Abstract

Increasing environmental concerns as well as land demands has led to a growth of hydraulic-filled areas. Hydraulic-filled materials are usually fine-grained stuff, like dredged materials, sewage sludge, tailings, etc. Therefore, hydraulic-filled areas are soft ground with high water content and very low hydraulic permeability. Vacuum preloading is by far the most popular technique for consolidating hydraulic-filled areas. However, due to extremely low hydraulic permeability of fine-grained materials, the vacuum preloading consolidation is too slow and its effect is very poor for deep hydraulic-filled soft ground.

Electro-osmotic consolidation can be an alternative solution for this kind of soft ground improvement. Electro-osmotic consolidation is much quicker than preloading method. However, corrosion of electrode and relatively high electrical energy consumption are two aspects that restrain its application. This paper presents the solutions for these issues.

A novel Electro-Kinetic Geosynthetics (EKG) was developed and it is corrosion-proof during electro-osmosis. Technique of polar reverse according to the variation of electric current during electro-osmosis was developed. This technique is based on a new model different to the classical Esrig model for electro-osmotic consolidation. A novel program-controlled DC power source was developed to realize the polar reverse technique.

A case study shows that electro-osmotic consolidation with the novel EKG and DC source is very efficient. The 19m×15m hydraulic filled area, with 5.8 m deep of dredged pool sludge, was improved from fluid-like status to a bearing capacity of 70 kPa and the water content was reduced from 62% to 36%. Comparing with the 36 days of treatment using electro-osmosis, it will take 3 years for the preloading method to achieve the same improvement. It indicates that for this specific case, it is actually impossible for the preloading method to consolidate the soft ground to such an extent.
1. Introduction

There are a lot of hydraulic-filled areas around the world. These areas are usually containment areas for dredged materials, sewage sludge or tailings. Hydraulic-filled areas are produced also from reclamation projects, which create lands from lake or sea. Increasing environmental concerns as well as land demands has led to a growth of hydraulic-filled areas.

Land reclamation has played a significant role in many countries, such as Netherlands, Japan, Singapore, Korea and China. For example, Netherlands is known as a reclaimed land from the ocean. The ancestors of Dutch have been working to reclaim land from the North Sea for over 2000 years and even in 1986 the Netherlands proclaimed a new province of Flevoland, which is the 12th province reclaimed from the ocean (Hoeksema 2007). In Singapore, growth of economy and population pushes it to create more lands by reclamation. Large scale of reclamation in Singapore started in 1960s and land area increase from 580 km² to 680 km² till 2003. The latest reclamation scheme is to increased land area in Singapore by 100 km² by the year 2030 (Yang 2003). In China, hydraulic fill reclamation has been going on in coastal cities like Xiamen, Tianjin, Wenzhou, Guangzhou, etc. For example, a reclamation area of 300 hectare was completed in Wenzhou in 2012 and three artificial islands, whose area is 350 ha for total, is on reclaiming for the Hong Kong-Zhuhai-Macau Bridge project.

Stuff for hydraulic fill is usually fine-grained materials which have high water content and very low hydraulic permeability. Therefore, it takes long time for the consolidation of these soft ground created by hydraulic fill method. Currently the most popular technique for consolidating hydraulic-filled areas is vacuum preloading. However, for materials with very low hydraulic permeability (usually below $10^{-7}$ cm/s) vacuum preloading is too slow. And also for deep hydraulic-filled soft ground (usually deeper than 4 m), the effect of vacuum preloading is limited.

For these fine-grained materials, electro-osmotic consolidation can be an alternative option. Electro-osmotic consolidation is a technique that removes water from soils under DC electric field. Phenomenon of electro-osmosis was discovered very early by Reuss in 1809. He found that DC field can create water flow from anode to cathode, and thus water can be removed from the soil through the discharging channel around cathode. Since the discovery of electro-osmosis, it has been applied in many geotechnical and geoenvironmental engineering, such as soft ground improvement (Casagrande 1952a, b; Bjerrum et al. 1967; Shang et al. 1996), tailing dam stability (Zhu et al. 1996; Liu et al. 1988), dredged silt disposal (Chen et al. 2006), sewage sludge dewatering (Xu 1980), food industry residues treatment (Chen et al. 1996; Al-Asheh et al. 2006), etc.

Electro-osmotic consolidation is much quicker than preloading method. Flow rate produced under electric field can be 100 to 10000 times greater than that under hydraulic gradient (Jones et al. 2008). However, there are two aspects that have been holding back its application in fine-grained soft ground improvement; one is corrosion of electrode and the other is relatively high electrical energy consumption. In this paper, a system of electro-osmotic consolidation, including novel Electro-Kinetic Geosynthetics (EKG), electric power source and methodology of electro-osmosis, is presented and it is followed also by a case study for interpretation of its in-situ application.
2. EKG Material

In order to solve the problem of electrode corrosion for electro-osmosis, a novel corrosion-proof EKG material was developed. The EKG is based on electric conductive polymer and analysis shows that the conductivity of EKG shall be higher than $10^3 \, \text{g}^{-1}\cdot \text{m}^{-1}$ (Zhuang 2005a, 2012b). According to recommendation of Zhuang in 2005, for better distribution of electric current into the soil and for convenience of wiring, it is worth to embed wires inside the conductive polymer.

The EKG material developed is shown in the figure 1. The EKG looks like classical PVD, only that it is made from conductive polymer with a conductivity of $10^3 \, \text{g}^{-1}\cdot \text{m}^{-1}$. The EKG is 100 mm wide and 0.8 mm thick. Every groove on the both sides of EKG is 3 mm wide and the thin-wall of these grooves is 0.8 mm thick. As shown in the figure 1 there are two bumps of 6 mm wide and 2.5 mm thick on both sides of the EKG. Two copper wires of $\Phi 1$ mm are embedded inside the bumps.

![Figure 1: Photo of EKG](image)

3. Methodology of Electro-osmosis and Electric Power Source

Classical theory for electro-osmotic consolidation proposed by Esrig in 1968 indicates that flow rate of electro-osmosis is a coupled result of voltage gradient and hydraulic gradient and electro-osmotic consolidation stops when the drive of electric field is balanced by that of hydraulic gradient from an opposite direction. However, research shows that the flow rate depends mostly on the mobility of ions in the soil and the consolidation stops when the mobility of ions is zero under the certain electric field. Based on this knowledge, to improve the effect of
electro-osmotic consolidation is to maintain as high as possible the mobility of ions during electro-osmosis (Zhuang 2005a, b, 2012a, b, c). For this purpose, the voltage applied on the soil shall be adjusted according the variation of electric current during electro-osmosis. In order to do so, a novel DC source was developed. The DC source has a power of 80V/2000A and it is controlled by a custom-developed program.

4. Case Study

A 19m×15m hydraulic-filled area was treated with electro-osmosis technique. The area was filled with 5.8 m thick of dredged pool sludge. The properties of sludge before electro-osmotic consolidation are shown in the table 1. The sludge has no strength before consolidation.

<table>
<thead>
<tr>
<th>Specific gravity</th>
<th>Water content (%)</th>
<th>Dry density (g/cm³)</th>
<th>Permeability (cm/s)</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.61</td>
<td>62</td>
<td>1.03</td>
<td>3.0×10⁻⁷</td>
<td>50</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1: Properties of sludge before electro-osmotic consolidation

The EKG electrodes were square arrayed at a space of 1 m. The whole treatment included two stages separated by 16 days of intermittence.

Stage 1: Electro-osmotic consolidation began under a constant-current mode of 290 A and lasted for 233.57 hours (~10 days). Then it is switched to a constant-voltage mode of 50 V and lasted for 28.55 hours (~1 day).

Stage 2: After the intermittence, electro-osmotic consolidation continues under a constant voltage mode of 80 V. It lasted for 215.02 hours (~9 days).

The whole treatment was controlled by program from computer. Electrode polar was reversed according to the trend of electric current variation. Generally, stage 1 had longer time of current in reverse direction, while stage 2 had longer time of current in forward direction. Purpose of this scheme for electro-osmosis was to main as much as possible mobile cation in the soil.

Test results show that the water content of soil decreased from 62% to 36%; the unconsolidated-undrained shear strength increased from 0 to 25 kPa; the soft ground was improved from a fluid-like status to a bearing capacity of 70 kPa. Comparison of soft ground before and after treatment is shown in figure 2. The average energy consumption for this treatment was 5.6 kwh/m³.

Preloading method for the consolidation of the same soft ground was analyzed for comparison. The soil had a coefficient of consolidation \( C_v=0.0029 \text{cm}^2/\text{s} \) and a compression index \( C_C=0.3611 \). Therefore, in order to achieve the same effect of consolidation (to reduce water content from 62% to 36%), there should be 132 kPa of preloading (around 6~7 m high of surcharge with soil); and it would take 1139 days, which is more than 3 years, to achieve 90% of consolidation. It is
almost an imposable mission for preloading consolidation, while electro-osmotic consolidation completed it in only 36 days, including 16 days of intermittence.

Figure 2: Comparison of soft ground before and after electro-osmosis treatment

5. Conclusions

(1) A novel geosynthetics, corrosion-proof EKG, was developed. It is made from electric conductive polymer with two copper wires embedded. The EKG is in a shape similar to PVD and has an electric conductivity of $10^3 \, \Omega^{-1}\cdot \text{m}^{-1}$.

(2) In order to improve the effect of electro-osmotic consolidation, it is important to maintain as high as possible the mobility of ions in the soil. For this purpose, polar reverse shall be carried out according to the trend of electric current variation. A novel DC power source was designed to meet this requirement; the automatic polar reverse can be realized by program.

(3) Application of EKG and DC source in the improvement of soft ground shows that it took only 36 days to reduce water content of dredged sludge from 62% to 36%. And after electro-osmotic consolidation the soft ground was improved from a fluid-like status to a bearing capacity of 70 kPa. It would take 3 years for preloading consolidation to achieve the same effect for this specific case.

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References


