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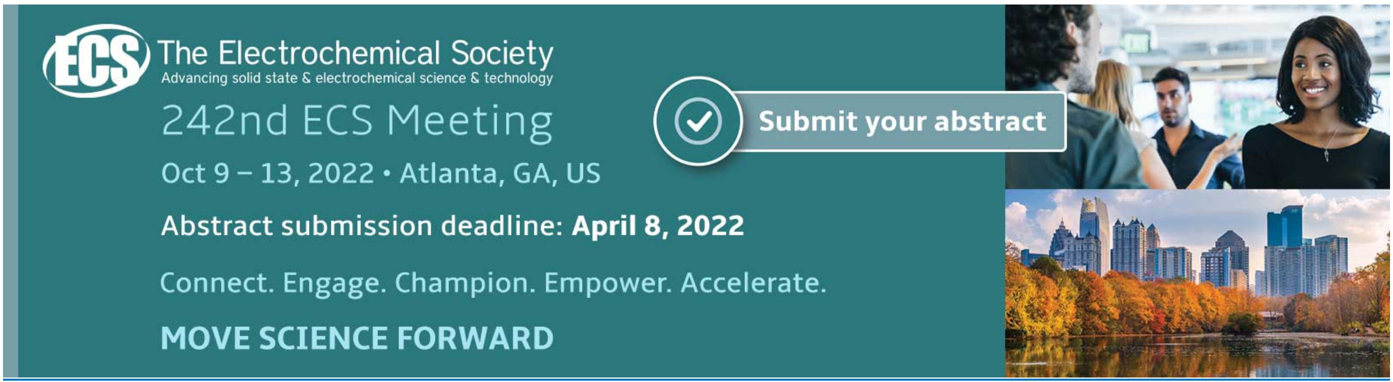

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Laboratory evaluation of electrokinetic dewatering of dredged marine sediment as an option for climate change adaption

M Malekzadeh[1], **N Sivakugan**[2]

[1] Faculty of Science and engineering, Southern Cross University, Lismore, NSW, Australia
[2] School of science and engineering, James Cook University, Townsville, QLD, Australia

Abstract. The climate change affects the coastal infrastructure including ports. This effect is through changes in the tides, waves, wind and coastal erosion. As a result, sedimentation in harbours and coastal area increases and therefore there is a need for more regular dredging as well as adaption to climate change to reduce the vulnerability. More frequent dredging means higher amount of dredging sediments need to be disposed or treated. One of the methods to be proposed to reduce the impact of high amount of dredging and reducing the environmental wastes as a by-product of dredging is to reuse or reproduce the dredged sediments. Electrokinetic stabilization is one of the environmentally friendly methods to dewater and strengthen the engineering properties of the soils and dredged sediments. This study investigates the effect of electrokinetic stabilization to improve the engineering properties of the dredged mud as an alternative option to reduce the environmental impact and use of a sustainable method for climate change adaption. Two laboratory designs are tested to determine the most efficient electrokinetic dewatering configuration and to examine the potential use of this method for dewatering and improving dredged mud. Electrokinetic stabilization is a promising method to dewater and expedite the settlement of the dredged marine sediments. However, the placement of electrodes can affect the power consumption and the efficiency of the technique and the resistivity of the soil. Some studies in the literature determine the best electrode configuration to optimize the electrokinetic stabilization. However, a few studies examined the electrode placement for electrokinetic dewatering and sedimentation. This study investigates the effect of electrode placement based on the efficiency of the method depending on power consumption versus dewatering, soil electrical resistivity, the settlement of the sediments, and treatment time. To reduce the energy expenditure first a constant voltage of 20 V is applied and the variation of electric current during the electrokinetic stabilization is monitored. Once the electric current approached zero, the voltage is increased to 30 V. Using constant voltage for both cases of electrode placement (anode on top, cathode at the bottom; anode at the bottom, cathode on top), it was observed that higher efficiency based on dewatering and power consumption is obtained when the cathode is placed on top.

1. Introduction

It is anticipated that climate change have an impact on coastal areas and navigational channels and ports. Climate change affects the sediment transport and through channels which are dredged regularly for flood mitigation and navigation purposes. According to Dahl et al. (2018) there are different climate projections that affect the dredging projects and the amount of dredging, which is a factor of sediment yield (eroded sediments that is transferred to rivers from landscape). Some of the studies in the literature look into the need of dredging and the rising of the water due to the climate change impact [3] and other studies investigate the delivery of the sediments because of the impact of climate change. Both models represent a higher amount of dredging as a requirement for maintaining and navigating the channels and coastal areas. Therefore, higher need of dredging will produces higher amount of disposal waste, which is not environmentally friendly, and there is a need to reduce the impact of these wastes. To increase the resilience and reduce the vulnerability to climate change we need to proactively identify vulnerabilities and determine solutions and plan options that can be taken into considerations for decisions to improve the resilience to the impact of the climate change.

Electrokinetic stabilization is a viable method to improve geotechnical properties of soils, especially for resolving consolidation problems. Electroosmotic consolidation reduces the compression index and increases the coefficient of consolidation of the soils, thus decreasing the final settlements and reducing the consolidation time [16]. Electrokinetic stabilization is the application of electric current to the soil through electrodes. Electrokinetic stabilization was introduced by Casagrande (1948) decades ago, however many aspects of this method are still unknown. The concerns of high power consumption, unavailability of standard designs and changes in the soil structure after the electrokinetic stabilization make this method one of the last options to be considered by geotechnical engineers. However, this method can be very useful in dewatering and consolidating slurries such as dredged sediments, mine tailings, and sewage sludge.

Once the electric current is applied to the soil slurry, the pore water migrates toward the cathode (negative pole) due to the electroosmosis. The volume of the soil reduces as the water migrates toward the cathode and that is how settlement of the soil increases. According to Lefebvre and Burnotte (2002), the electroosmotic consolidation can be up to 100 times faster than the conventional consolidation if the optimum efficiency is reached. The electric field intensity is defined as the initial applied voltage over the distance between electrodes, which is denoted by i_e (V/cm). The electroosmotic flow (Q_e) is expressed by analogy with Darcy's law:

$$Q_e = k_e \, i_e \, A \tag{1}$$

where k_e is the electroosmotic permeability and A is the cross sectional area of flow.

The electroosmotic permeability of soils depend on the zeta potential ζ (V), water permittivity $\mathcal{E}_w$ (F/m), dynamic viscosity $\boldsymbol{\mu}$ (Ns/m2), and soil porosity n, and is given by

$$k_e = \frac{n \mathcal{E}_w \zeta}{\mu} \tag{2}$$

Electrokinetic consolidation settlement depends on the changes in electroosmotic permeability, and electroosmotic permeability is a function of zeta potential, which is a function of soil pH. Therefore, electrokinetic flow depends on the zeta potential. Zeta potential, which is usually negative for clay soils, is the development of electric current in response to the movement of colloidal particles [16].

Two major problems associated with the use of electrokinetic stabilization for marine sediments are the high power consumption and the corrosion of the anode [28]. The problem associated with the corrosion of anode during electrokinetic stabilization is presented in Malekzadeh et al. (2016). When the electric current is applied to the soil, the electric potential loss near the electrodes reduces the efficiency of the method and increases the power consumption.

It is reported in the literature that electroosmosis is more energy efficient when lower voltages are used [14, 13, 34], however depending on the type of the soil, the critical voltage at which the electroosmosis has the optimum efficiency (based on energy consumption, amount of dewatering, time and settlement) needs to be investigated. The mineralogy and properties of the soil also affects the electroosmotic potential of the soil and the efficiency of the method (Based on Jones et al. 2008). Figure 1 shows how the efficiency increases with high water content (w), low cation exchange capacity (CEC), high conductivity (σ) which means high concentration of free electrolyte, pH, and surface charge density (A0).

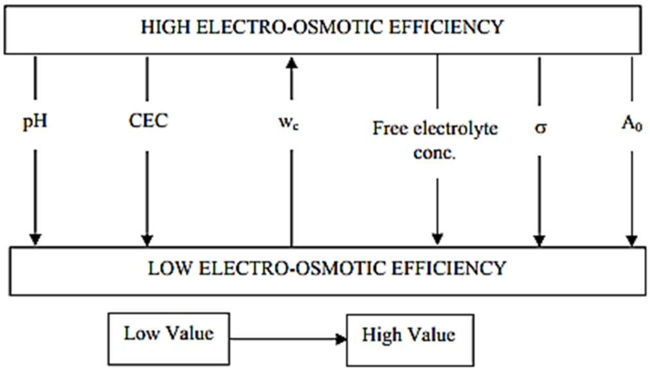


Figure 1. Effect of soil properties on efficiency of electroosmotic dewatering and consolidation [5]

Different laboratory models are used to investigate the effectiveness of the method. The laboratory model of Liaki et al. (2010) is based on the Casagrande (1948) method, where two sheets of metal are used as electrodes that inserted into designed compartments on the left and right hand side of the set up. This model shows the soil behaviour in response to electrokinetic stabilization and suitable for decontamination purposes where the contamination can be removed and monitored in cathode compartment. In another method proposed by Jayasekera and Hall (2007) two metal tubes, one of which is cathode, are perforated and inserted into the soil. During electrokinetic stabilization, the water can be pumped out from the cathode. This is analogous to a field simulation where electrodes could be inserted into the soil in arrays of anodes and cathodes. However, this method is effective if the purpose is to increase soil shear strength. With this method, the analysis of the soil consolidation and dewatering is not very accurate, and it is difficult and perhaps not possible to keep the electrodes in place in the case of soil slurries in reclamation areas (paddocks). Therefore, the laboratory simulation of electrokinetic dewatering and sedimentation should be based on the model introduced by Shang (1998). He introduced a set up based on self-weight settlement column models for slurries. This model is the best way to evaluate electrokinetic consolidation of slurries. There are few studies that place the cathode at the top [30, 18]. However, the effect of electrode placement is not clear in the literature and therefore this study investigates how change of electrode placement in electrokinetic dewatering and consolidation can affect the settlement and power consumption.

2. Experimental set up – soil

The dredged marine sediments used here is obtained from port of Brisbane in Australia. These sediments are then are prepared in the form of a slurry. The physical properties of the studied sediment are determined using Australian standard, which is presented in Table 1. The mineralogy of the dredged marine sediment is shown in Table 2 is obtained from Analytical centre at James Cook University. The dredged sediment is classified as high plasticity clay with only 10% sand according to USCS (unified soil classification system). Due to evaporation, the samples of dredged marine sediments stored in the laboratory lost their moisture content to 30 %, which is far from the initial moisture content when sediments are dredged and poured into the paddocks. Therefore, to bring up the moisture content to the average moisture content of 250%, water is added and mixed with the soil lumps and a slurry of dredged marine sediments are prepared.

Table 1. Physical properties of the dredged sediments [26].

Property	
Liquid limit (%)	92
Plastic limit (%)	40
Plasticity index (%)	52
Linear shrinkage (%)	33
Specific Gravity	2.61
Soil classification (USCS)	CH – Clay with high plasticity
pH	8.05-8.13
Conductivity (electrical) (mS/cm)	4.8
Salinity (ppt)	2.9
Colour	Grey
Sand (%)	10
Silt (%)	37
Clay (%)	53

Table 2. Mineralogy of the dredged mud (Malekzadeh et al. 2016).

Name of the minerals	% weight
Quartz - (SiO_2)	31
Kaolin - $Al2(Si_2O_5)(OH)_4$	21
Illite/ Muscovite	25
Amphibole	2
Sodium Plagioclase - $NaAlSi_3O_8$	-
Sodium Calcium Plagioclase - $(Na, Ca)Al(Si, Al)_3O_8$	2
Potassium feldspar - $KAlSi_3O_8$	11
Calcite - ($CaCo_3$)	-
Halite - (NaCl)	-
Pyrite - FeS_2	5
Expansive Clay	2

3. Electrokinetic testing setup

The electrokinetic setup used in this study is demonstrated in Figure 2. The setup is comprised of a settlement column which is made of plexiglass Settlement columns made of acrylic cell tubes are prepared. The bottom of the acrylic tube is attached to a plain Perspex glass sheet with a circular opening to the diameter of the acrylic tube. Another plain sheet with a 3 mm opening to admit the anode/cathode connection is then attached to the other sheet with screws. One galvanized steel electrode is attached at the bottom and the top galvanized steel electrode is placed on the top after the slurry is poured into the acrylic column cell. Since providing drainage at the bottom reduces the efficiency of the electrokinetic method (Malekzadeh et al. 2017), the bottom of the electrokinetic cell is enclosed and the drainage is only allowed from the top.

The electrodes are in the form of a thin circular galvanized steel sheet of 4 mm thickness with diameter of 90 mm. Both electrodes are perforated to allow water filtration. Galvanized steel is chosen as an electrode material due to their availability and low cost. When galvanized steel anode corrodes, it induces Fe3+ to the soil and depending on its cation exchange capacity; it can increase the soil strength. Other electrodes such as copper and aluminium can be a source of contamination [24]. Inert electrodes such as titanium are expensive to use, and the carbon footprint from carbon-based electrodes makes them environmentally undesirable.

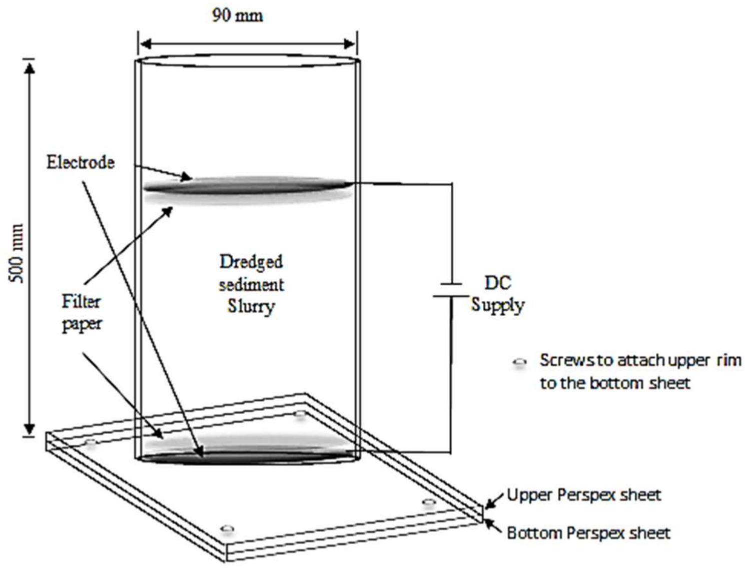


Figure 2. Electrokinetic stabilization setup.

4. The application of electric potential and changes of electric current during the experiment

The current at the beginning of the test provides an indication of the amount of ions originally associated with the soil, which appears as salt precipitates or as metal contaminants. As time passes, the current decreases because the mobile ions are constantly electro-migrating toward the electrodes, and as they migrate, the excess ions are neutralized by reacting with the soil, other species in solution, or by reacting with the oppositely charged electrode. The reason for the long-term stabilized current being difficult to understand is due to the complex chemistry. H+ and OH− ions are generated at the electrodes due to electrolysis, but when these ions electro-migrate toward the oppositely charged electrode, they can meet and react to form water, thus making their contribution to the current relatively minor [7]. However, the adsorption of these ions into the soil and the slow dissolution of minerals and/or salt precipitates that may result from pH changes could lead to a long term and steady supply of charge carriers [8].

It was assumed that soil resistivity builds up depending on the amount of voltage. Therefore, low constant voltage of 20 V is applied to the soil initially. Once the electric current approached to zero showing that the soil resistivity is at its maximum the voltage is increased to 30 V at time t_{30}. However, once the voltage increased to 30 V, no significant changes in electric current are observed. This shows that when a constant voltage is applied to the dredged sediment, the soil resistivity changes such that further increase in voltage gradient does not appear to affect the dredged sediment anymore. Figure 3 shows the variation of electric current with time for when the cathode is located on the top on the surface of the dredged mud slurry mix and for when it is located at the bottom of the column, below the dredged mud slurry mix. Voltage of 20 V is initially applied and then stepped up to 30 V after electric current approaches zero.

It can be seen from figure 3 that the variation in electric current with time follows a similar pattern regardless of anode/cathode configuration, however when the cathode is placed at the top, a slightly higher maximum electric current can be achieved. In addition, a lower electric current is observed when the voltage increases to 30 V when the cathode is placed at the bottom of the settlement column.

The variation of electric current with time in this study is different from the behaviour observed by Rittirong et al. (2008). In Rittirong et al. (2008) when a voltage gradient of 25 V was applied, the electric current fluctuates at about 0.1 Ampere whereas application of 45 V results in the electric current reducing from 0.14 to 0.10 Ampere after 6 days and fluctuates at about 0.1 Ampere afterward. The reduction in electric current is attributed to the voltage drop at the electrode-soil interface and the increase in resistivity of the electrodes, which are electric vertical drains. The resistivity of the anode is increased from 4 to 16 $\boldsymbol{\Omega}$/m after 6 days, when the electric current starts to reduce. The reduction in electric current of the soil herein is solely attributed to the increase in resistivity of the soil, since the electrode-soil contact is kept during the process by keeping the water in the system and draining the excess water at the end of the process, the flow of electricity is not interrupted.

It is also shown that the dredged sediment experiences less peak resistivity when the cathode is placed at the top of the settlement column. When a voltage gradient is applied, the current flow increases showing an effective electroosmosis, however, at a specific point in time the current starts to fall due to the built-up resistance [17]. Higher voltage gradients results in even higher soil resistivity and further reduction of electric current and lower electroosmotic efficiency [19]. However, Lockhart (1983) argues that faster electroosmotic dewatering and higher final solid content, and higher pH near the cathode are obtained with higher voltages. He also stated that 5 times less energy is consumed when the sequential voltage is applied to the soil for the same amount of dewatering hence a sequential application of voltage is applied herein.

As stated by Hamed and Bhadra (1997) high pH results in depletion of water and higher resistance to the electric current flow. Therefore, the reduction of electric current after 11 hours is attributed to an increase of pH near the cathode and how far the pH is increased. Since the current drops, it can be concluded that the energy consumption reduces as the pH of the soil increases.

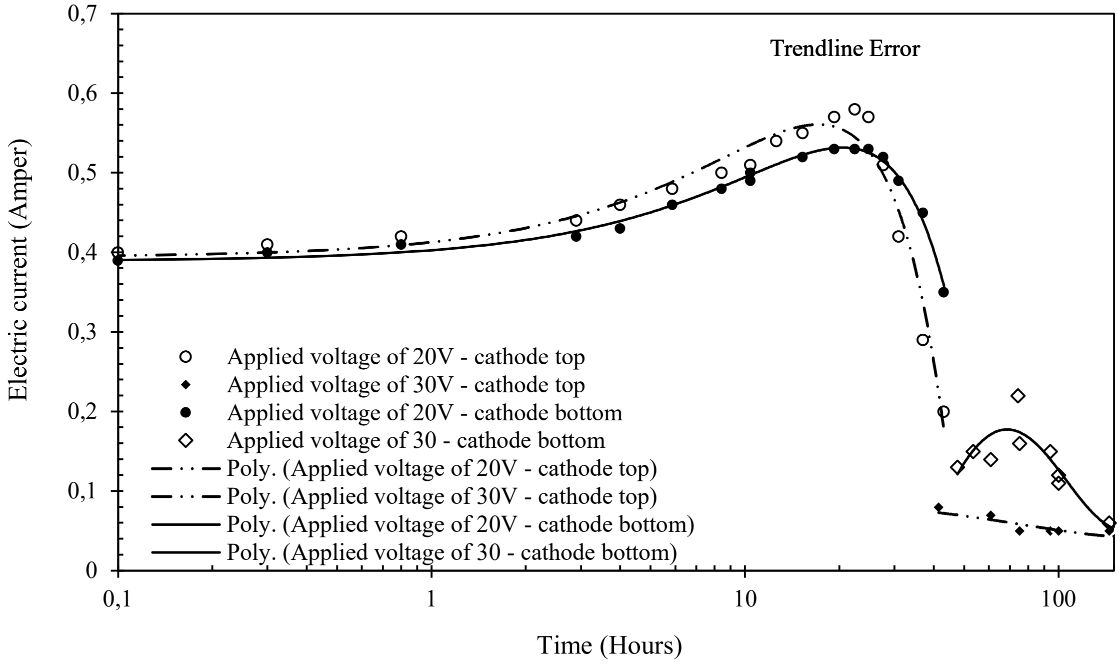


Figure 3. Variation of electric current with log time.

5. Electrokinetic settlement

Figure 4 shows the vertical strain (100 ΔH/H0) versus time in hours. A uniform water flow is generated by application of constant electric current. The initial electric current of 20 V is applied until the soil resistivity increased significantly. Then a 30 V of constant electric potential is applied to see if the increase of constant voltage to 30 V would affect the process of sedimentation.

When a slurry settles, it normally goes through three stages of sedimentation, first is the free settling stage at which particles settle individually, second is hindered settling stage which is settlement of the flocculated particles, and third stage is consolidation that happens when the soil starts to gain strength of more than 1kPa.

Velocity of hindered settling (the slope of the second portion of settlement versus time curve) is much faster when the cathode is at the top in comparison with cathode at the bottom. It is also observed in figure 5 that the generation of desiccation cracks and their pattern affects the sedimentation process. The horizontal cracks when the cathode is placed on the top increases the soil resistivity and therefore reduces the sedimentation of the soil in comparison with when the cathode is placed at the bottom where the horizontal cracks is mainly close to the anode. The application of electric current to the soil mainly accelerates the settling velocity of the particles with grain size less than 5 μm, therefore it is effective in reducing the time of settlement [30].

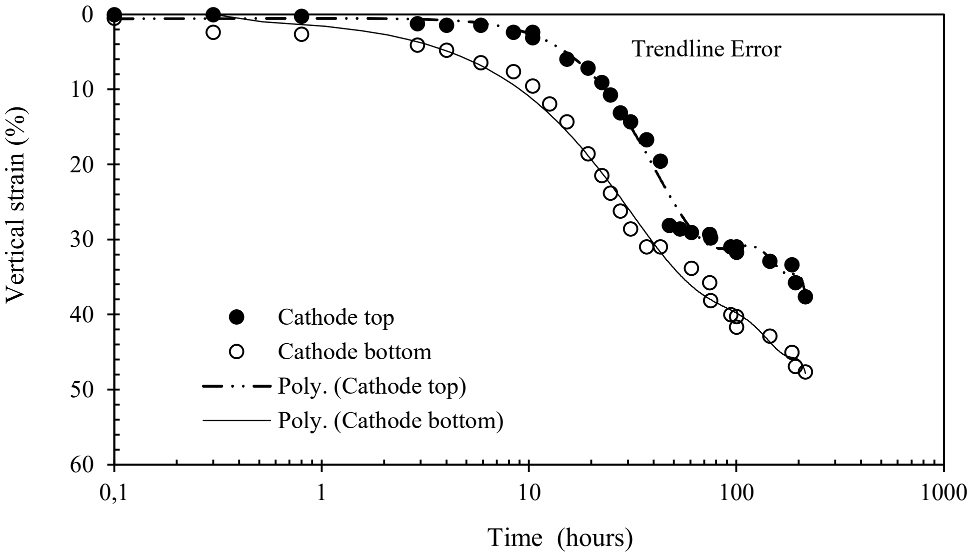
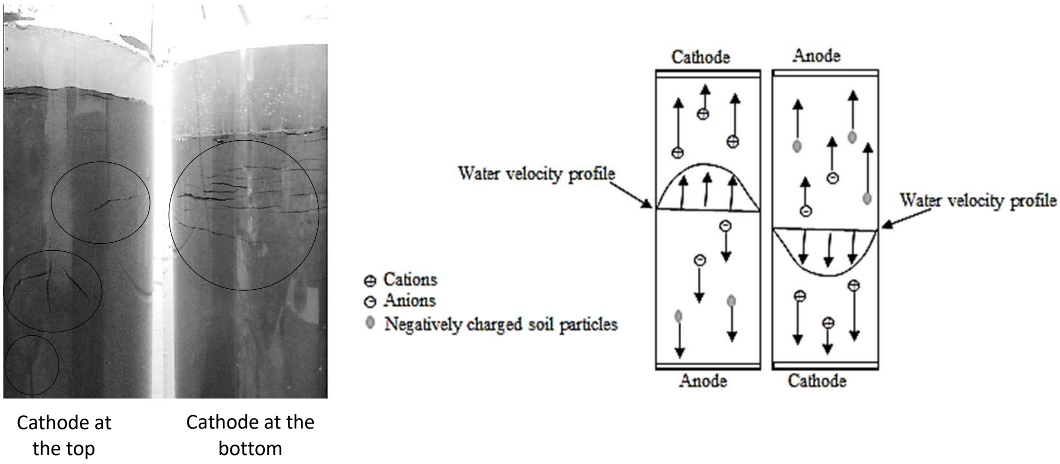


Figure 4. Vertical strain ($\Delta H/H_0$) versus time in hours.



Cathode at the top

Cathode at the bottom

Figure 5. Generation of desiccation cracks during electrokinetic settlement when the cathode is at the top and the bottom.

6. Dewatering

Electroosmotic efficiency is defined as the quantity of water drained per unit of electrical current, which is proportional to electroosmotic permeability [5]. The reduction of water content and increase of shear strength near the anode is higher than near the cathode [29]. Dewatering efficiency is based on the amount of water to be removed in comparison with the initial moisture content (W_i).

$$Dewatering\ efficiency = \left(\frac{W_i - W_f}{Wi}\right) \tag{3}$$

Where W_f is water content of the soil after electrokinetic stabilization.

As Lockhart (1983) stated when water is drained and porosity of the soil reduces, the thickness of the electric double layer reduces such that it overlaps with that of the adjacent particle and cations remain with the clay particles and zeta potential of the soil reduces. Therefore, hydraulic conductivity reduces significantly and further soil improvement by the same voltage is not possible to achieve. A higher voltage should be applied in order to further improve dewatering and increase the solid content. This explains why the voltage is changed to 30 V, that further dewatering occurred, which also meant further power consumption.

The dewatering efficiency is calculated as 67% and 48% for the case where the cathode is placed at the top and where the cathode is placed at the bottom, respectively. Therefore, considering the dewatering efficiency, it is more efficient to place the anode at the bottom and the cathode at the top. In addition, when the cathode is placed at the top, due to the electromigration of the ions, most of the cations in the soil can be extracted from the cathode. Whereas if the cathode is placed at the bottom, the contaminants in the form of cations will stay in the sediment since they settle with the soil particles and get trapped there.

7. Resistivity versus energy consumption

According to Acar et al. (1995) energy expenditure depends on the soil electrical conductivity, and the interface resistivity is inversely proportional to the conductive areas between electrodes and soil [37]. As soil, electrical conductivity increases the energy-required increases [30].

Kuma (2005) shows the result from several field and laboratory trials for evaluating the efficiency of the method based on power consumption and soil resistivity with consideration of the effect of electrode materials. Showing that the method is more effective if greater density of the array is applied. Also the greater the surface area of the electrode and the lower the electrical resistance of the material, the better 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), Kuma (2005) defines the electrical cumulative energy (E) as:

$$E = \frac{V^2 t}{R} \tag{4}$$

By taking logarithm of its components, equation (6) becomes

$$\ln E = 2 \ln V + \ln t - \ln R \tag{5}$$

If the voltage is constant, the cumulative energy consumption depends on the changes of electric current with time. It is due to the resistivity of the soil that electric current changes with time, therefore the resistivity is already taken into account of the electric current.

8. Conclusion

This paper presents empirical results obtained from bench-scale laboratory investigation of dredged sediments treated electro-kinetically. Two laboratory models where the cathode is placed at the top and at the bottom of the settlement column are evaluated based on the efficiency which depends on the power consumption. The effectiveness of the method is evaluated on the amount of dewatering, soil settlement, and soil resistivity. Following conclusions can be made from the observations in this study:

1) The electrokinetic stabilization is an effective method to stabilize the dredged sediments. With electrokinetic stabilization the rate of soil settlement, especially free settling and hindered settling increase significantly. However, the consolidation settlement needs to be further investigated.

2) A higher settlement rate and 60 mm more settlement are obtained when the cathode is placed at the top.

3) With the application of 20 V electric potential, the electric current increases till soil resistivity reaches the maximum of 19 kΩ/m3 when the cathode is placed on the top and 35 kΩ/m3 when the cathode is placed at the bottom, respectively. After that, electric current reduces to zero at the point where the electrokinetic process effectively finishes. By applying additional electric potential, up to 30 V the variations in electric current are not significant and it is almost constant, which shows that the soil reached its maximum resistivity by applying an electric potential of 20 V.

4) The amount of dewatering increased to 19 % when the cathode is located at the top, and also less power is consumed in this case.
5) A more effective electrokinetic stabilization, based on cumulative power consumption and soil resistivity, is obtained when the cathode is placed at the top and an electric potential of 20 V is applied rather than 30 V.
6) The electrokinetic stabilization has been shown to be an effective method to dewater and improve the dredged sediments.

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