non-coated anode, the settlement of the dredged mud is 1.8 times higher than when non-coated anode is used. Therefore, the application of 5 V electric potential with coated anode is beneficial and more economical, however the decision to use coated anode should be based on the specific project features, including available budget and timeline. In this study, because 30 V electric potential with non-coated and coated anode shown a similar sedimentation to 5 V coated anode. The application of 30 V with non-coated anode is used for further investigations on other design parameters due to the lack of resources.

Chapter 7: Effect of electrode material on physiochemical properties

7.1 General

The electrokinetic stabilization affects the properties of soils by electrochemical reactions. The effects of electrode configuration and electrode material on electrokinetic sedimentation of the dredged mud are presented in chapters 3 and 4. However, little attention is paid to the physiochemical changes of the treated soil and their interpretation after electrokinetic stabilization. The physiochemical changes influence the soil behaviour by affecting the particles in microscale level. The changes of soil behaviour due to occurrence of the chemical reactions lead to changes in soil permeability, water filtration, strength, and soil erosion. Therefore, it is necessary to study the effect of electrokinetic stabilization on physiochemical behaviour of the dredged mud. For this purpose, samples at four different depths are taken from the treated soil (after electrokinetic stabilization is completed). Atterberg limits, changes in pH, electric conductivity, and salt content of the samples are measured. The changes of physiochemical properties of treated dredged mud when galvanized steel (DM-GS), aluminium (DM-AL), and coated galvanized steel (DM-CA) are used, are determined when all samples were treated under 30 V electric potential.

7.2 Changes of pH

Changes of pH are the consequences of electrochemical reaction during electrokinetic stabilization of soils. Specific chemical reaction only occurs at certain pH values. Soil pH affects the dispersion and flocculation of soil particles (e.g. Goldberg and Forster 1990; Chorover and Sposito 1995). The flocculation or dispersion behavior of soil is governed by salt content, cation valence, cation exchange capacity, and clay mineralogy (Goldberg et al., 1999). The cation exchange mechanism of illite, smectite, vermiculite, and hydroxides (goethite and hematite) is pH-dependant.

Clay particles have a negative surface charge and because of these charges the electrokinetic stabilization is efficient with soils that has clay content of greater than 30% (Mosavat et al. 2012). Zeta potential shows the amount of charges in the soil, and has a direct relationship with pH. The pH at which the soil is electrically neutral is known as point of zero net charge and is related to the pH of the electrolyte that the solid particle is submerged into. If the pH increases above the point of zero net charge the negative charges increase, and the positive charges reduce. When soil is at pH of point of zero net charge, the soil particles start to flocculate quickly.

Figure 7.1 shows the changes of pH with depth after electrokinetic stabilization when aluminium (DM-AL), galvanized steel (DM-GS), and polyaniline coated (DM-CA) electrodes are used. The high pH (alkaline environment) near the cathode is due to the movement of H^+ ions and the generation of hydroxides. Conversely, the pH near the anode is acidic, due to the electrolysis reaction. When anode is coated, the area near anode is more acidic than when galvanized steel and aluminium are used. However, the alkalinity of the soil near the cathode when coated anode is used is less than galvanized steel and greater than aluminium. When the pH is greater than 8.5 more hydrogen ions are dissolved in the soil and the surface charge is more negative (Baumgarten 2013). Showing that in all cases the soil near cathode has more negative surface charges.

The point of zero charge for magnesium oxide is less than 4, and for Fe or Al oxides it is greater than 7. The pH near the anode when galvanized steel and coated galvanized steel is used is less than 4. This shows the presence of magnesium oxides in the soil when galvanized steel is used, and the pH greater than 7 shows the presence of aluminium oxides when aluminium is used. When soil reaches the point of zero charge, this is an indication that the electrokinetic stabilization is completed. The low pH of less than 4.5 (Baumgarten 2013) in soils with higher salinity leads to a better aggregation and flocculation, and as a result the soil near the anode has higher strength in comparison with the other part of the treated sample.

Clay particles reorient and restructure themselves while settling. The strongest orientation occurs when soil pH reaches the neutral value of 7. This layer of soil is known as consolidation zone (Lewis 1967). The zone of consolidation in this study is recognized as a discoloration in the soil at a particular depth during electrokinetic stabilization (Figure 7.1b). When the changes of pH with depth is determined (the grey strip in Figure 7.1a shows the consolidation zone layer on the graph), it was observed that this layer has neutral pH, therefore, the consolidation zone layer in this study occurred at the depth between 13 cm to 15 cm. The depth at which consolidation zone layer occurs depends on the initial pH of the soil. The initial pH of the dredged mud (the yellow dashed line in Figure 7.1a) is 8.1. It was observed that the type of electrode material did not affect the depth at which consolidation zone layer happened.

In chapter 5, section 5.2 the variation of electric current with time is shown, and it is observed that the electric current approaches zero regardless of the applied electric potential. In chapter 4, section 4.5 it is shown that increase of electric potential from 20 V to 30 V did not improve the electrical resistivity of the soil. Citeau et al. (2011) studied the changes of pH with zeta potential and observed that at low pH of 2.6 the sludge is at its isoelectric point (zero point of charge). If the isoelectric point of dredged mud happens at low pH values, this can be another reason for interruption of the electric current.

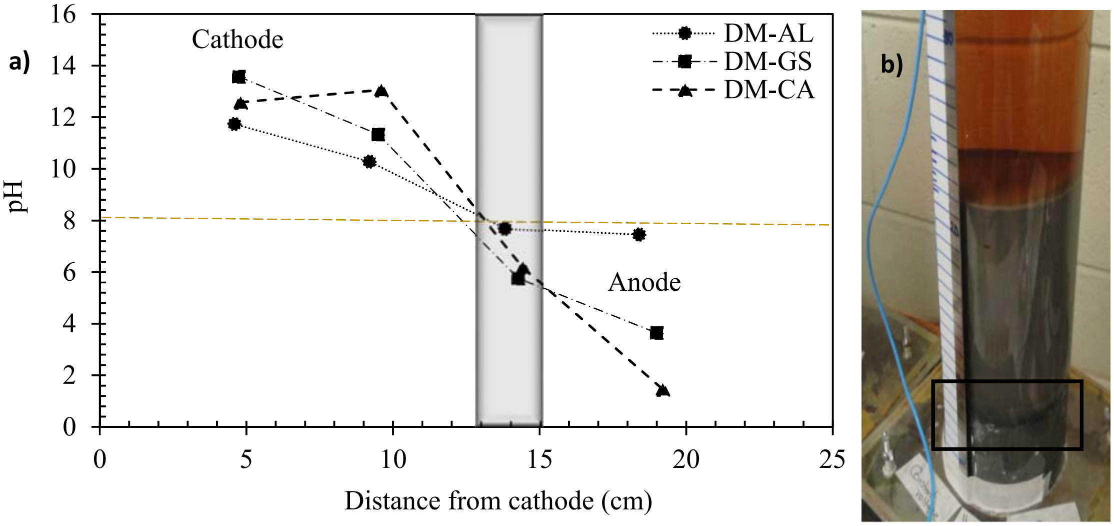


Figure 7.1 a) Variation of pH with depth b) Zone of consolidation

7.3 Changes of electrical conductivity

The electric conductivity of the soil changes during and after electrokinetic stabilization due to the electromigration of ions. Figure 7.2 shows the changes of electric conductivity with depth. In general, the electric conductivity of the soil near the anode is higher than the electric conductivity near the cathode. The larger electric conductivity near the anode is due to the generation of conductive hydrogen ions and the lower electric conductivity near the cathode is due to the calcium hydroxide precipitation (Jayasekera and Hall 2007).

When hydrogen ions move toward the cathode due to electromigration, the electric conductivity of the soil increases proportionally as the concentration of H^+ increases. When the anode is coated with polyaniline the electric conductivity of the soil near anode is higher than using aluminium and galvanized steel electrodes, showing higher production of hydrogen ions at the anode when polyaniline coated electrodes are used. High electric conductivity near the anode shows the polyaniline coating is disintegrated when 30 V of electric potential is used.

It is observed from the plot, that the solubility of aluminium is higher than galvanized steel in electrokinetic stabilization. Therefore, the electrical conductivity of the soil near the anode when aluminium is used is less than when galvanized steel electrode is used. An increase in electric conductivity of the soil from anode to the cathode when galvanized steel is used shows the mobility of the magnesium in the soil. Magnesium can react with soil and cause soil hardening near the anode.

The electrical conductivity of the untreated soil is 4.8 mS (yellow dashed line in Figure 7.2). When galvanized steel is used, the electrical conductivity of the treated soil near the anode is lower than the electrical conductivity of the untreated dredged mud, showing that the magnesium that is released to the soil from galvanized steel is highly conductive and has migrated to the cathode.

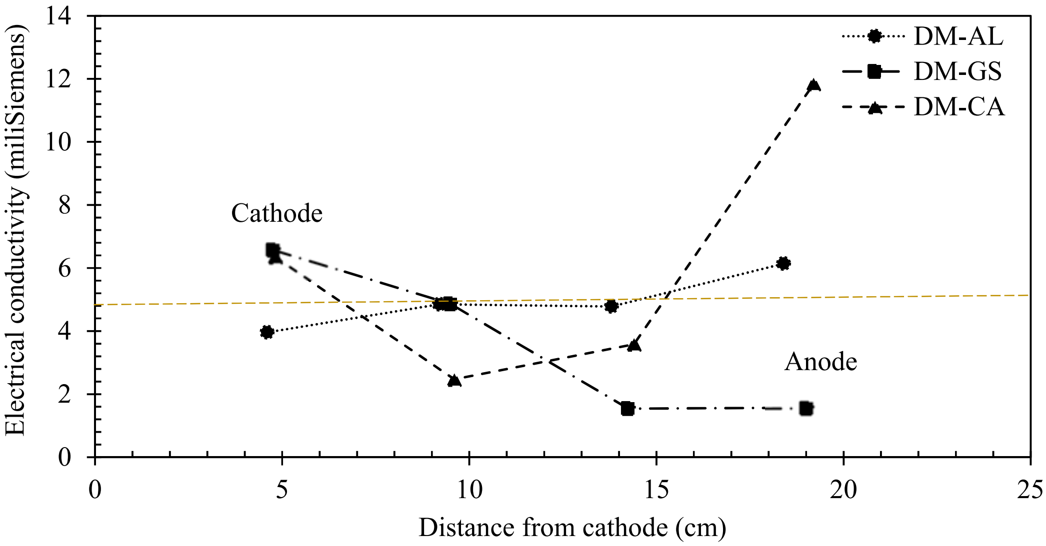


Figure 7.2 Variation of electrical conductivity with depth

7.4 Changes of salt content

The hydrogen ion that is generated due to oxidation reaction near the anode, affects the electrical conductivity of the soil, therefore measurement of electrical conductivity is not a reliable measure of soil salinity (Jayasekera and Hall 2007). Therefore, in this study the salinity of the treated soil is measured directly using the probe presented in chapter 3. During electrokinetic stabilization dissolved salt in pore water migrates from the anode to the cathode. The movement of salt ions depends on their interaction with soil minerals.

During sedimentation, the clay particles repel each other due to their negative surface charges. Therefore, the settlement of clay particles takes a long time to be completed. In the presence of salt, the sodium and chloride ions neutralize the negative surface charges and accelerate the soil sedimentation. This is true for the self-weight consolidation. However, in case of electrokinetic stabilization, depending on salt concentration the rate of corrosion at the anode increases. As discussed earlier in chapter 2, the limit of salinity at which the electrokinetic stabilization starts to be inefficient is not clear in the literature.

Figure 7.3 shows the variation of salt content with depth. As shown in the Figure, in all cases the salt content near the anode is higher than the salt content near the cathode. In case of coated anode (DM-CA), the salt content of the dredged mud drops. When aluminium electrodes are used, the changes of salt content from anode to cathode are not as significant as when galvanized steel and coated anode is used. However, drop of soil salinity below 2.9 ppt from anode to the cathode shows that the salt content of the treated soil reduced when aluminium electrodes are used. Comparison between salinity of the treated soil when coated anode and galvanized steel is used, shows that higher desalination can be obtained using coated anode than galvanized steel.

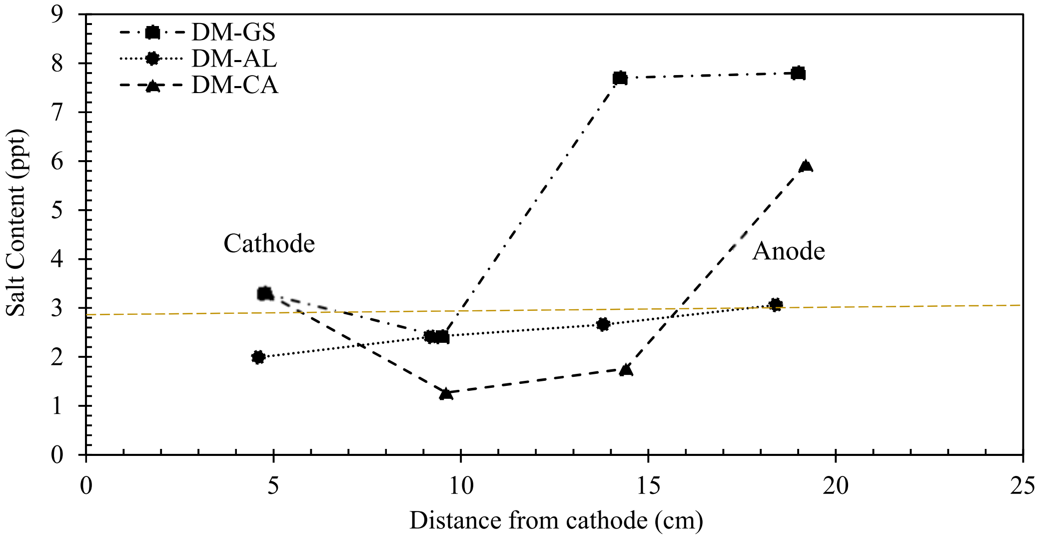


Figure 7.3 Variation of salt content with depth

7.5 Changes of liquid limit

Changes of pH, electrical conductivity and the salt content alter the soil structure and as a result, its index properties. In electrokinetic stabilization, reduction of pH near the anode results in lower liquid limits than near the cathode where an increase of pH causes an increase of liquid limit. However, the pH itself is not the only reason for changes in Liquid limit. The liquid limit of the soil mainly changes due to the alteration in soil mineralogy (Mitchell 1993).

Figure 7.4 shows the variation of liquid limit with depth. When aluminium electrodes are used, the liquid limit of the soil did not change significantly, although the pH of the soil changed abruptly from anode to the cathode. In case of galvanized steel and coated galvanized steel electrodes, the liquid limit of the soil reduced from the cathode to the anode. When galvanized steel is used, the liquid limit of the treated soil was smaller than original soil from depth 10 cm to 20 cm that is near the anode. This shows that the soil improvement is extended to a larger area when galvanized steel is used. Therefore, galvanized steel electrode is preferred for stabilizing the dredged mud sediments.

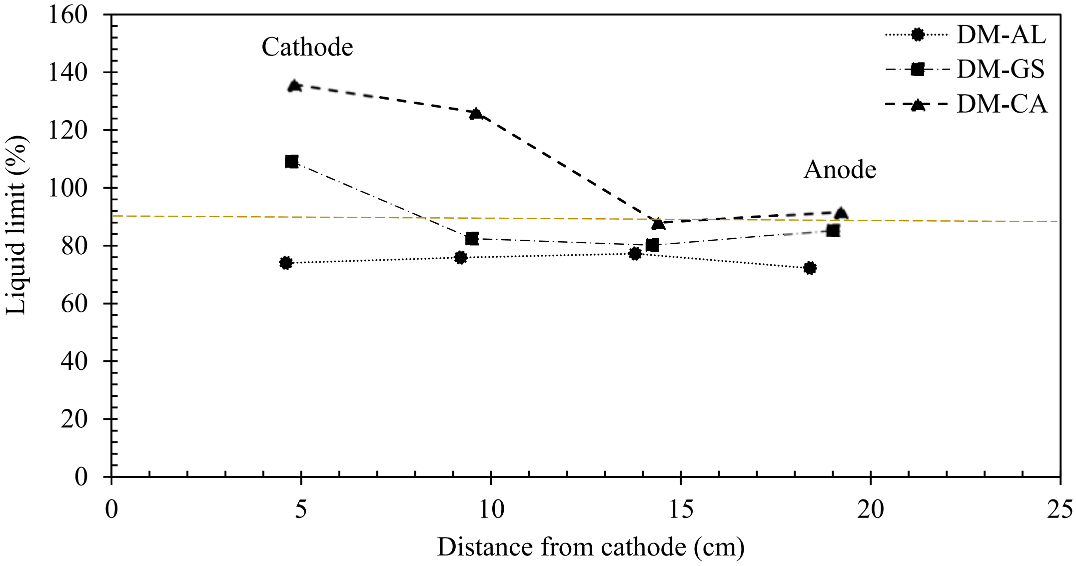


Figure 7.4 Changes of liquid limit with depth

7.6 Summary

In this chapter the effect of electrode material on physiochemical properties of the dredged mud is investigated using galvanized steel (DM-GS), coated galvanized steel (DM-CA), and aluminium electrodes (DM-AL). High electric conductivity near the coated anode, indicates that the coating is separated and entered to the soil at this voltage. It is observed that based on the changes of pH, electric conductivity, and salt content of the treated soil with depth, the galvanized steel and coated anode is preferable to aluminium electrodes. However, considering the changes of the liquid limit of the treated soil with depth when galvanized steel electrode is used, the area of stabilization with lower liquid limit is extended to half of the depth showing an improvement in soil properties. Therefore, galvanized steel is preferable to coated galvanized steel.

Chapter 8: Summary, conclusion and recommendations

8.1 Summary

This chapter presents a summary of this thesis, conclusions and recommendations for future research. In general, this dissertation aimed to investigate the possibility to improve the properties of the dredged mud by changing the different design parameters and to maximize the efficiency of the method including power consumption, amount of dewatering, and electrokinetic settlement.

The overview of the electrokinetic stabilization method presented in chapter 2 shows the effect of different factors on the efficiency of electrokinetic consolidation. The effect of these factors on electrokinetic consolidation process is investigated in this thesis to achieve optimal design criteria and further enhancement to the method. One-dimensional, two-dimensional and vertical electrode configuration are studied. The comparison between electrode configurations shows that the efficiency of electrokinetic stabilization can be maximized by optimizing the distribution of electric field through changing the electrode configuration. A comparison based on soil settlement and its effect on electrokinetic stabilization between placing the cathode on the top and at the bottom is presented.

Type of electric current application is another factor that influences the electrokinetic stabilization due the changes of soil resistivity. The application of regular intermittent current is proven to positively improve the electrokinetic efficiency of the soil. The irregular intermittent current application is investigated as a possibility to further reduce the power consumption and cost of the treatment. Along with the application of intermittent current, the effect of providing drainage at the bottom of the settlement column is also studied. Electrodes often corrode during electrokinetic stabilization. The corrosion rate of the anode and its reactivity with soil depends on the type of the electrode material. The effects of electrode material on electrokinetic stabilization and the changes of physiochemical properties are presented along with the effect of polyaniline coating which is often used to reduce the corrosion rate of metals in acidic environment.

8.2 Conclusion

In this investigation, research has been carried out to determine the effect of various parameters on electrokinetic settlement of dredged mud. A summary of the pertinent findings can be found below.

- The experimental study on effect of one-dimensional electrode configuration showed that electrokinetic consolidation reduced the compression index of the dredged mud by 52 % and reduced the coefficient of volume compressibity, thus making the sediment stiffer. The recompression index is also reduced up to 88 % of the recompression index of untreated dredged mud.

- Generally, it was observed that the consolidation properties of the dredged mud improved due to one-dimensional electrokinetic stabilization. However, when one-dimensional electrokinetic stabilization is used, the spacing between electrodes is an important design factor to be considered. The lower the spacing between electrodes, the better the effectiveness of the method. However, this results in higher power consumption. For more effective electrokinetic stabilization two-dimensional electrode configuration can be used. Two-dimensional electrokinetic stabilization improved the undrained shear strength of the dredged mud by reducing its water content especially near the anode. The water content and shear strength of the soil near the cathode did not show significant improvement as near the anode.

- Based on the result of the study, when 20 V electric potential is applied, the electric current increased till soil resistivity reached the maximum. The maximum soil resistivity is less, when the cathode is placed on the top. When further electric potential of up to 30 V is applied the variations in electric current was not significant and electric current remained constant, showing that the soil has reached its maximum resistivity by applying an electric potential of 20 V. The dewatering efficiency improved from 48% (when cathode is placed at the bottom) to 67% (when cathode is located at the top) with less power consumption. Therefore, based on this experimental study, it is better to place the cathode on top to get maximum settlement and dewatering.

- The coefficient of electroosmotic permeability increased as the applied electric potential increased which led to a better soil sedimentation. However, increase in magnitude of the electric potential resulted in higher power consumption. When 30 V electric potential is applied to the soil, a significant increase in settlement was observed in comparison with application of lower voltages. Therefore, application of irregular intermittent current with 70% intermittent ratio was studied and it is shown that intermittent current application resulted in higher settlement in comparison with application of constant electric potential of 30 V. Higher settlements were obtained while the energy consumption reduced to half.

- Polyaniline coated anode increased the settlement of the dredged mud at low voltage of 5 V electric potential while increased the electrokinetic sedimentation coefficient from 0.46 to 0.98. Comparison between the changes of resistivity when coated electrodes are used shows that resistivity reduced when 5 V electric potential is applied, whereas it increased when 30 V electric potential is applied. The increase of resistivity during 30 V electric potential is due to the disintegration of polyaniline coating.

8.3 Further research

The findings of this study is to be used as the basis for further future research in electrokinetic dewatering and consolidation of dredged mud in land reclamation areas. The followings are recommended for further investigation:

- This study investigated the unknown effect of some design parameters on electrokinetic settlement of the dredged mud. The design parameters investigated in this study are influenced by changes of chemical properties of the soil such as changes of zeta potential. The effect of changes of zeta potential on electrokinetic settlement of the soils need to be further investigated. Further research is required to develop a correlation between zeta potential and the efficiency of the electrokinetic settlement.

- Further investigation on effect of intermittent current ratio greater than 50% on changes of electrokinetic settlement of the soil is desirable to reduce the cost of the method.
- When soil particles of the slurry settle, the density of the soil changes at each layer. The changes of density during the self-weight consolidation can be measured by sending an x-ray of the soil slurry. However, due to the safety issue only special laboratories are

allowed to perform this test in Australia. The undisturbed measurement of the density and pore pressure with depth is to be further investigated if possible.

- A comparative study of the laboratory investigation of electrokinetic stabilization and its field application need to be performed to test the implication of the proposed method.

- The simulation of electrokinetic settlement of the soil in which the estimation model of electrokinetic stabilization is determined, is required to estimate the settlement of the soil without laboratory investigation. However, extensive laboratory experiments on effect of chemical properties needs to be included in the numerical models.

- Homogeneity of the soil after the treatment and the generation of desiccation cracks can be investigated using unsaturated soil theories of Fredlund to investigate the effect of generation of crack on the settlement of the soil.

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