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Thermal prefabricated vertical drain for vacuum consolidation of Hong Kong marine deposits with temperature changes

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ABSTRACT: The consolidation of marine deposits for marine infrastructure, dredged mud disposal, as well as new reclamation, is a time-consuming process due to the low permeability of the soft marine clay. In vacuum preloading, the discharge efficiency of prefabricated vertical drains (PVD) significantly decreases with bending and clogging as soils consolidate. In this study, a physical model test was carried out for vacuum preloading on Hong Kong marine deposit (HKMD) slurry with a heating aided PVD for stepwise heating. The temperature distribution and evolution in the model, the water discharge volume of the slurry, and the response of water discharge rate to temperature change at different stages of consolidation are analyzed and discussed.

1 INTRODUCTION

Land shortage is one of the major challenges of urbanization and economic development, especially in coastal regions, which are usually the population and commercial centers, such as Hong Kong. Land reclamation and other marine infrastructures are of vital importance to urban development in these areas. In coastal regions, the land and seabed are usually covered with thick layers of soft marine deposits, with high water content, low strength, and high clay content. Marine reclamation and other construction activities, such as ground improvement and channel dredging, are closely associated with marine deposits to be effectively treated. In fact, due to lack of gravel and sand fills, it has been proposed and applied to use soft marine deposits as a fill material for reclamation (Yin *et al.* 2022). In these cases, the time-consuming consolidation process of dredged deposits as well as the natural in-situ deposits is a key challenge.

Vacuum preloading is effective in accelerating the consolidation of soft soils, with a sealing system, a vacuum source, and drains, mostly prefabricated vertical drains (PVDs) (Baral *et al.* 2021; Cai *et al.* 2017). Although PVD-vacuum preloading has been successfully applied in the past decades, there are still significant challenges, such as the deformation and clogging of PVDs, non-uniform consolidation, and formation of soils columns during vacuum preloading, which will reduce the rate of consolidation of the soils (Wang P. *et al.* 2020; Zhou & Chai 2017). Solutions have been proposed to such issues, one of which is to increase the temperature in the soft soils treated (Abuel-Naga *et al.* 2006; Artidteang *et al.* 2011; Du *et al.* 2021; Wang J. *et al.* 2020). Under elevated temperature, the viscosity of porewater is significantly reduced, and the permeability of the soil will be much higher (Cho *et al.* 1999; Chen *et al.* 2023). One convenient way of heating soft soils is to integrate the heating sources, such as electric heating wires with the PVDs to be inserted in to the soils. Previous studies showed that using such thermal PVDs, the speed of vacuum consolidation obviously increases with temperature, and the non-uniform consolidation effects is improved (Chen *et al.* 2022). Most studies are focused on isothermal tests. In practice, heating procedures might be complicated, and the temperature

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effects might vary at different stage of consolidation. It is beneficial to understand the influences of temperature change at different consolidation state, towards a more efficient and less energy-consuming design of the heating scheme.

In this study, a reduced-scale axisymmetric model test was conducted on Hong Kong marine deposits. A PVD with heating wires was installed at the center of the soil, and a complicated heating-cooling-reheating schedule with vacuum pressure was implemented. The temperature distribution and evolution in the model, the water discharge volume of the slurry, and the response of water discharge rate to temperature change at different stage of consolidation are analyzed and discussed.

2 TEST SETUP

2.1 *Materials*

The soil material used was the Hong Kong marine deposits (HKMD), which is a typical type of marine clayey soil. The particle size distribution is shown in Figure 1. There is around 20% of clay particles (sized <2μm) and 62% of silt (sized <50μm) in the HKMD sample. The permeability of HKMD is back-calculated through oedometer tests using Terzaghi's theory. It is reported that the void ratio-dependent permeability follows $e = 1.487 \log k_v + 15.09$ under 20°C and $e = 1.435 \log k_v + 14.77$ under 40°C (Chen *et al.* 2022). It can be seen that permeability increases with temperature.

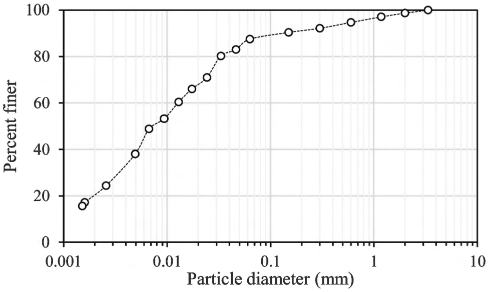

Figure 1. Particle size distribution of HKMD in the model test.

2.2 *Design of the physical model*

The layout of the model is shown in Figure 2. Before consolidation, the HKMD was mixed with water and reconstituted into a slurry with a water content of 100%. A band-type PVD with thickness of 5mm, width of 100mm, and length of 500mm was installed at the center of a rigid steel cylinder with diameter of 294mm and height of 500mm. The heating wire was connected to aa temperature-control unit. A flexible heating wire was fixed on the surface of the PVD. Then the HKMD slurry was poured inside. Temperature sensors were installed inside the soil body to monitor the temperature distribution of the soils. Finally, the slurry was covered with a layer of plastic membrane for air sealing. The PVD was connected to a vacuum pump and a water collection chamber.

2.3 *Test schedule*

The slurry was firstly settled for a couple of days without vacuum preloading and heating. Then vacuum pressure of −50 kPa was applied in stages in one hour and maintained constant for the whole process. The temperature was controlled by tracking the sensor T0. The

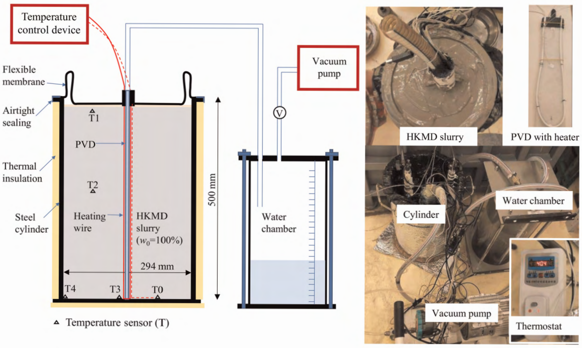

Figure 2. Setup of the model test.

temperature of T0 was firstly set to 30°C for a while and cooled down to around 20°C for around 2 days. Afterwards T0 was increased again to 40°C for 11 days, then reduced to 30°C for 4 days, and to 20°C for 3 days. After that, T0 was again increased to 30°C for more than 20 days, and finally reduced to around 20°C by turning off the control system. The setting of temperature can be found in Figures 3 and 4.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Temperature evolution and distribution*

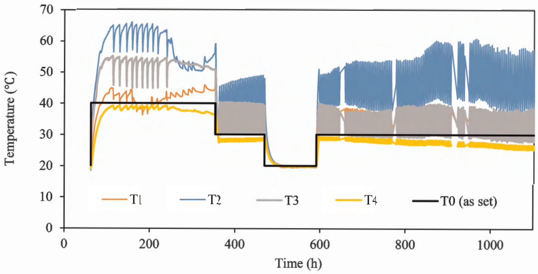

Figure 3. Temperature–time curves at five locations.

Figure 3 shows the temperature evolutions at locations of T0, T1, T2, T3, and T4. T0 is connected to the temperature controller. First of all, it can be found that the temperature is not uniform within the soil. Possible reason is the heat loss by thermal diffusion and radiation the top and bottom boundaries. Another reason is the thermal convection with water flow from the surrounding soils to the PVD, compensating part of the thermal diffusion from PVD to the edge. In the lateral direction, temperature near the heating source at the middle (T3) is higher than temperature at the middle and boundary (T0 and T4), because the working temperature of the heating wire was higher that the setting. T0 and T4 are close, indicating good insulations at the lateral boundaries. Along the vertical direction, temperature at the middle depth (T2) is higher than T1 at the surface and T0 at the bottom, due to the heat loss at the surface and the boundary. The middle depth of soils received the most heat since it is farthest to the boundaries.

For the temporal distribution, firstly, it can be found that except T0 with stable control, temperature at all measuring points exhibits significant fluctuation. The reason for fluctuation is that the working temperature of the heating wire is as high as 70°C, and the temperature control is a dynamic control process. Secondly, under the same T0 = 30°C, T2 gradually increases with time. This is due to the increasing thermal conductivity with gradual reduction of void ratio.

3.2 *Water discharge volume*

Figure 4 shows the volume of pumped water from the physical model with time. It can be found that the volume change of the slurry is significant, as the initial volume of the slurry was only around 30 L. During vacuum preloading, when there is a heating, a sharper slope of water discharge curve can be observed, even when the heating period is short. When there is a cooling process, the slope of water discharge curve immediately becomes much gentler. Therefore, heating process has fatal contribution to the consolidation settlement of clay slurry.

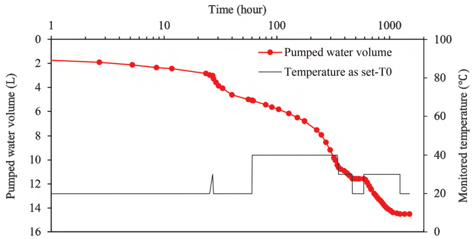

Figure 4. Water discharge volume and temperature setting with time during vacuum preloading.

3.3 *Effects of temperature change on water discharge rate*

The consolidation of soils is dependent on both temperature and void ratio. It is important to investigate the rate of consolidation with temperature change at different stages of vacuum consolidation. The water discharge rate $\dot{V}_w$ is calculated by:

$$\dot{V}_w = \frac{dV_w}{dt} \approx \frac{V_{w,i+1} - V_{w,i-1}}{t_{i+1} - t_{i-1}} \tag{1}$$

where $\dot{V}_w$ is the water discharge rate, V_w is the volume of pumped water, "$i-1$" and "$i+1$" represent the measuring time moment before and after the current time moment, t is the elapsed time.

Figure 5 shows the water discharge rate and temperature with water discharge volume. Firstly, under a constant temperature, the rate of consolidation always decreases with time.

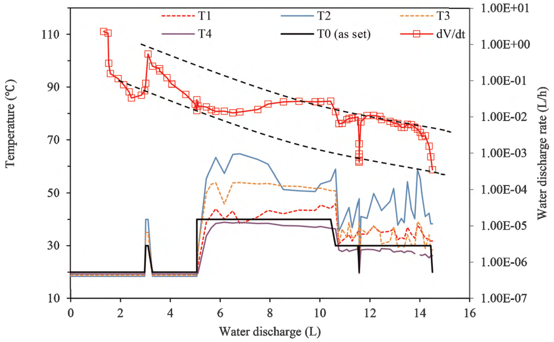

Figure 5. Water discharge rate and temperature setting with time during vacuum preloading.

This is due to (a) the nonlinear compression and consolidation of the soil; (b) the reduced water discharge capacity due to deformation of PVD; (c) the clogging of the PVD as well as the formation of soil column, especially without heating (Chen *et al.* 2022). Secondly, with heating, the rate of consolidation always increases, due to the enhanced permeability by reduced water viscosity, especially in the clogged regions.

However, the test results indicate that the HKMS slurry might response to temperature differently at different consolidation stages. At the earlier stage, there is a trial heating to 30°C for only several hours. However, the increase of consolidation rate is very significant and sensitive. As the high-water content slurry has relatively low thermal conductivity, the heating mainly affects the middle region. Therefore, the consolidation of soils close to the PVD is especially accelerated, and soil column may form faster.

At the second heating stage from 20 to 40 for 11 days, the temperature is higher, but the increase of water discharge rate is rather slow. It seems that a certain period is needed for heating to make an obvious contribution. During the previous consolidation stage, the PVD is deformed, the soil column has formed around the PVD, and non-uniform consolidation is significant. Therefore, the effects of PVD heating on the consolidation rate slowly increases as the non-uniformity is slowly reduced after some water discharge under a higher temperature.

At the final stage, when the temperature of T0 was set from 40 to 30°C, the water discharge rate drops a bit and increases again to the original track. Meanwhile, a short cooling-heating cycle was conducted quickly at this stage, and the rate of water discharge quickly experienced a drop-rise cycle. The heating effects of consolidation rate is obvious at this stage. The reasons behind this phenomenon might be: (i) The soil is already dense, so the thermal conductivity is high and the temperature re-distribution is faster to cause quicker response in the soils. (ii) After a long-term of heating, the non-uniformity of consolidation has been reduced (Chen *et al.* 2022), which causes the further increase of consolidation.

3.4 *Final stage of soils*

After the test, the vacuum pressure was stopped and the membrane was removed. It was found that the soil was highly hardened. The soil surface is very dry, with some surface cracks. The water content of the surface was measured to be only 3%.

4 SUMMARY

In this study, a laboratory model test was conducted on HKMD slurry under vacuum preloading with heating and PVD. The slurry was subjected to non-isothermal conditions with different temperatures at different consolidation stages. Several remarks can be summarized as follows.

(a) The temperature fluctuation at different locations is significant due to the dynamic control of the heating wire and the heat loss at the top and bottom of the soils, which should be paid attention in field application. With consolidation going on, the thermal conductivity is gradually increased.

(b) Under elevated temperature, the settlement of HKMD slurry is significantly increased. The rate of water discharge always increases with increasing temperature. A highly stiff layer can form after treatment with vacuum preloading and heating.

(c) At the earlier stage of consolidation, the response of water discharge rate to temperature is faster than at the middle stage of consolidation. With the formation of soil column and PVD deformation, the improvement of consolidation rate by heating will take a certain period. However, further explorations are necessary to clarify the specific mechanisms for such behaviours.

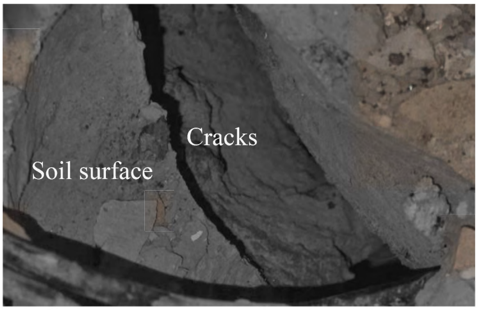

Figure 6. Final state of the soil surface after the tests.

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