Application of Electrokinetic Stabilisation (EKS) Method for Soft Soil: A Review

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Abstract. Soil properties such as low shear strength, excessive compression, collapsing behavior, high swell potential are some of the undesirable properties of soils in geotechnical engineering and those properties would cause severe distress to the structures. To solve these, an innovative stabilization of Electrokinetic (EKS) has been introduced. Electrokinetic is an applicable technique to transport charged particles and fluid in an electric potential. The EKS demonstrates changes in soil pH due to electrolysis reactions, water flow between the electrodes and migration of ions towards the cathode. This treatment has proven its efficiency in consolidating organic, peat and clayey silt as well as less expensive than other methods. Otherwise, this method also gives advantage by not disturbing site. The primary objective of this review is to discuss the application of electrokinetic and to investigate the current knowledge of electrokinetic in geotechnical application through a literature search and review, including consideration of certain aspects related to the soft soil application that may be relevant to the future study and at the same time addressing some key issues and their implications on soil behaviors.

1. Introduction

The growth of cities and industries, suitable sites, which can be used without some ground modification, is becoming increasingly scarce. Additionally, the replacement of soft soils with high quality materials is intensely expensive [1]. In Southeast Asia, soft clays are fairly widespread, and these deposits exist extensively in the vicinity of capital cities. Most construction works have met formidable obstacles (instability) when the construction area must be built over the soft clay deposits characterized by low undrained shear strength and high water contents. Additionally, ground subsidence associated with the consolidation of soft clay deposits correspondingly pose considerable threats to surface structures [2]. Soft soils and marine deposits are very common around the world. There are many infrastructure projects and coastal high-rise buildings which foundations are often supported by such soils of low shear strength and high compressibility. The construction of these projects on soft soils can lead to a very expensive foundation system [3]. These poor engineering properties of the soft clay often pose foundation problems to structures. Due to high rapid of construction activity, there is a necessity to improve the engineering properties of the soft clays and accelerate the process of soil consolidation [4]. Any construction cannot proceed before the soil condition gains adequate bearing capacity [5]. When the application of traditional
ground improvement techniques, such as surcharge, pre-loading, wick drains, and vacuum pre-loading, is not appropriate for a particular situation, innovative techniques such as EKS need to be considered [6].

There are various alternatives in dealing with problematic soils such as bypassing the poor soil, redesigning the structure for the poor condition or improving the soil properties by mixing soil with materials such as cement, lime, gypsum and fly ash amongst other ground modification techniques. The latter option can be used for surface improvement, such as road and rail subgrade improvement, or in deep soil mixing or jet grouting technologies, which are soil improvement approaches, mixing in situ soil with strengthening agents [1].

Conventional methods have been known to be successful in minimizing several damages, however they are expensive, time-consuming and may be difficult to implement in some existing structures [7-11]. Obviously, the damages came from major settling or tilting of buildings, instability and road embankments. Electrochemical or electrokinetic treatment methods can be used as alternative soil treatment methods for remediation of those deficiencies underneath building foundations, roads, railways or pipelines [8][12][13]. Furthermore, this technique involves an approach with minimum disturbance to the surface while treating subsurface contaminants and improving the engineering characteristics of subsurface soils [14-16].

2. History of EKS Method

Electrokinetic stabilisation was first succeed in soil remediation which was performed in the Netherlands in 1986 and some other places in Europe and US for the removal of the toxic chemical species. Through these successful studies and applications, it encourages other researchers and in-situ studies, resulting in some breakthroughs in the understanding of electrokinetic phenomena to improve physical properties of low permeable soils for many approaches such as; improving stability of excavations and unstable embankments, backfill strengthening and slope stabilisation, stabilisation of fine-grained soils, remediation of salt affected soils, dewatering of sludge, assisting pile driving and treatment of dispersive soils [7][14].

According to Shenbagavali & Mahimairaja [9], the first observation made in 1808 by Ruess showed the electrokinetic phenomena was used when a DC current was applied to a clay-water mixture. Next, the first treatment by Helmholtz in 1879, a study of electroosmosis phenomena had been done analytically and provided a mathematical basis. History of electrokinetic treatment also shows that Casagrande started his studies in 1930 on electro-osmosis in order to stabilise clays mainly by removal of the water. It also proves that several Russian researchers used electro-migration in prospecting metals in 1960.

Mohamedelhassan, [3], conducted an investigation of the feasibility of decreasing the water content and increasing the shear strength and axial load capacity on soft clays by applying the electrokinetic treatment. By using fresh water in the experiment, the researcher found the former was more efficient that the latter. In year 2011, a study by Misic, Shang & Lo [5], on electrokinetic strengthening of soft marine clays adjacent to skirted foundations showed an evidence where the soil’s shear strength was further increased with time after the electric field was withdrawn where it attributed to the electrokinetic induced soil particle cementation during post-treatment ionic diffusion.

3. EKS in Geotechnical Application

The electrokinetic stabilisation processes have been reported by many researchers to cause a significant increase in the shear strength of soils [17-22], and soil compressibility [23-24].

Changes in the physical properties are attributed to the electrochemical effects under the influence of electrical gradient including electroosmosis, electromigration, electrolysis, hydrolysis and degradation of electrodes [23]. These processes are invariable across the soil samples from anode to cathode which contribute to the changes of physicochemical of treated soil. This electrochemical effect can also be associated with the changes of clay-water-electrolytes system which leads to the dissolution of chemical compounds or clay minerals, ion exchange capacity, adsorption, desorption, complexation, precipitation and mineralisation (secondary mineral). When a direct current is applied to soil liquid medium, water in the immediate vicinity of the electrodes is electrolyzed [24]. Oxidation occurs at the anode, generating an acid front, while reduction takes place at the cathode, producing an alkaline front. These reactions cause
the pH to decrease at the anode and increase at the cathode [22]. The development of this pH gradient (known as acid/base profile) and its effects on the species transport through soil porous medium have been investigated in detail and well documented by many researchers, including Ozkan, et al. [17], Alshawabkeh & Sheahan, [18], Rogers et. al., [20] and Barker et al. [21].

In electrokinetic stabilisation methods, when cations are used as stabilising agents, ions migrate into soils through the processes of electroosmosis and electromigration. These ions improve the soil strength by three mechanisms, namely cation replacement, precipitation of species in the pore fluid and mineralisation. It is precipitation or mineralisation that provides the greatest contribution to increase in strength [21-22][26]. However, this type of reaction usually occurs when pH values of the soil solution are greater than seven [18][21]. Therefore, the pH values of the soil solution need to be maintained above seven during treatment in order to maximise its efficiency by appropriate injection of chemical ions at both electrodes [18].

According to Boardman et al. [27], the solubilities of some common metal hydroxides as a function of pH are illustrated in Figure 1 and Figure 2. In short term tests, some researchers have observed that at the beginning of the test, the soil weakening occurred at the anode due to acidification of the soils causing dissolution of carbonates, silicates and hydroxides of aluminium and iron (depends on solubilities of metal compound at low pH).

Figure 1. Solubilities of metal hydroxides as a function of pH (Boardman et. al., 2004)
For long term, as time progressed and subsequent reduction of the water content, the release of the these cations from the clay surface or clay mineral lattice will be replaced by stronger valence cations, larger cations or a concentration of cations by mass action. This displacement led to a decrement in the thickness of the diffuse double layer, thus promoted the edge to edge attraction, closer contact of clay platelets, or flocculation, and resulted in improvement of soil properties [20-21]. This is also called as molecular bonds and these bonds are weakened by moistening [29-30]. Subsequently, stronger and more stable bond arose between the soil particles and the strength as a whole can be attributed to a coagulational-crystallisational process.

4. Process of EKS Method

Laboratory experiments have been conducted broadly by various researchers to investigate and report the different factors affecting the soil behavior by electrokinetic stabilisation technique. Electrokinetic stabilisation is the combination process of electroosmosis and chemical grouting and it is most effective for silty and clayey soils because of its low hydraulic conductivity. A study by Chien et. al., [31] has shown the application of stabilising agents through the anode or cathode during electroosmosis is effective in strengthening soft clay. It is also defined as the physicochemical transport of charge, action of charged particles, and effects of applied electric potentials on formation and fluid transport in porous media. It uses direct current (DC) or a low electric potential difference to an array electrodes placed in the soil form removing organic, inorganic and heavy metal in particles from low permeable soils by electric potential [7].

Basically, this technique is used to improve the volume stability of soil around and beneath foundation. This technique involves applying an electrical current across the soil mass to boost the chemical migrates from the injection point with the purpose of reacting beneficially with the soil to bring out an improvement in its properties.

Electrokinetic stabilisation suits for weak clayey soils which have low hydraulic conductivity and require strengthening for soil condition. Otherwise, it is also can be used to stabilise the heavily over consolidated clayey soil. The advantage by using electrokinetic stabilisation instead of traditional mix-in-place chemical stabilisation is that the technique allows to remote treatment through soil without any excavation works [32].

Electrokinetic stabilisation technique can be enhanced by using some non-toxic stabilising agents such as lime or calcium chloride solutions. These chemical solutions can be fed at anode or the cathode depending on the ions to be transferred into the soil. Addition of these chemical stabilisers will alter some properties of the soil such as texture, plasticity, compressibility and permeability. Hence, it can be very effective in improving soil characteristics by reducing the amount of clay size particles and increasing the
shear strength [7]. In enhancing the soil stability, addition of chemical solution into soil during electroosmosis was adopted in recent years. Previously, chemical solutions such as calcium chloride and sodium silicate were applied as grouting material where Ca$^{2+}$ and SiO$_3^{2-}$ in those solutions will migrate in clay under electric field and will induce as a good cementation between the soil’s particles. Furthermore, the injection of stabilising agents towards the soil during electroosmosis will enhance the soil strength [33]. Previous laboratory work by Ou, et. al., [34], explained the result of injection of calcium chloride and sodium silicate solutions could improve the soil near the cathode and anode, respectively. Injection of those stabilisers towards EK treatment could yield fairly good improvement result for the entire soil sample.

5. Advantages and Disadvantages of EKS Method

Electrokinetic stabilisation has several advantages when compared to traditional ground improvement methods such as mass preloading and in-situ or ex-situ mixing of clay with stabilisers prior to compaction [35]. The advantages by using electrokinetic stabilisation are cost effective, applicable to apply in-situ and ex-situ, rapid installation, easy to operate, having silent operation, not disturbing site activities, and having short treatment duration. From the results obtained in electrokinetic stabilisation laboratory test and field work, it was clarified that this technique could be applied towards low permeable soils [7].

Nevertheless, electrokinetic stabilisation technique has the following limitation, such as the excessive heat generated in the vicinities of electrode can cause some adverse effect like desiccation or cracking in the specimen. It shows that some undesirable product such chlorine gas can be generated at the electrodes during the process as a results of electrolytic decomposition (redox) reactions of water [36].

Previous studies suggested to control the variation changes in pH of the soil which caused by the application of electrokinetic stabilisation treatment. In order not to harm the biodegradation process due to the high acidic conditions and electrolyte decay can corrode some anode materials, the electrodes were coated using corrosion resistant material and incorporated into a geosynthetic material such Electrokinetic Geosynthetic (EKG). By forming the electrode as a geosynthetic, EKG overcomes the problem of removing clean water by utilising the drainage and filtration functions of geosynthetics. Another major concern is by using a proper chemical stabiliser to enhance the electrokinetic stabilisation treatment [37]. Using different types of chemical stabilisers could potentially increase the properties of the soft clay. Based on the data presented in previous studies the best combination suggested is calcium chloride at the anode and sodium silicate at the cathode.

Some studies showed that heavy metals in their metallic state have not been successfully dissolved and separated from the soil samples. This electrokinetic technique may not efficient if the target ion is in low concentration and non-target ion concentration is high. Besides, the migration path could be very long or there might be stagnant zones between wells where the rate of migration is slow resulting in incomplete remediation of the contaminated soil [9]. Electrolysis reaction in the vicinity of the electrodes may cause the changes in pH that may change the solubility of the contaminants in the soil. Heterogeneities or subsurface anomalies at sites, such as rubbles, building foundations, large quantities of iron or iron oxides, buried conductor, large rocks or gravel, or submerged cover materials such as seashells, can reduce the effectiveness of the technique [7].

6. Solution for Disadvantages of EKS Method

The effectiveness of electrokinetic treatment is directly related to the electric field intensity. Previous researcher mentioned that the effectiveness of electrifikinet treatments can be maximized by the optimization of the electric field distribution through the electrode configuration [38-39]. In order to increase the efficiency of electrokinetic stabilisation technique, several solutions should be taken into consideration [7]. The solutions that should be considered along electrokinetic stabilisation process are;

i) Injection of proper chemical stabilisers for soft clay strengthening purpose as a couple with electrokinetic treatment technique to prevent production of hydrogen ions in a relatively short time which will lead to the reduction of electroosmosis flow and cationic contaminants removal.

ii) Prevent desorption and precipitation of the contaminants.
iii) Before selecting configuration and spacing arrangement, optimize all variables such as current, voltage levels, processing time, installation, operation cost, etc.

iv) Use inexpensive non-reactive electrodes such as in carbon forms which are available in almost all countries rather than expensive nonreactive metals such as electrodes like titanium or titanium coated materials.

v) Use perforated electrodes with some drilled holes on the electrode’s surface to allow the liquid move freely into the sample and enhance electrokinetic stabilisation process.

vi) Managing the development of non-conductive regions as a result of soil drying is another important issue which requires careful considerations in developing appropriate practical method guidelines for full scale implementation of the electrokinetic stabilisation process.

vii) Avoid toxic effects on the soil.

7. Factors Affecting EKS Methods

Several problems have been denoted associated with corrosion and deterioration of anodes, generally the electrical resistance will be increased and hence, the electrical current will reduce. Various design considerations should be given attention which can have important influences on the efficiency of the electrokinetic stabilisation technique [13]. The design considerations includes;

i) Modify and correct the electrodes installations to ensure good electrical contact with the subsurface, avoid an electrical bridge through surface water or top soil.

ii) Maintain the low electrical resistance in the soil to ensure a high degree of saturation.

iii) Provide subsurface features such as slip surfaces, and sand or gravel lenses, in which electrical bridges where injected stabilisers will preferentially migrate.

iv) Analyse the effect of any acid/base front propagating through the soil, particularly in relation to underground services.

v) Fully control the depth of the water table if treatment is applied under existing structure to avoid unwanted ground movement.

vi) Careful consideration of sleeve material, augered holes may have to be sleeved to prevent infill (side wall raveling or collapse).

8. Conclusion

There are various alternatives in dealing with problematic soils such as bypassing the poor soil, replacing its superior soil, redesigning the structure for the poor condition or improving the soil properties by mixing soil with materials such as cement, lime, gypsum and fly ash amongst other ground modification techniques. The latter option can be used for surface improvement, such as road and rail subgrade improvement, or in deep soil mixing or jet grouting technologies, which are soil improvement approaches, mixing in situ soil with strengthening agents. Conventional methods have been known successful in minimizing several damages, however they are expensive, time-consuming and may be difficult to implement in some existing structures.

This review has revealed that EKS method provides many advantages to solve soft soil problem. Consideration of many factors in the design which affect their workability and efficiency of the system are also discussed further such as voltage gradient, electrode installation and injection of chemical stabilisers into the system. The relevance and applicability of the EKS technique in geotechnical, geoenvironments and soft soil applications are also highlighted to help the direction and method of future study might utilise, and with ideas for EKS implementation improvements. Various laboratory tests and field tests have been conducted to assess the efficiency of electrokinetic in various applications. Most of the findings showed encouraging results and great potential that electrokinetic can be an effective means of soil improvement and to solve problematic soils related to the soil soil.

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