Improvement of silty clay by vacuum preloading incorporated with electroosmotic method

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Abstract: A laboratory test was performed to assess the effectiveness of vacuum preloading incorporated with electroosmotic (EOM) treatment on silty clay (combined method) for reclam ation projects like new disposal ponds, where the horizontal electrode configurations beneath the soil layer were possible and the drainage pipes and the prefabricated vertical drains (PVDs) system could be easily installed in advance before the sludge dragged from sea bed or river bed was filled into the site. Three groups of tests were conducted on the silty clay from Qinhuai River in Nanjing, China. The model is able to apply vacuum pressure at the bottom of the soil layer and a direct current electric field simultaneously. It is also possible to measure the pore pressures at different depths of soil column, and the changes in settlement and volume with the elapsed time. In this study, the vacuum preloading method, vacuum preloading applied at the bottom (VAB method), was applied and the cathodes were installed beneath the soil layer. The results obtained indicate substantial reduction in water content, and increases in dry density and undrained shear strength in comparison with those obtained by the vacuum preloading only, particularly at the positions close to the anode. The combined method utilizes the vertical drainage flow created by the electroosmosis integrating the horizontal drainage flow created mostly by the vacuum pressure. The total drainage flow can be calculated as a result of the vertical drainage flow by electroosmosis only and the horizontal drainage flow by the vacuum preloading only. The way of placement of the cathode and the anode in the combined method also overcomes the disadvantage of EOM method itself, i.e. the appearance of cracks between the anode and the surrounding soil. Moreover, it is observed that the vacuum preloading plays a primary role in earlier stage in deduction of free pore water; meanwhile, the electroosmotic method is more efficient in later stage for absorbing water in the diffused double layers of soil.

Key words: vacuum preloading; VAB method; soil improvement; consolidation; pore pressure; undrained shear strength; dry density; electroosmotic method

1 Introduction

1.1 Fundamentals of vacuum preloading

The concept of vacuum preloading technique introduced by Kjellman [1] at the Royal Geological University in Sweden is an efficient method to improve the strength of clayey soils. The basic procedure of the vacuum preloading consists in removing air pressure from a confined sealed medium of soil and maintaining the vacuum during a predetermined period of time. The technological problems associated with this method include: (1) maintaining an effective level of vacuum and an effective drainage system under the membrane that expels water and air throughout the whole pumping duration; (2) maintaining a leak proof system in particular at the pumps/membrane connections and over the whole membrane area, sealing the system at the periphery; and (3) reducing the lateral seepage towards the vacuum area. The basic technical principle of this method is that, instead of increasing the effective stress in the soil mass by increasing the total stress by means of conventional mechanical surcharging, the vacuum preloads the soil by reducing the pore pressure while maintaining a constant total stress.

In comparison with the conventional surcharge preloading, vacuum preloading has some remarkable advantages, e.g. the increase in effective stress is isotropic, the lateral surface is therefore compressive, no shear failure happens and the preloading can be applied at a rapid rate. No surcharge loading is
necessary and the requirement for other construction activities is greatly reduced [2]. Especially the vacuum preloading is cost effective compared to the conventional surcharge preloading. In the Tianjin New Harbour project, the calculation indicated that the overall cost for the vacuum preloading was about 2/3 of that for the surcharge preloading [2]. The vacuum preloading is especially useful for very soft clay when using surcharge preloading alone is not feasible, because it is difficult to place a fill embankment several meters high on it [3]. It should be noticed that, for the vacuum preloading method, prefabricated vertical drains (PVDs) are generally used to shorten the drainage paths, and the horizontal coefficient of permeability of soils, _k_h, is employed. In most deposits, the horizontal coefficient of permeability, _k_h, is several times greater than the vertical one, _k_v. Hence, in most of calculation methods, only the horizontal drainage of soil is considered and the vertical drainage is assumed equal to zero [4, 5].

1.2 Fundamentals of electroosmotic method

Electroosmotic method was first demonstrated and used successfully as a dewatering tool in Germany by Casagrande in 1936, and since then the method has been employed successfully in many occasions in North America, Europe and China. Electroosmosis is a process wherein positively charged free water in a clay-water system moves from the anode to the cathode. Upon application of a direct current, cations in the diffused double layers of water moves towards the cathode to gain electrons and thereby becomes discharged. As the cations move, they carry water with them so that there is a new movement of water towards the cathode. Consolidation will happen if the water is removed at the cathode but not replaced at the anode [6].

The electrokinetic phenomenon in soils includes three main components: electroosmosis, electrophoresis and ion migration (see Fig.1). Electroosmosis is defined as the movement of pore water resulting from an applied electrical potential gradient to an electrical gradient, acting as a driving force. Electrophoresis is defined as the movement of charged suspended solids in a fluid because of an applied electrical potential gradient. Ion migration is defined as the movement of charged soluble ions in the pore fluid induced by the applied electrical potential [7].

For existing tailing ponds, installation of horizontal electrodes may not be technically or economically feasible. The vertical electrode configuration may be used in these cases. On the other hand, the horizontal electrode configuration is preferred for new reclamation projects like disposal ponds [7].

It should not be confused among the electroosmotic drainage flow, the electroosmotic permeability coefficient, _k_e, and the hydraulic drainage flow, the hydraulic permeability coefficient, _k_h. The magnitude of _k_e is principally dependent on the electric potential gradient, the chemistry of the soil-water system, and the relationship between the pore water tension and the intergranular stresses, and it can be determined by laboratory tests. The average value of _k_e for typical soils including sands ranges from 2 × 10^{-5} to 5 × 10^{-5} cm²/(V · s) [8].

The electroosmotic permeability coefficient, _k_e, indicates how quickly a soil can be dewatered. Comparison of the electroosmotic permeability coefficient, _k_e, with the hydraulic permeability coefficient, _k_h, may illustrate why electroosmotic method is such a useful tool for dewatering fine-grained soils. Casagrande [8] indicated that, if it was assumed that _k = 5 × 10^{-8} cm/s and _k_e = 4 × 10^{-4} cm²/(V · s) for a clay, and an applied voltage gradient of _i = 0.5 V/cm and an effective consolidation stress equivalent to a hydraulic gradient of _i = 10, the time required for an equal reduction in water content would be

\[ t = 400t_e \] (1)

where _t and _t_e are the required time for hydraulic consolidation and electroosmotic consolidation, respectively. In other words, it would take 400 times as long to achieve the same degree of improvement in a clay deposit by loading the surface as it would do by applying electroosmotic method.

1.3 Combination of two methods and the aim of the study

The advantages of the vacuum preloading applied at the bottom (VAB method) in comparison with that applied at the top of the soil layer (VOT method) have been stated by the authors in a previous study.
It is found that the VAB method is much more effective than the VOT method on soil improvement. The undrained shear strength $C_u$ of soil is increased by about 35% with the VAB method. The VAB method is also less time consuming. Moreover, it is easier to create vacuity in the whole soil body with greater effective depth of improvement.

Originating from the idea of a combination of vertical and horizontal drainages, to assess the probable effectiveness of vacuum preloading incorporated with electroosmotic treatment on silty clay for reclamation projects like new disposal ponds, where the horizontal electrode configurations beneath soil layers were possible and the drainage pipes and PVDs system could be easily installed in advance before the sludge dragged from sea bed or river bed was filled into the site (see Fig.2), a laboratory test program was undertaken. The VAB vacuum preloading method was applied. In the paper, it is concisely called vacuum preloading. The anode was placed on the top and the cathode was placed beneath the soil layer. It means that the drainage force created by electroosmosis is in the vertical direction from top downward to bottom.

### Experimental program

#### 2.1 Materials

Three groups of tests with six soil samples were conducted on silty clay from Qinhuai River in Nanjing, China. Each group included two soil samples with the same water content. One sample was tested under the vacuum preloading of 80 kPa only and the other one was tested under the vacuum preloading of 80 kPa and direct current electricity with a voltage gradient of 0.15 V/m simultaneously. Table 1 lists the typical properties of the silty clay before testing.

#### Table 1 Typical properties of silty clay.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Natural water content, $w_0$ (%)</th>
<th>Liquid limit, $w_L$ (%)</th>
<th>Plastic limit, $w_p$ (%)</th>
<th>Undrained shear strength, $C_u$ (kPa)</th>
<th>Specific gravity, $G_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.6</td>
<td>53.35</td>
<td>26.95</td>
<td>0</td>
<td>2.72</td>
</tr>
<tr>
<td>2</td>
<td>102.8</td>
<td>54.29</td>
<td>31.41</td>
<td>0</td>
<td>2.72</td>
</tr>
<tr>
<td>3</td>
<td>98.7</td>
<td>52.68</td>
<td>30.52</td>
<td>0</td>
<td>2.72</td>
</tr>
</tbody>
</table>

#### 2.2 Testing apparatus

The testing apparatus used in this study, as shown in Fig.3, was developed by Institute of Geotechnical Engineering, Hohai University. It is able to simultaneously apply the vacuum pressure on soil sample at a desirable value and a direct current electric field. It is also capable of measuring the pore water pressure at different depths of soil layer, the vertical settlement and the volume change during tests.

![Fig.2 Suitable reclamation projects for application of combined method.](image-url)

![Fig.3 Description of the testing apparatus.](image-url)
The soil samples were placed in a cylindrical container made of plexiglas, 100 cm in height \( (h_0) \) and 18.5 cm in inner diameter. A vacuum moderator was used to adjust the required vacuum pressure and keep it stable during the test. The moderator was plugged into an airtight, graduated and transparent glass bottle. This bottle has two functions, one is to control the vacuum pressure through the vacuum moderator, the other is to collect the water expelled from the soil samples during test. A dial gauge is mounted on the top of the sample to record the settlement changing with the elapsed time. In addition, the vacuum gauges could be mounted at different levels, i.e. \( 0.02h_0 \) (point \( T \)), \( 0.26h_0 \), \( 0.5h_0 \), \( 0.74h_0 \) and \( 0.98h_0 \) (point \( B \)) to measure the pore pressures at different depths. For the tests presented in this paper, the vacuum pressure was applied at the position corresponding to point \( B \). In the case of applying a direct current electric field, a variable voltage direct current power supply was used; two aluminum plate electrodes were placed at the top and the bottom of the soil layer, the anode and the cathode, respectively. The plate electrodes, particularly the anode, were perforated and covered by a filter cloth to prevent entry of solids.

2.3 Samples preparation and testing procedure

After the soil was sampled from the Qinhuai River and packaged in plastic bags, it was left for several days to expel the extra water until the soil reached its original status under the river bed as closely as possible. The rubbish was carefully taken away from the soil to avoid its effects on the test result.

For three groups of tests, to avoid any difference between different parts of the soil samples, the soil needs to be mixed carefully to make sure that the water content is the same for the whole sample. In order to reduce the friction between the soil and the inner surface of the cylindrical container, the inner surface of cylinder was lubricated with the machine oil. Before the soil sample was placed into the cylindrical container, a layer of sand mat with the thickness of 4.0 cm was laid in advance at the bottom of the cylindrical container.

Three PVDs, whose sizes of horizontal cross-sections are 25 mm in length and 4.5 mm in width, were installed in triangular shape. The equivalent diameter of single PVD is \( d_w = \frac{2(a+b)}{\pi} = 1.88 \text{ cm} \) [4].

The drainage influence zone is therefore calculated by Bergado et al. [10]: \( D_e = 1.05S = 14.7 \text{ cm} \), where \( S = 14 \text{ cm} \) is the gap between PVDs in triangular shape (see Fig.4).

As shown in Fig.4, the influence zone of PVDs sufficiently covers the whole horizontal sections of the cylinder. Finally, the soil sample was covered with a rubber membrane to ensure the vacuity of the soil samples during the test. After the soil sample was placed into the container, it was left for consolidation by deadweight, and then the vacuum pressure or the vacuum pressure incorporated with the direct current electric field was applied.

The settlement, the volume of pore water expelled from the soil sample and the pore pressure all were monitored during the tests. The tests were continued until most of the soil samples had been treated, or until the rate of discharge decreased to a small fraction of the initial value. After that the index and pocket CPT tests were performed. As far as possible, the test specimens were selected so as to avoid the portions of the treated samples in the immediate vicinity of the anode and the cathode.

3 Results and discussions

3.1 Water content, soil density and degree of saturation

The average water contents are presented in Table 2, and illustrated by Fig.5 for different depths of soil samples. Table 2 indicates that the vacuum preloading already has remarkable effects on the reduction in the water content. The water contents decrease by 28.8%, 37.6% and 34.6% for test groups No.1, No.2 and No.3, respectively. However, the treatment performed by the combined method has a better effect on dewatering of pore water. The water contents obtained by this method decrease by 35.4%, 42.6% and 39.2% for groups No.1, No.2 and No.3, respectively.
Table 2 Average water contents.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Method</th>
<th>Average water content (%)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before tests</td>
<td>After tests</td>
</tr>
<tr>
<td>1</td>
<td>Vacuum preloading</td>
<td>92.6</td>
<td>63.8</td>
</tr>
<tr>
<td></td>
<td>Combined method</td>
<td>92.6</td>
<td>57.2</td>
</tr>
<tr>
<td>2</td>
<td>Vacuum preloading</td>
<td>102.8</td>
<td>65.2</td>
</tr>
<tr>
<td></td>
<td>Combined method</td>
<td>102.8</td>
<td>60.2</td>
</tr>
<tr>
<td>3</td>
<td>Vacuum preloading</td>
<td>98.7</td>
<td>64.1</td>
</tr>
<tr>
<td></td>
<td>Combined method</td>
<td>98.7</td>
<td>59.5</td>
</tr>
</tbody>
</table>

Figure 5 shows that for both methods, the deeper the soil is, the higher the water content is. In addition, at the same depth, the water content obtained by the combined method is lower than that obtained by the vacuum preloading only. It can be simply explained that the vacuum preloading method with PVDs mostly takes advantages of the horizontal drainage and ignores the vertical drainage, or even assumes that there is no drainage in vertical direction. When the vacuum preloading is incorporated with the electroosmotic method, both the horizontal and the vertical drainages must be considered because the electroosmotic drainage flow could be 400 times faster than that hydraulic drainage flow, as mentioned above in Section 1.2. Resultant drainage flow may be described by Fig. 6. If the vertical hydraulic permeability coefficient of soil is assumed to be very small and can be ignored, it could be supposed that the resultant drainage flow induced by the combined method may be calculated as follows:

\[ Q_{ve} = \sqrt{Q_v^2 + Q_e^2} \]  

(2)

where \( Q_v \) is the drainage flow induced by the EOM only, \( Q_e \) is the drainage flow induced by the vacuum preloading only, and \( Q_{ve} \) is the resultant drainage flow induced by the combined method.

The average degrees of saturation of soil after tests are summarized in Table 3. It shows that in both cases, the soil changes from saturated state to unsaturated state, which reflects that \( S_r \) cannot be used as an evidence in other phenomena such as the decrease of void ratio or the increase in shear strength for this case.

Table 3 Average degrees of saturation after tests.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Average degree of saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vacuum preloading only</td>
</tr>
<tr>
<td>1</td>
<td>0.96</td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>0.96</td>
</tr>
</tbody>
</table>

In a similar manner, the dry densities at different depths are illustrated in Fig. 7. It also shows that, for all tests, the dry densities gained by the combined method are higher than that obtained by the vacuum preloading only. The average values of dry densities gained by the combined method for three groups of tests increase by 10.9%, 14.9% and 14.5%, respectively, in comparison with those gained by the vacuum preloading method. On the other hand, Fig. 7 indicates
Fig. 7 Dry density versus depth.

that for both testing methods, the deeper the soil is, the lower the value of soil dry density is. These obviously indicate that the combined method is more effective on soil improvement. The water content has a greater decrease, but the dry density has a greater increase.

3.2 Atterberg limits

To illustrate the effect of electroosmotic treatment on Atterberg limits of the soil, Table 4 summarizes the results of liquid limit, plastic limit and plasticity index.

The following general observations were made: (1) the electroosmotic treatment increased the liquid limit by 16%−22%, with the effect being substantially more at the anode than that at the cathode, in other words, the magnitude of the changes decreased towards the cathode; (2) the plastic limit increased by slightly, 11%–13% at most; and (3) as a result of the combinations of these facts, the plasticity index also increased but the liquidity index substantially decreased.

The liquid limit of the soil increased, which was indicative of fundamental changes in the soil properties as a result of electric treatment. In accordance with the results of other investigations (e.g. Refs.[11, 12]), the liquidity index of the material would seem to be a suitable indicator of the overall change in material properties.

3.3 Undrained shear strength \(C_u\)

The pocket CPT test was implemented to find the undrained shear strength \(C_u\) of soil. The initial undrained shear strength of soil before the test was almost zero. The results of the undrained shear strength at different depths are presented in Table 5. It is shown by Fig.8 that the value of \(C_u\) gained by the combined method is much higher than that gained by the vacuum preloading only. Particularly, a side effect of electroosmosis is the heating of the soil near the anodes. The anodic end of the soil sample gradually became dewatered and the strength of the soil attained the strength of a soft rock. The same phenomenon was observed by Casagrande et al. [13]. Table 5 indicates that for three groups of tests, the average values of \(C_u\) gained by the combined method, excluding those of the anodic parts, are about 32% higher than those obtained by the vacuum preloading. This difference is primarily because the water content gained by the combined method decreases largely. Hence, the pore water pressure decreases greatly while the total stress remains unchanged, thus the effective stress increases largely, and the consequent consolidation and the shear strength of soil are therefore better improved. The strength of the soil treated by the combined method increases as a result of the following factors: (1) formation of menisci in the soil voids; and (2) bonding and/or cementation of the soil particles [13].

For a clearer understanding, the curves of \(C_u\) are again illustrated with void ratio curves in Fig.9, where void ratio \(e\) is scaled up to 50 times for observing convenience. It shows clearly that these two groups of curves are in reverse direction, the higher the depth of soil is, the higher the void ratio is, and the smaller the value of \(C_u\) is. In addition, the high values of \(C_u\) corresponds to the low void ratio.

3.4 Drainage flow

The drainage flow of the tests (for groups No.1 and No.2) is presented in Fig.10. It shows obviously that the total water volume expelled from the soil by the combined method is normally greater than that by the vacuum preloading only. It was also observed that, for the case of the vacuum preloading, normally after about 7 days, there was not discharge water anymore. It can be stated that after 7 days the vacuum pressure has no more effect on dewatering. On the other hand, when using the combined method, after 7 days there was still water discharging. This can be explained by the principles of the vacuum

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Time (day)</th>
<th>(w_L) (%) Before tests</th>
<th>After tests (anode)</th>
<th>After tests (cathode)</th>
<th>(w_P) (%) Before tests</th>
<th>After tests (anode)</th>
<th>After tests (cathode)</th>
<th>(I_p) Before tests</th>
<th>After tests (anode)</th>
<th>After tests (cathode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>53.35</td>
<td>64.35</td>
<td>61.65</td>
<td>26.95</td>
<td>31.16</td>
<td>30.55</td>
<td>26.4</td>
<td>33.2</td>
<td>31.1</td>
</tr>
</tbody>
</table>

Table 4 Effect of electroosmotic treatment on index properties.
Table 5: Average undrained shear strengths.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Undrained shear strength (kPa)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vacuum preloading</td>
<td>Combined method</td>
</tr>
<tr>
<td>1</td>
<td>14.2</td>
<td>19.1</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>20.5</td>
</tr>
<tr>
<td>3</td>
<td>16.3</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The vacuum preloading and the electroosmotic treatments that the vacuum preloading can probably only absorb the free pore water; meanwhile, electroosmosis generally occurs in the fine clay soils and consists of the movement of the polar water ions through the diffused double layer of clay from the anode towards the cathode.

Water flows through the diffused double layer of saturated clay under an electrokinetic potential due to the negatively charged surface of the clay particles. The water is oriented in such a manner by the applied electrokinetic field that the positive pole is attracted to the negatively charged clay surface and simultaneously the negative pole is repulsed from the negatively charged clay surface. It can be concluded that the vacuum preloading plays a primary role in the earlier stage in extruding the free pore water; meanwhile, the electroosmotic method is most effective in later stage for absorbing water in the diffused double layer of soil. It was also observed that, when the electrodes were vertically placed, as those in the combined method, no crack appeared in cathode zone, which often happened in the cases that the electrodes were horizontally placed. Thus, the incorporation of two methods is more effective for dewatering of silty clay soil.

4 Conclusions

To assess the effectiveness of the vacuum preloading incorporated with the electroosmotic treatment on silty clay, the excess pore water pressure at different depths, the settlement, and the volume change were all monitored during the consolidation process. Based on the measurements and above analyses, the following conclusions can be
drawn:

1. Both two methods have great effects on the improvement of soft soil; however, the combined method is more effective for soil improvement.

2. The water content, the void ratio and the dry density gained by the combined method are better than those gained by the vacuum preloading alone; full treatment reduces the water content by about 33% for the vacuum preloading method and 40% for the combined method, with reduction at the top of the soil layer more than that at the bottom. Particularly, the reduction in water content near the anode is much more significant than that near the cathode for the combined method.

3. The combined method increases the liquid limit by 16%–22%, with the effect being substantially more at the anode than that at the cathode.

4. The plastic limit also increases by 11%–13% at most; as a result, the plasticity index also increases, and the liquid index substantially decreases.

5. The drainage flow obtained by the combined method is greater than that gained by the vacuum preloading method alone.

6. In comparison with the vacuum preloading method alone, the undrained shear strength $C_u$ of soil gained by the combined method has a greater increase, especially near the anode. The treated soil behaves as a soft rock; the average difference in the undrained shear strength gained by the two methods is about 32%.

References


