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Review of Osmotic and Mechanical Loading on the Behaviour of Soft Clays

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Abstract. It is well known that the soft clays possess low strength and high compressibility characteristics and are often encountered in geotechnical engineering practice and needs ground improvement. Several methods have been developed for the improvement of soft clays and one of the popular methods is preloading. Preloading involves the application of surcharge load on the soil in excess of the anticipated structural load on to the soil layer. Preloading can be carried out in combination with vertical drains which decreases the drainage path and thus accelerates the rate of settlement of soft clays. Apart from the mechanical preloading, it is possible to induce the physico-chemical mechanisms in clays soils using certain ionic solutions such as sodium chloride and calcium chloride solutions to reduce the volume of clays. This volume reduction of clays occurs due to two processes known as osmotic consolidation and osmotic induced consolidation. The osmotic consolidation occurs because of the decrease in the thickness of the diffuse double layers from the ionic solutions. The osmotic induced consolidation occurs because of outflow of water molecules from the clay soil in response to chemical or osmotic gradients. This paper reviews the detailed mechanisms of preloading and osmotic consolidation for the improvement of soft clays and compares both mechanical and osmotic loading effects on clays soils.

Keywords: Soft Clay; Preloading; Physico-Chemical; Osmotic Consolidation; Osmotic Induced Consolidation

1 Introduction

Soft clays are those which possess low strength and high compressibility characteristics and are often encountered in geotechnical engineering projects. Generally, clays with unconfined compression strength in the range of 25 kPa to 50 kPa are known as soft clays. Due to rapid urbanization there has been huge surge in the demand for construction sites and so it becomes imperative to consider even the problematic soils such as soft clays for the construction of structures. The main problems associated with the construction on soft clays are excessive settlement and bearing capacity failure of these deposits.

Many ground improvement methods are widely available for treatment of soft clays to facilitate construction on these deposits. Some of the treatment techniques are: removal and replacement of soil, sand compaction piles (SCP), addition of additives etc. But the most effective treatment techniques are the hydraulic modification which involves surcharge preloading, preloading with vertical sand drains, preloading with prefabricated vertical drains (PVDs), electro-osmosis, vacuum preloading, vacuum preloading with vertical drains and combination of vacuum preloading and surcharge preloading with vertical drains.

Many methods have been combined together to effectively treat the soft clays. However, there may be a possibility of treating these deposits by combining the preloading with vertical drains and osmotic flows. This paper provides a detailed review of the available hydraulic modification techniques and osmotic techniques for the improvement of soft soils.

2 Overview of State of Art

A comprehensive literature review focusing on the preloading, PVDs, vacuum preloading, electro-osmotic treatment and osmotic effects are presented in this section.

2.1 Preloading

The preloading technique involves loading an area with a temporary structure with the load greater than that of its final anticipated load and it is known to be one of the most promising techniques for improving the strength properties of soft soils (Indraratna et al., 2005). The basic principle of preloading is to reduce the voids in the geomaterial through consolidation by applying static loads on the ground surface for certain duration of time and later removing it for the construction of the permanent intended structures (Mitchell and Jardine, 2002).

A surcharge embankment is constructed in stages on the ground to be improved. The buildup of pore water pressure and also the embankment stability is taken care by constructing the embankment in stages with some rest after each stage before moving on to the next stage of embankment construction (Jamiolkowski et al., 1983). The surcharge load to be placed on the ground generally consists of earth fill materials. This technique even though can be used for all kinds of soils it is most effective for soft cohesive soils (Hausmann, 1990).

Stamatopoulos and Aneroussis (2002) examined the effect of preloading on the dynamic response of soils. In their study they measured the shear velocity before and after preloading and concluded that due to preloading there will be decrease in the surface acceleration. The earliest recorded use of preloading technique as one of the method of ground improvement technique was given by Tomlinson (1956).

2.2 Prefabricated vertical drains (PVDs)

One of the first prefabricated vertical drain (PVD) was developed by Swedish Geotechnical Institute. The PVDs were developed as an alternative to the sand drains. Basically, PVDs consists of an outer filter covering made up of a geosynthetic material with an inner plastic core for providing longitudinal flow paths for the flow of water. Combining the preloading method with PVDs accelerates the consolidation rate as the PVDs provide shorter drainage paths for the dissipation of excess pore water pressure.

Consolidation behavior and pore water pressure of soil due to PVDs

Gandeharioon et al., (2010) analyzed the installation disturbance of PVDs driven by mandrel in the soft clays by developing a novel theory of elliptical cavity expansion. They showed that the estimated and measured excess pore water pressures were the same by verifying the theoretical variation of excess pore pressure obtained from the large scale consolidometer tests

Indraratna et al., (2011a) studied the behavior of soft clay when it was subjected to cyclic loads by conducting the large-scale triaxial tests on soft clay samples. From their tests results they found that the PVD was able to dissipate the excess pore water pressure developed during and after the application of the cyclic loads.

Zhou and Chai (2017) conducted some model tests and finite-element analysis to determine the effect of the non-uniform consolidation within the unit cell of the PVD on the average degree of consolidation. Their results showed that the overall degree of consolidation is affected by the non-uniform consolidation of the PVD unit cell.

Guo et al., (2018) proposed a curve fitting method to bring out the relationship between degree of consolidation and non-dimensional time factor. Based on this relationship a modified Asaoka's observational method was developed which was able to predict the higher ultimate consolidation settlement than the Asaoka's method by about 1%.

For the case of ground improvement by prefabricated vertical drains, Yu et al., (2019) gave a practical consolidation solution by considering the available time dependent rate of discharge around the PVDs. The proposed solution was able to predict the degree of consolidation and excess pore water pressure much accurately.

Smear effects due to PVD installation

Madhav et al., (1993) introduced three distinct zones in order to study the smear effect. Those zones are as given below.

1) Inner smear zone comprising of highly remolded soil.
2) Outer zone of transition
3) Soil unaffected zone by the installation of drain.

Parsa-Pajouh et al., (2014) predicted the minimum waiting time required after the trial embankment construction to accurately predict the smear zone properties. Their results showed that the radius of smear zone and the smear zone permeability can be accurately predicted when the degree of consolidation reaches 33%.

Babak et al., (2016) conducted numerical analyses to study the effect of the reduced OCR in the smear zone on the ground deformation characteristics. Their results indicated that viscoplastic strain rate and creep strain limit is influenced by the OCR profile of the smear zone and therefore affects the deformation of the soil.

Choudhary et al., (2016) established a new approach in which the smear zone properties were estimated by considering the hydraulic gradient variations resulting from the values of the excess pore pressure data which was measured in the radial direction. This method was found to be advantageous as it could be adopted with the least soil disturbance and with lesser number of soil samples.

Discharge capacity of PVDs

Liu and Chu (2009) introduced a new variety of PVD in which the filter and the core were integrated in to a single component by the process of heat melting. This new type of PVD had improved performance and properties as compared to those of existing PVDs. They also conducted some laboratory tests and their results showed that both the discharge capacity and tensile strength of the new type of PVDs was greater than the conventional PVDs.

Bo et al., (2016) considered factors such as hydraulic gradient, duration of the test, nature of surrounding materials, apparatus dimensions, the vertical drain deformation profile and the confining pressure to present the equations for determining the discharge capacity of the PVDs under laboratory testing. One of the most important conclusions which they deduced was that the PVD under folded conditions was the deciding factor for the reduction in the discharge capacity of a PVD.

Huang et al., (2016) modeled the PVD as an elliptical cylindrical drainage body in order to simulate the actual shape of the PVD. The newly obtained solutions which were found by considering varying equivalent diameters were compared with the traditional solutions and it was found that the conventional method with the perimeter equivalent model overestimated the drainage effects on the PVDs.

Nguyen et al., (2020) conducted laboratory studies on a drain made by wrapping the cores made from coconut by Indian jute sheath filters also known as biodegradable prefabricated vertical drains (BPVDs) and they compared its performance with the conventional synthetic prefabricated vertical drains (SPVDs). Their test results showed that BPVDs had enough discharge capacity to accelerate the consolidation process in the soil and their ability to mitigate the excess pore water pressure was comparable to SPVDs

2.3 Vacuum Preloading

The vacuum preloading method was first introduced in 1952 by Walter Kjellman who was the then director of Swedish Geotechnical Institute. He described this new method in which the atmospheric pressure was used as a temporary surcharge for preloading the clays. In the method described by him a filter layer consisting of either sand or gravel is clinched to the clay strata which is submerged under the ground water table and a rubber or plastic membrane is placed over the filter. The air is sucked out from the filter by the means of a vacuum pump. In this method a vacuum pressure of around 60-70 kPa is applied which is roughly the height of a 5 m sand fill.

Consolidation effects in soil due to vacuum preloading

Kianfar et al., (2013) suggested a modified radial consolidation model by considering the effects of vacuum preloading. They utilized the data obtained from a modified Rowe cell for proposing the model. The proposed model was found to be advantageous as it predicted a more accurate flow behavior during consolidation and it eliminated the requirement of threshold hydraulic gradient to differentiate between the linear and non-linear flow relationships.

Lam et al., (2015) conducted studies on the behavior of soft Bangkok clay with vacuum preloading in combination with surcharge loading and PVDs. They evaluated the performance by using numerical simulations by using ABACUS software and analytical methods for computing the settlements and flow parameters. Their results confirmed the fact that vacuum PVD method had higher settlement rate in comparison to conventional preloading method.

Wang et al., (2016) suggested a new technique of vacuum preloading to consolidate the clay-slurry fill in which they integrated both vacuum and an air pressurizing system with some modifications. Field tests were performed both by the vacuum preloading and the improved method for comparison. Results show that the improved method gave better consolidation results.

Wang et al., (2018a) developed a technique in which the dredged slurry was initially treated with sand before subjecting it to vacuum consolidation. They performed vacuum preloading tests on two groups to understand the effects of the sand content. Their results indicated that sand content had a more predominant effect than the sand size in improving the consolidation characteristics of the dredged slurry during vacuum consolidation.

Combined vacuum and surcharge preloading

Indraratna et al., (2011b) adopted the combined surcharge and vacuum preloading along with PVDs to improve the soft clay deposit at Port of Brisbane. They developed analytical solutions to forecast the excess pore water pressure and settlements of the clay deposit and also presented the field monitoring data to showcase the embankment performance during the construction.

Chai and Rondonuwu (2015) studied the deformation characteristics of clayey soils subjected to combined surcharge and vacuum preloading by performing a series of radial drainage odometer and triaxial tests. The test results were used for determining a technique for finding the surcharge loading rate (SLR) which will lead to minimum lateral displacement of the deposit when it is treated with combined surcharge and vacuum preloading.

Zhou et al., (2017) proposed an analytical solution for a multi-layer soil deposit installed with PVDs and treated with combined vacuum preloading and surcharge loading. The proposed solution was found to be accurate and it was observed that the combination of surcharge and vacuum preloading increased the effective stress but had little influence on the consolidation rate.

Wang et al., (2019a) conducted laboratory model tests on dredged soils to investigate the effects of surcharge loading rate (SLR) when the soil was subjected to a combination of surcharge and vacuum preloading. The results suggest that adopting a higher SLR leads to higher degree of consolidation, shear strength and bearing capacity.

Vacuum preloading in combination with additives

Wu et al., (2016) conducted experimental studies on solid-liquid separation of construction waste slurry by combining vacuum preloading and flocculation precipitation method. The results showed a reduction of water content from 163% to 37%, a reduction in the clay content and an increase in the silt content because of flocculation and the porosity of the slurry decreased in the radial direction.

Wang et al., (2017) combined the vacuum preloading and lime treatment methods to improve a dredged fill in eastern part of China. In this method the hydrated lime was first added to the dredged fill which improved the properties of the dredge like the permeability and shear strength. It was observed that there was an increase in the shear strength of the soil particularly in the deeper areas and also the observed consolidation rate was higher than conventional vacuum preloading method.

Wang et al., (2019b) proposed a technique for enhancing the properties of the dredged slurry by combining multiple-flocculant treatment and vacuum preloading. This technique involved the addition of lime and anionic polyacrylamide (APAM) before applying the vacuum preloading. The results showed that the shear strength and consolidation rate increased with the use of this method.

2.4 Osmotic effects on soils

Clay particles have a net negative charge on their surface. This negative charge on the clay particles may be attributed to the broken bonds or otherwise known as isomorphous substitution. To compensate for the negative charge present on the clay particles a diffuse double layer develops on the surface of the clay particles. Many researchers have pointed out that the net long range repulsive and attractive stresses (*R-A*) between the clay particles is the governing factor in controlling the shear strength and volume change behavior of clay soils. The volume changes that happen in clays when the clay specimens are inundated with electrolyte solutions has been accredited to the decrease in the thickness of the diffuse double layer due to reduction in the net repulsive and attractive stresses (*R-A*). Barbour and Fredlund (1989) named this volume change process as osmotic consolidation.

Volume change behavior in soils due to osmotic effects

Barbour and Fredlund (1989) in their classical paper presented an alternate theory to explain the volume changes in the clayey soil due to osmotic effects which mainly occurred due to changes in the pore fluid chemistry. They presented two mechanisms osmotic consolidation and osmotically induced consolidation to explain the osmotic volume change behavior in clayey soils. Their experimental results conducted on two soils with concentrated sodium chloride solutions indicated that osmotic consolidation was the most predominant contributor for osmotic volume changes in clays.

Barbour et al., (1992) described the state variables for soils where there is a change in the osmotic pressure of the pore fluid. They showed that for saturated soils two state variables are sufficient to describe the stress sate. Those variables are the effective stress and the net electrostatic repulsive stresses between the soil particles. The model proposed by them was used to study the volume change behavior in saturated soils.

Thyagaraj (2018) studied the compressibility, structure and collapse behavior of compacted soil due to physico-chemical effects. The sodium chloride and calcium chloride solutions were used as the pore fluids in different combinations to study the physico-chemical effects. The results showed that the mixing of clay specimens with distilled water and then inundating it with salt solutions caused outward osmotic flows and increased the collapse potential. Whereas initially mixing the clays with salt solutions and then inundating it with distilled water caused inward osmotic flows and decreased collapse potential.

Bulolo and Leong (2019) studied the effect of salt solutions on volume change behavior of soil specimens with kaolin-bentonite mixtures. Their results showed that the soil specimens underwent additional settlement along with the consolidation settlement due to vertical stress but there was no effect on the soil compressibility and it was also shown that a large osmotic suction was required to induce a settlement equivalent to that induced by vertical stresses.

Pasut et al., (2019) performed numerical modelling and laboratory experiments on unsaturated loamy sands to study the effects of glycerol concentration gradients. Their results supported the hypotheses that the chemical induced water flow is primarily by matric effects and secondarily by osmotic effects which displaced only around 3% to 10% of water.

Matric and osmotic suction

Thyagaraj and Rao (2010) conducted experiments to study the effects of induced osmotic suction gradient on the soil-water characteristic curves (SWCCs) of compacted clay specimens inundated with sodium chloride solutions/distilled water at vertical stress of 6.25 kPa in oedometer cells. Their results suggested the need to incorporate the effects of the osmotic suction in determination of the matric SWCCs.

Thyagaraj and Salini (2015) conducted experiments on compacted expansive clay and their results showed that with an increase in the pore fluid osmotic suction the matric suction was found to increase and the reason for this was attributed to changes in the soil structure. The results from the Scanning electron micrographs showed that the particle aggregation increased with the increase in the pore fluid osmotic suction and cation valence due to reduction in diffuse double layer thickness. Their result also showed that the method of using non-contact filter paper for obtaining matric suction was reliable.

Leong and Abuel-Naga (2018) studied the effects of osmotic suction on the shear strength of soils by conducting unconfined compression tests on three soil specimens inundated with different pore water concentrations and compacted to different densities. The results of the unconfined compression test conducted on these specimens indicated that the shear strength of the specimens was same irrespective of the pore fluid, elapsed time and the compacted water content indicating that there was no effect of osmotic suction and osmotic suction gradient on the shear strength of the soil.

Li and Xu (2020) developed a calculative method to determine the osmotic suction of salt solutions. Osmotic suction determined from the calculated osmotic coefficient was verified by filter paper tests conducted on the soil specimens. A good match was found between the proposed method and experimental results. They further explained the mechanical behavior of clays in saline solutions from both microscopic and macroscopic viewpoint in relation to osmotic suction.

2.5 Electro-Osmotic Consolidation

The first observation of flow of water due to application of direct current was made by Reuss in 1809 and this phenomenon was coined as electro-osmosis. Clay particles have a net negative charge on their surface due to which it attracts positive ions leading to formation of diffuse double layer. When electrical potential is applied these positive ions move towards the cathode and in the process, they drag the free water with them. The movement primarily occurs in the diffuse double layer as it contains large concentration of positive ions.

Consolidation characteristics of soil subjected to electro-osmosis

Wu et al., (2017) conducted laboratory experiments and proposed a 1D model to investigate the non-linear variations of soil compressibility, electro-osmotic and hydraulic conductivities. The results of the studies showed that the degree of consolidation and excess pore pressure development for soils with high compressibility were greatly impacted by the non-linear variations of electro-osmotic and hydraulic conductivities.

Hu et al., (2019) studied the effects of the soil pH and ions on the electro-osmotic consolidation of kaolin. It was found that with increase in pH the voltage loss near to the anode, drainage rate and total volume of water discharged increased. It was also found that the addition of sodium ions increased the total volume of water discharged and the drainage rate. While the addition of copper ions decreased the dewatering efficiency.

Zhao et al., (2020) derived a solution for 1 D consolidation of double layer soil subjected to electro-osmosis. Parametric studies were conducted using the model and the results show that there will be a sharp increase in the excess pore water profile at the interface between the layers and a higher coefficient of volume compressibility in the second layer resulted in slower dissipation of the excess pore water pressure. They also studied the effects of the thickness of layer and soil permeability on the dissipation of excess pore water pressure.

Electro-osmosis in combination with surcharge and or vacuum preloading

Peng et al., (2013) carried out experimental investigation to study the mechanism and effectiveness of the electro-osmosis combined with vacuum preloading on ultra-soft soil. The results of their tests indicated that the shear strength increased by 60% and the reinforcement effect was better when electro-osmosis was combined with vacuum preloading than that of electroosmosis after vacuum preloading.

Liu et al., (2014) proposed a new method in which they combined electro-osmosis, surcharge loading and vacuum preloading. A field test was conducted to compare the proposed method with vacuum preloading combined with surcharge preloading and it was found that the proposed method induced 20% larger settlement, saved 50% treatment time, increased both the shear strength and bearing capacity of the soil in comparison to vacuum preloading combined with surcharge preloading method.

Sun et al., (2015) made a comparative analysis between vacuum preloading and vacuum preloading with electro-osmosis on a test site in China. In comparison to vacuum preloading the vacuum preloading with electro-osmosis was energy efficient, had a good reinforcement effect and saved construction time.

Wang et al., (2018b) conducted experimental studies to study the effects of electro-osmosis activation time in combined electro-osmosis and vacuum preloading on dredged slurry. The test results indicated that the most suitable electro-osmosis activation time was when the degree of consolidation of the soil reached 60%.

Wang et al., (2020) proposed a solution for the nonlinear consolidation under combined electro-osmosis, preloading and vacuum preloading. A parametric study was done to understand the effects of consideration of nonlinearity. The results indicated that the negative pore water pressure was found to be larger and the consolidation rate seemed to be faster due to consideration of nonlinearity.

3 Comparison of Treatment Methods

Table 1 compares the different treatment methods. From Table 1, it can be observed that the rate of consolidation is slower in the preloading method and is fastest in the case of vacuum preloading and electro-osmotic consolidation. The construction period in the case of vacuum preloading and electro-osmotic consolidation is much shorter than the preloading and preloading combined with PVDs. Even though the vacuum preloading and electro-osmotic consolidation methods seem to be advantageous, the installation cost appears to be high and they are less energy efficient as these methods require electricity for their operation. Overall, the geotechnical engineer must ensure that the treatment method adopted for improving the ground is both effective and economical.

Table 1. Relative comparison between different methods

	Treatment method			
Parameter	Preloading	Preloading with PVDs	Vacuum Preloading	Electro-Osmotic Consolidation
Consolidation rate	Slow	Fast	Very Fast	Very Fast
Pore water pressure	Positive	Positive	Negative	Negative
Soil deformation	Outward	Outward	Inward	Inward
Energy Efficiency	Efficient	Efficient	Low Efficiency	Inefficient
Construction Period	Very Long	Long	Short	Short
Cost	Low	Low	High	High

4 Conclusions

From the literature review, it is evident that many methods exist to treat soft clays like surcharge preloading, preloading with vertical drains, vacuum preloading, vacuum preloading with capped PVDs, combination of vacuum preloading with surcharge preloading, Electro-osmotic treatment, and combination of vacuum preloading, surcharge preloading with PVDs. Along with the above-mentioned methods, it may be possible to treat the soft clay deposits by combining the surcharge preloading, PVDs and introducing osmotic flows in the soils which has not been highlighted by the researchers. Hence, there exists a definite need to explore the possibility of this new method by conducting a series of laboratory tests involving surcharge preloading, PVDs on soft clays inundated with ionic solutions like NaCl and $CaCl_2$ solutions. The results obtained from the studies may be useful in understanding the osmotic and mechanical effects on the behavior of the soft clays.

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