# Electro-Osmosis Dewatering and Consolidation—G-I China Scan Tour Overview

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## ABSTRACT

As one of the electrokinetic phenomena, electro-osmosis has been used since 1970s as a soil improvement method to assist dewatering from soil, especially soft clay. The application of electro-osmosis for dewatering or consolidation involves installing anodes and cathodes, which induces directed water movement toward cathode. Over the past decade, due to the invention of different conductive materials, the electrodes can now be made from polymer; as a result, the electrodes can be made into the form of Prefabricated Vertical Drains (PVDs) to serve dual functions. Such development facilitated the wider adoption of electro-osmosis to treat clay soil. G-I sponsored Soil Improvement Committee a scan tour in China in 2018. A large land reclamation project in Taizhou, China, was visited during that scan tour. The soil at the site consisted of 3–4 m of dredging fill that was underlain by approximately 20 m of peat. The reclaimed land will be used for warehouse, roads, and office buildings. The estimated post-construction settlement would be in the magnitude of meters if soil was not treated before construction. Multiple soil improvement methods were utilized to drain the water from dredging soil and peat, among which electro-osmosis was used in one test section. Totally, two hundred electrodes were installed in the sections and connected to DC power. The electric current was monitored and adjusted in real time by a central control unit to ensure a good progress of the dewatering. During our site visit, the measured settlements was in a ranged from 500 to 750 mm, 32 days since the start of electro-osmosis dewatering/consolidation. The settlement values were significantly higher than these obtained from the neighboring sections with conventional vacuum preloading to consolidate the clay. The average energy consumption of the electro-osmosis ranged from 4 to 7 kwh/m$^3$ for the project. The project indicates that the electro-osmosis has great potential to treat clay with the newly developed polymeric electrodes.

## INTRODUCTION

Electrokinetic phenomena refer to a family of effects in heterogeneous fluids that are induced under electrical field. Electrokinetic phenomena were reported as early as 1809 (Reuss 1809). Over the years of applications and studies, it has been categorized into eight major phenomena: electrophoresis, electro-osmosis, diffusiophoresis, capillary osmosis, sedimentation potential, streaming potential/current, colloid vibration current, and electric sonic amplitude (Dukhin and Derjaguin 1974). In the past half century, electrokinetic phenomena have been utilized in soil dewatering, contamination remediation, fertilizer mobilization, land reclamation, wastewater treatment, contaminant barrier etc. (Lageman et al. 1989; Yao et al. 2012; Zhuang et al. 2015). Even though there have been plenty of promising data relevant to the application of electrokinetics over the world, many fundamental mechanisms are still uncertain as they are rather complicated, involving electrical engineering, electro-chemistry, mineralogy, colloid-chemistry, material science, physics, and soil mechanics (Hunter 1989; Zhuang et al. 2015).

Among the eight electrokinetic phenomena, electro-osmosis has been used since 1970s as a soil improvement method, which refers to the directed flow of liquid in a porous medium upon the application of electric field. The flow is caused by the dragging effect of ions to the surrounding pore water. Since there are more cations than anions in the water, the flow driven by the electro- osmosis effect results in net water migration from anode to cathode as shown in Figure 1. Due to the movement of cations and anions, $OH^-$ and $H^+$ are accumulated near anode and cathode, respectively, which lead to acid and base environments near the anode and cathodes accordingly.

The outstanding advantage of electro-osmosis is that it can significantly accelerate water flow in soil, especially soil with low permeability. Especially, it significantly facilitates flow in unsaturated soil. Many studies have proved that, unlike hydraulic permeability, electro-osmotic permeability is essential independent of grain size, which results flow rates of 100 to 10,000 times greater than hydraulic flow in fine-grained soils (Jones 1996). Zhuang et al. (2015) summarized the electric permeability of commonly encountered soils at different water contents and indicated that the electric permeability in clay soil with high water content could be as high as $6.9 \times 10^{-9}$ $m^2/(s\cdot v)$. Such high electric permeability made significant electrokinetic phenomena possible.

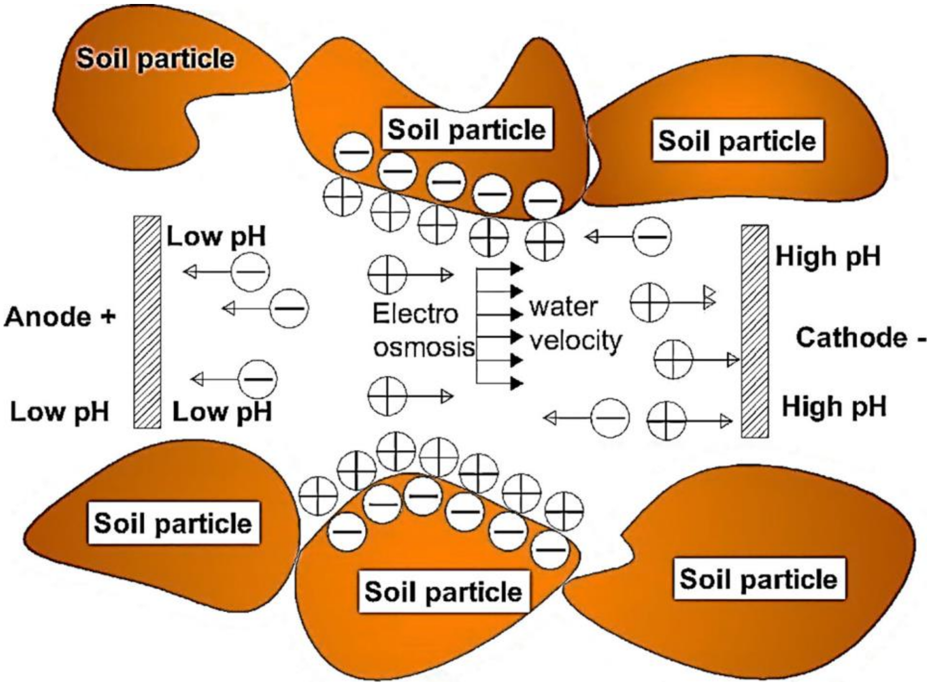


**Figure 1. Conceptual schematics of electro-osmosis (Moghadam et al. 2016).**

## DESCRIPTION OF TECHNOLOGY

The application of electro-osmosis for dewatering or consolidation involves installing anodes and cathodes into soil and removing water timely from cathode as shown in FIG. 2. Depending on the targeted flow direction, the electrode array can be arranged in different pattern to achieve different flow pattern, for example, parallel flow in FIG. 2 and radial flow in FIG. 3. In recent year, electro-osmosis dewatering/consolidation has used in conjunction with preloading/vacuum preloading to further expedite the water flow and reduce the void ratio (Sun et al. 2017; Wang et al. 2014).

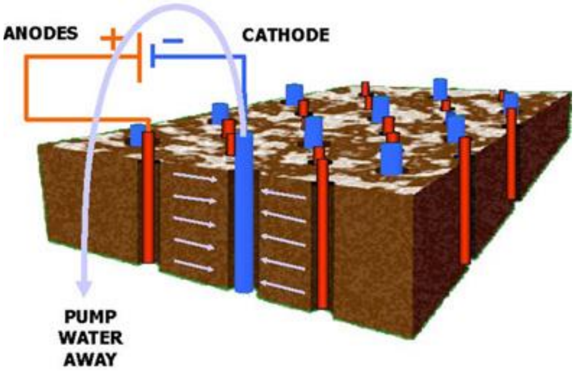


**Figure 2. Application of electro-osmosis: parallel flow (Jones 2011).**

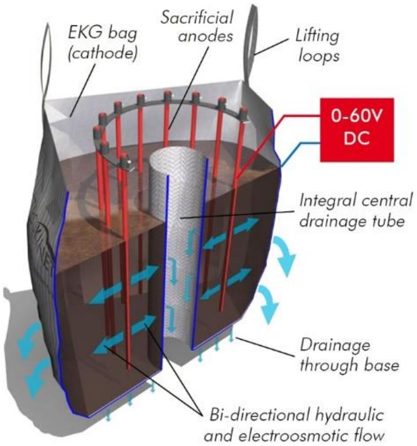
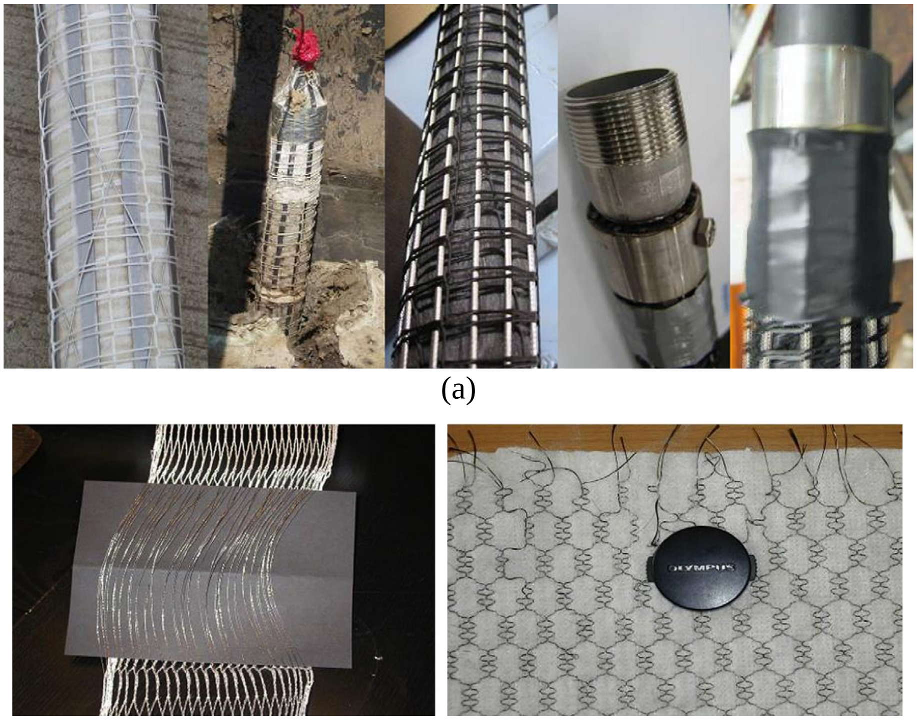


**Figure 3. Application of electro-osmosis: radial flow (http://www.electrokinetic.co.uk/bagswork.htm).**

In general, electro-osmosis has been started used in practice since 1970s; however, its application has not been as popular as many other dewatering/consolidation techniques, for example, PVD, and preloading, for two major reasons: (1) the energy consumption is high, which leads to high cost; and (2) the corrosion of electrodes is a challenging issue in the field (Zhuang et al. 2014; Zhuang et al. 2015). Newly emerging Electrokinetic Geosynthetics (EKG) plausibly solves the problem of electrode corrosion but brings the cost even higher because of the cost EKG itself (Hamir et al. 2001; Jones 2011). As a result, electro-osmosis is commonly used in the projects, where other techniques are ineffective, or schedule is crucial.

The concept of EKG was first presented more than 20 years ago (Jones 1996; Nettleton et al. 1998). In its early age, EKG was manufactured by embedding metal wires or rods into geosynthetics to form sheets or tubes as shown in FIG. 4. In recent years, China has patented an EKG, which was made from conductive polymer with resistivity of $10^{-3}$ Ω•m as shown in FIG. 5 (Zhuang et al. 2012). The EKG was flexible and was made into a PVD-like shape to allow it to be installed by the existing PVD equipment. Two copper wires of 1 mm in diameter were included to assist the electric current distribution as well as provide convenience for the connection with electrical source. Even though such an EKG does not bring the total cost down, it makes the fast installation possible in the field.


(a)

(b)

**Figure 4. EKG used in practice: (a) EKG tubes and (b) EKG sheets (modified from Jones (2011)).**

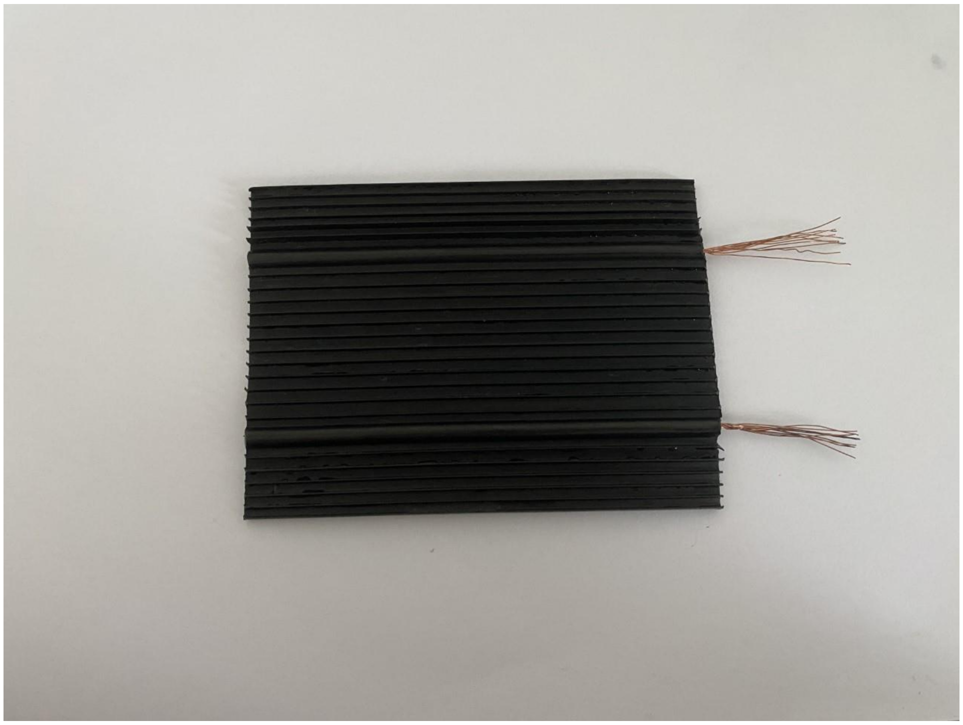


**Figure 5. EKG made from conductive polymer (patented in 2012 in China) (Zhuang et al. 2012).**

## THEORIES OF ELECTRO-OSMOSIS DEWATERING/CONSOLIDATION

Based on the Terzaghi consolidation framework, Esrig (1968) suggested the electro-osmosis water flow in the soil skeleton is counteracted by the flow driven by the hydraulic gradient in the opposite direction. In another word, the flow ceases when the electro-osmosis and hydraulic gradients balances each other. Based on his theory, the Terzaghi's 1-D consolidation formula is still valid, i.e.,

$$C_v = \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{1}$$

where $C_v$ is the consolidation coefficient, u is pore water pressure, t is time and z is drainage distance.

Based on Esrig's theory, the following boundary condition should apply to consider electro-osmosis flow during consolidation:

$$\begin{cases} t = 0, 0 < z < H; u(z)|_{t=0} = u_o(\beta - \frac{\alpha z}{H}) \\ 0 < t < \infty, z = 0; u|_{z=0} = 0 \\ 0 < t < \infty, z = H; \frac{\partial u}{\partial z}|_{z=H} = \frac{k_e}{k_h}\gamma_w \frac{v_o}{H} \end{cases} \tag{2}$$

where $u_o$, $\alpha$, and $\beta$ are constants to describe the initial spatial distribution of pore water pressure; H is the distance between anode and cathode; $k_e$ and $k_h$ are electrical and hydraulic permeability, respectively; $\gamma_w$ is unit weight of water and $v_o$ is the voltage between anode and cathode.

The Helmbolts-Smoluhowski's theory (Helmholtz 1879; Mitchell 1991; Mitchell 2005; von Smuluchowski 1914) was used to estimate the electrical permeability, $k_e$, which treated the double layer as a capacity.

$$k_e = \frac{\zeta \varepsilon n}{4\pi\eta} \tag{3}$$

where $\zeta$ is the potential of double layer; $\varepsilon$ is the dielectric coefficient; n is the porosity; $\eta$ is the viscosity of water.

Utilizing Equations 2 and 3 can be used to calculate the total water removed from soil, by assuming that the soil remains saturated during dewatering/consolidation. However, soil has a high chance of becoming unsaturated due the high-water flow rate. In addition, the unstated assumption for the equations is that the current is constant, which may not be true for many occasions. To improve the accuracy and broaden the application into unsaturated soil, Zhuang (2005) and Zhuang and Wang (2005) proposed a so-called "energy level gradient theory", which was based on the accumulation, consumption and transformation of energy. Based on the theory, the total volume (Q) of electro-osmotic dewatering can be estimated by:

$$Q = k_q \frac{V(I_{ototal} - I_{\infty total})}{a^2 \Delta x^2}(1 - e^{-at}) \tag{4}$$

where $k_q$ is flow rate coefficient ($m^2 \bullet Pa^{-1} \cdot s^{-1}$ ); V is the voltage applied on the soil (V); $I_o$ is initiate electric current (A); $I_\infty$ is levelled off electric current (A); t is time (s); a is time factor ($s^{-1}$); $\Delta$x is the distance between anode and cathode (m), and

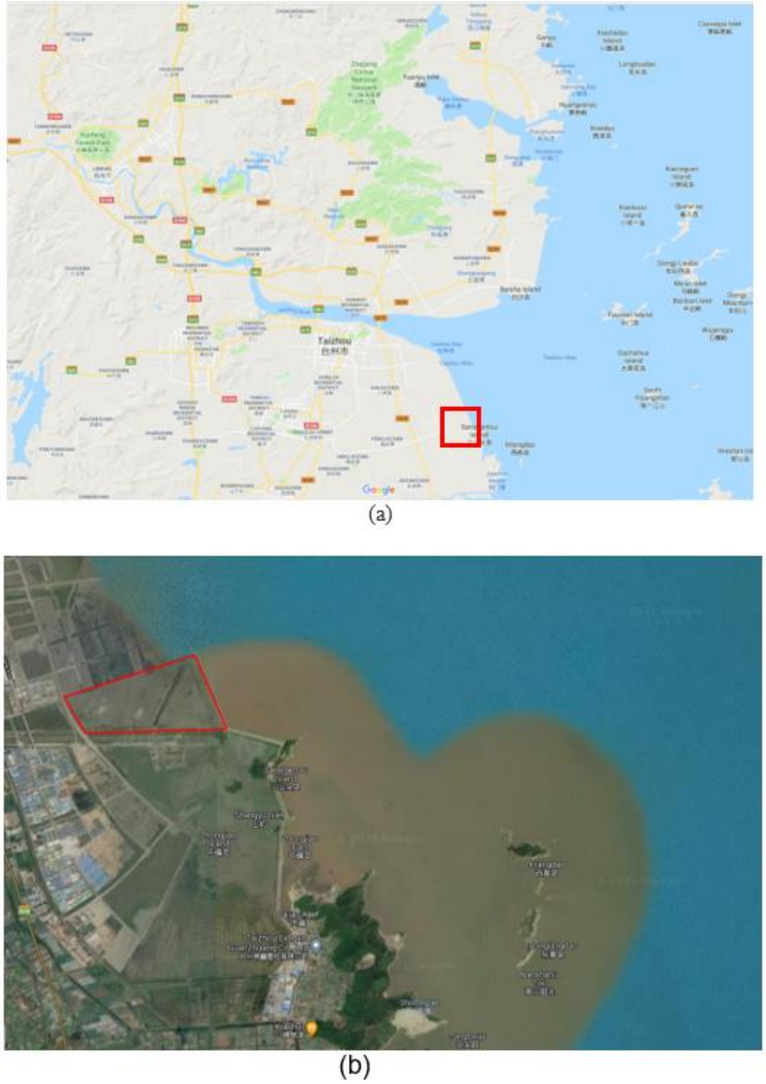
$$I_{ototal} = N j_o A \tag{5}$$

$$I_{total} = (I_{ototal} - I_{\infty total}) e^{-at} + I_{\infty total} \tag{6}$$

Where $I_{total}$, $I_{0total}$, and $I_{\infty total}$ are total electric current of t moment, initial time and infinity (A), respectively; $j_0$ is initial surface current density ($A \cdot m^{-2}$); N is number of circuits (dimensionless); A is area that perpendicular to electric current ($m^2$).

## PROJECT SITE INFORMATION

The project involves in dredging marine deposits to reclaim 2.528 million sqaure meter of land for residential and commercial usage. The project is located in City of Taizhou, Zhejiang Province of China, which is 400 km (240 milies) south of Shanghai. The reclaimed land project is on the west shoreline of East China Sea and at the Taizhou Bay where the Jiaojiang River enters the East China sea as shown FIG. 6.



(a)

(b)

**Figure 6. Location of the project site: (a)Taizhou Bay; and (b) site location.**

After dredging was completed, a site investigation indicated that below the 5 ~ 6 m dredging fill there was 22 ~ 26 m of peat and more than 20 m of silty clay layer as shown in the boring log in FIG. 7. The soil testing showed that the dredging fill had a moisture content of 50~83% and only provided a bearing capacity of 20 ~ 30 kPa, not applicable for any construction activities. In addition, the underlying peat and silt clay had a moisture content of 46 ~7 5% and 33 ~ 59%, respectively. The reclaimed land will be used for manufacturing plants, roads, a park and an airport. Therefore, the top 1.5 m needed to be first treated to reduce its compressibility and increase its bearing capacity to give access to construction equipment and personnel. For most of reclaimed area, the PVD and vacuum preloading were used together to drain the water from the soil. On the east side of the reclaimed area, a 1,000 $m^2$ was selected as a test zone (shown in FIG. 8 as "Test area") where electro-osmosis and vacuum preloading were used jointly, expected to achieve a fast dewatering/consolidation than other treatment methods. The 1,000 $m^2$ test zone was divided into equally into 5 sections (K1, K2, K3, K4 and K5), i.e., 200 $m^2$ per section. The designed treatment depths for the 5 sections were 0, 5, 7, 9 and 10 m, respectively. The zero depth represented the vacuum preloading only situation.

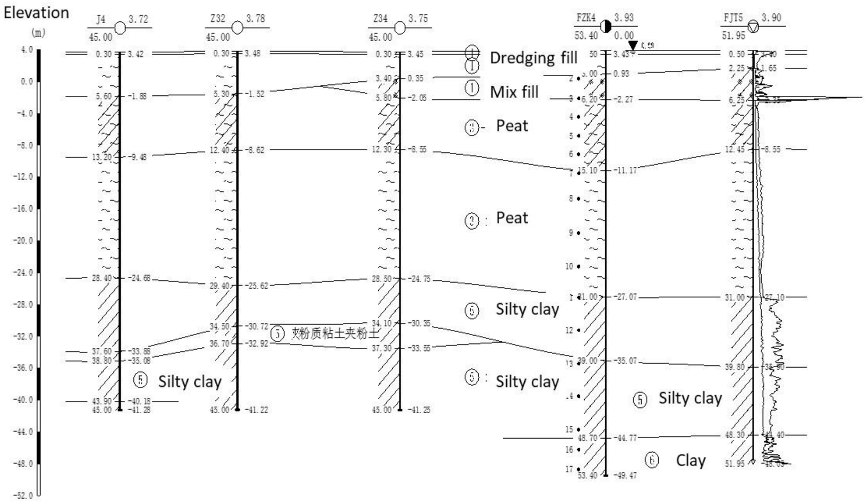


**Figure 7. Boring log of the project site.**

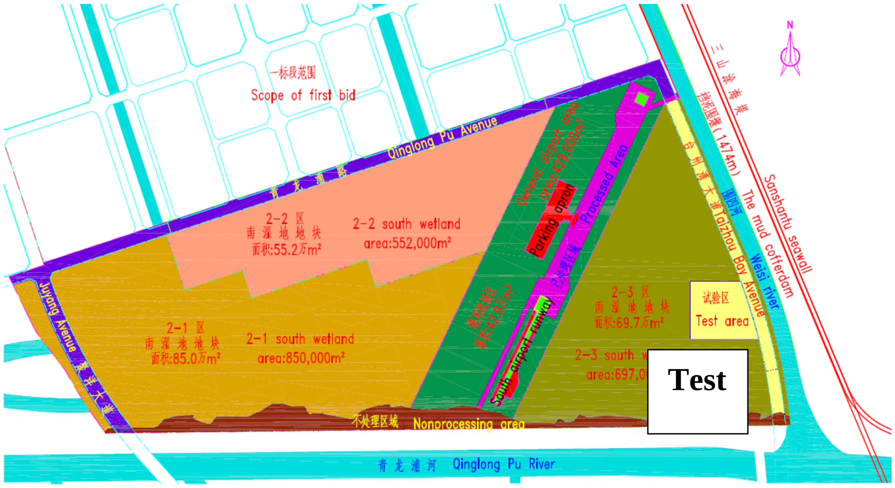


**Figure 8. Electro-osmosis + vacuum preloading test area.**

## ELECTRO-OSMOSIS DESIGN AND PVD INSTALLATION

The PVD used for electro-osmosis consisted of an EKG core (shown in Figure 5) and a geotextile sleeve, which made it look like conventional PVDs. The properties of the used PVD are listed in Table 1 below:

**Table 1. Properties of PVD with EKG core**

| Specimen | Resistance ($\Omega\cdot$m) | Elongation (%) | Tensile strength (MPa) |
|---|---|---|---|
| PVD with EKG core | $4.0486\times10^{-3}$ | 9.32 | 4.46 |

Before the installation, design was performed to determine the key parameters of the electro-osmosis dewatering/consolidation following the procedure below (Zhuang 2016):

- Obtain flow rate coefficient $k_q$, time factor a and initial surface current density $j_0$ through lab scale model test,
- Select DC power, electrode spacing and rolling electro-osmosis scheme according to dewatering time requirement and project budget and calculate initial total current,
- Calculate dewatering time according to current ~ time curve,
- Calculate total dewatering volume; estimate water content of sludge after electro-osmotic dewatering; estimate the settlement after consolidation. If final moisture content and settlement do not meet the criteria, go to Step 2 to re-select DC power and rolling electro-osmosis scheme and repeat the remaining steps.

Based on the design, the layout of each test section is presented in FIG. 9. The PVDs were installed with 1 m spacing in both horizontal and vertical directions. For each section, two DC power sources of 80V/60A were used as shown in FIG 10. Five alternating rows of PVDs were connected to the anode of the power source and the other five alternating rows of PVDs were connect to the cathode of the same power source, which was expected to form parallel flow in the soil mass. At the boundary of each test section, 0.5 m space was reserved to allow the anchorage of geomembrane used for the vacuum preloading. There were totally four such sections as shown in FIG 9. The remaining 200 m$^2$ section was treated only with vacuum preloading for comparison purpose.

The installation took the following procedure, which is also shown in FIG. 10:

- Lay out a layer of geotextile to allow access of equipment and personnel.
- Install PVDs (Note: 4 different depths were used for different sections).
- Lay out and connect surface drainage pipes, which were used guide the water to ditches at sides of each section.
- Wrap PVDs around pipes and then connect them to wires that were then connected a connector. The connection theme of PVDs were shown in Figure 10.
- Lay out a layer of geotextile and geomembrane sequentially.
- Connect the pipe to a vacuum pump and then connect wire to power sources. The vacuum reloading started first. 7 days after the start of vacuum preloading, the power for the electro-osmosis dewatering/consolidation turned on.

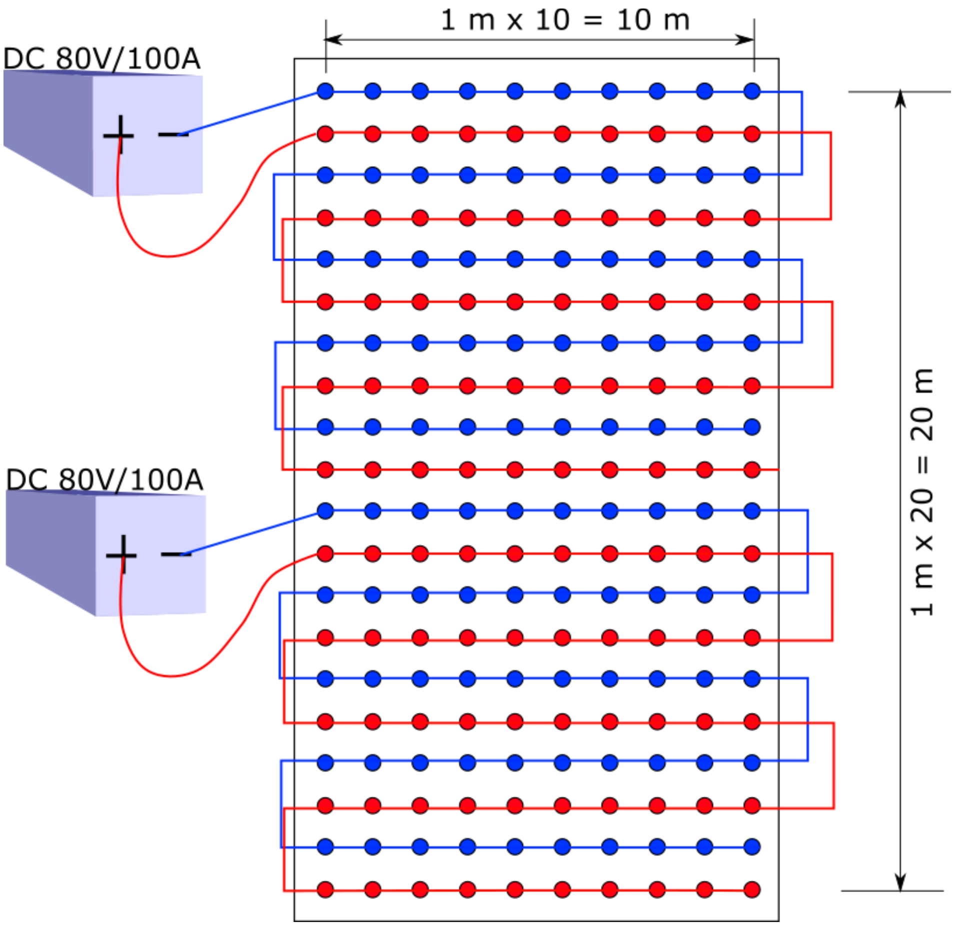


**Figure 9. Layout and connection theme of PVDs.**

## TREATMENT TIME AND SETTLEMENT ESTIMATION

Treatment time and settlement estimation are based on the energy level gradient theory as previously discussed (Zhuang et al. 2015; Zhuang and Wang 2005). The experiment was designed to be carried out following voltage sequence of 10V, 20V, 40V and 80V. In every level of voltage, electric current intensity followed Eq. 6.

In this field test, $a=10^{-5}$ $s^{-1}$, so according to the equation, electro-osmotic consolidation under every level of voltage would last for 7 ~ 8 days when current intensity degraded to 2‰~1‰ of its initial value. Therefore, total treatment time was estimated to be 28~32 days.

According to the energy level gradient theory, dewatering of electro-osmosis can be estimated by Eq. 4. By using the roll polling technique (Zhuang 2021), the 80V/400A DC power supply was in charge of 800m$^2$, which originally would require 3 times of current intensity. Namely, in point of view of energy density, the power of 80V×400A was actually corresponding to an area of 1/3 of 800m$^2$.

By integrating Eq. 4, the final total dewatering volume was:

$$Q = k_q \frac{V(I_{ototal} - I_{\infty total})}{a^2 \Delta x^2}(1 - e^{-at}) = \frac{4.5 \times 10^{-13} \times (10 + 20 + 40 + 80) \times 400}{(10^{-5})^2 \times (1^2)} = 270(m^3)$$

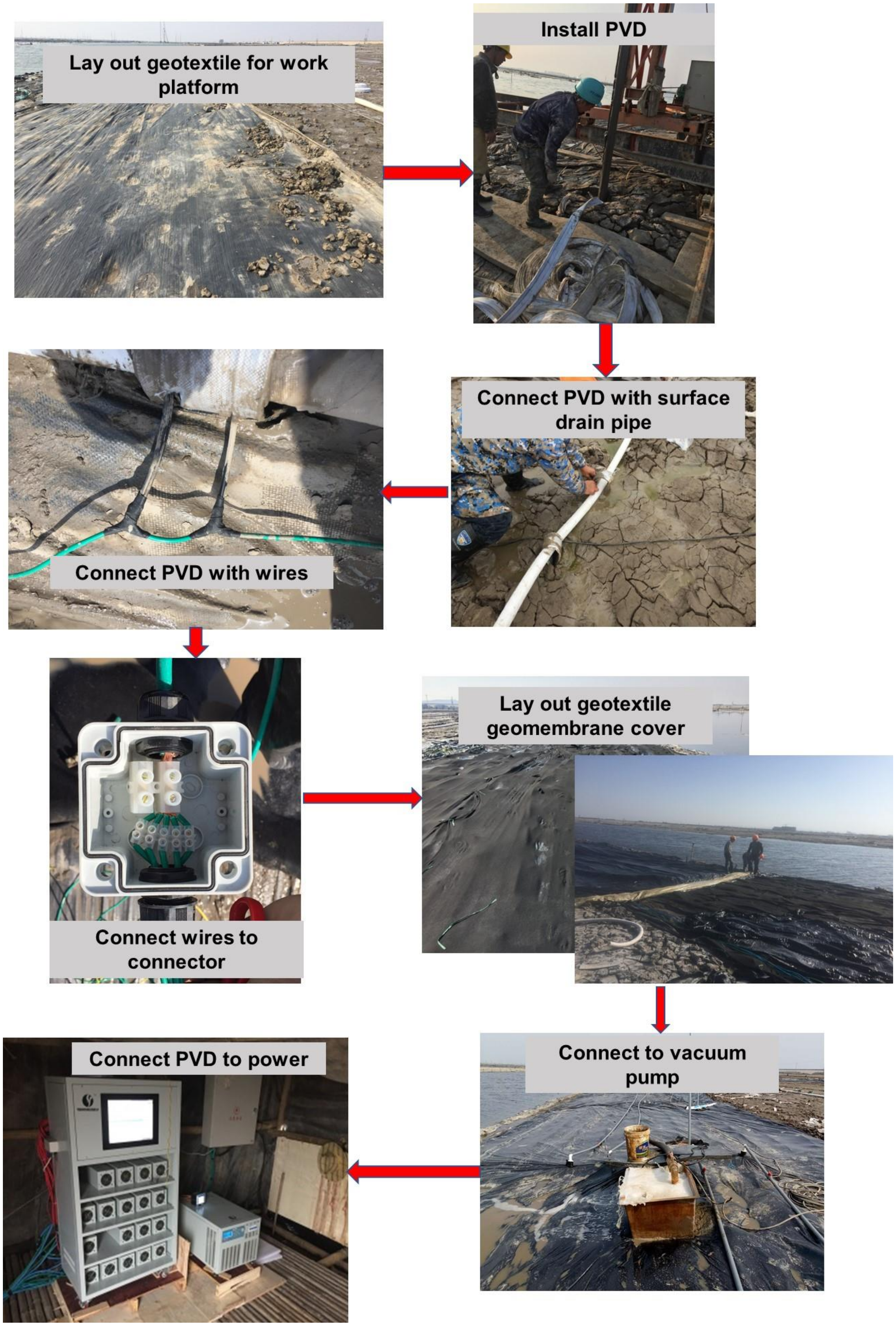


**Figure 10. Procedure of installation and construction (courtesy of Hangzhou Shenyuan Environmental Sci-Tech Co. Ltd).**

The settlement could be estimated as follows if the soil was assumed to be saturated during electro-osmotic consolidation.

$$\Delta H = \frac{Q_\infty}{A} = \frac{270}{800/3} = 1.013(m) = 1013(mm)$$

Please note that the settlement of about 1 m would be a bit overestimated because the soil may not be always saturated, especially at later stage of consolidation. And the treatment may be underestimated because there would be discharging process during polar reversion, which cost extra time.

## KEY FINDINGS AND FUTURE STUDY

A field test zone was performed to evaluate the effectiveness of joint usage of electro-osmosis and vacuum preloading techniques. The test area was 1,000 $m^2$, only covered a small portion of the 2.528 $km^2$ reclamation site. The remaining of the project were primarily treated with vacuum preloading with conventional PVD. The treatment was still in progress at time the project site was visited on May 25th, 2018. Based on the data obtained by then, the measured settlement ranged from 500 to 750 mm from the five test sections, 32 days since the start of electro-osmosis dewatering/consolidation. The settlements were significantly higher than those obtained from the neighboring conventional PVD treated areas, indicating the effectiveness of electro-osmosis. The technology showed its advantage in fine-grain soil, especially under unsaturated situations, compared to the conventional PVD methods. Besides the visit leads many other important findings:

- The technology is labor intensive, because it involves in connecting PVDs with wire and waterproof connectors have to be used to prevent electricity leakage.
- The cost of this technology is high, which comes from energy consumption and EKG PVD. The energy consumption was approximately 0.55 $kwh/m^3$. It is possible to supplement the energy from none-peak-hour solar or wind source to offset the total cost. The EKG PVD is expensive compared with conventional ones because of the small market volume.
- The conductivity of EKG PVD will reduce gradually due to the leaching of the chemical compounds. In addition, due to the accumulation of chemical around the electrodes, the current may be significantly reduced during operation.

However, regardless of these problems, electro-osmosis dewatering/consolidation is a promising soil improvement technology to treat dredging fill in a large scale.

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