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# EFFECTIVE DEPTH OF VACUUM PRELOADING

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ABSTRACT: Vacuum preloading is one of the methods that can be used to improve the engineering properties of soft clay. However, there is a misconception that the vacuum preloading method is only effective for soil within a depth of 10 m, as the maximum depth for water lifting using vacuum is 10 m. In this paper, the mechanisms of water lifting and vacuum preloading are examined and the differences between the two processes are explained. A simple physical model is used to demonstrate that the effective depth of vacuum preloading is not related to the maximum depth for water lifting. Two case studies are also presented to illustrate that in practice the vacuum preloading method can be used effectively for soil as deep as 20 m.

Keywords: Compressibility, consolidation, preloading, pore water pressure, soil improvement

## INTRODUCTION

The vacuum preloading method has been successfully used in numerous soil improvement projects around the world (Holtz 1975; Chen and Bao 1983; Choa 1990; Jacob et al. 1994; Bergado et al. 1998; Chu et al. 2000, Tan and Shang 2000, Yan and Chu 2003, 2005). The mechanisms of vacuum preloading have been discussed by a number of researchers (Kiellman 1952; Holtz 1975; Qian et al. 1992). Vacuum preloading is similar to water lifting using vacuum, as in both cases, water is pumped out from underground using a vacuum pump. As the maximum depth for water lifting using vacuum is only 10 m, there is a misconception that the effective depth of vacuum preloading, that is, the depth to which the vacuum preloading method is effective, is also within 10 m. Although there are practical cases that show the vacuum preloading method can be used to treat soil at a depth deeper than 10 m (Chen and Bao 1983; Choa 1990; Chu et al. 1990; Tang and Shang 1990; Yan and Chu 2003, 2005), some researchers and engineers are still not convinced and believe that the improvement of the soil at a depth deeper than 10 m may be caused by other mechanisms rather than by vacuum preloading directly. Therefore, there is a need to clear this misconception by explaining the mechanism of vacuum preloading and the difference between water lifting using vacuum and vacuum preloading. A study by Mohamedelhassan and Shang (2002) has established that the vacuum pressure generates nearly identical effects compared to a surcharge pressure of the same magnitude under one-dimensional conditions. However, this study does not address the effective depth issue. Furthermore, whether the study can be verified or be generalised into three-dimensional conditions has yet to be confirmed (Lei and Shi 2004). It would be much more convincing if a simple physical model can be used to explain the mechanisms of vacuum preloading and to demonstrate in an unambiguous way that the effective depth of vacuum preloading can be greater than 10 m. The objectives of this paper are to explain the mechanisms of vacuum preloading by comparing it with that of surcharge preloading, discuss the differences between vacuum preloading and water lifting and identify the factors that affect the effective use of vacuum preloading. A simple model was set up and used to demonstrate the process of vacuum preloading and to illustrate the differences between water lifting and vacuum preloading. The model shows that the effective depth of vacuum preloading is related only to the depth where vacuum pressure can be transmitted, and is not related to the magnitude of the vacuum pressure applied. The maximum depth for water lifting, on the other hand, is controlled by the magnitude of the vacuum pressure applied. As the maximum vacuum pressure can only be the same as the atmospheric pressure of 98 kPa, the maximum depth for water lifting is only 10 m. Two case studies are also presented to examine the variation of pore water pressure with depth at different time intervals, and to demonstrate that in practice, the vacuum

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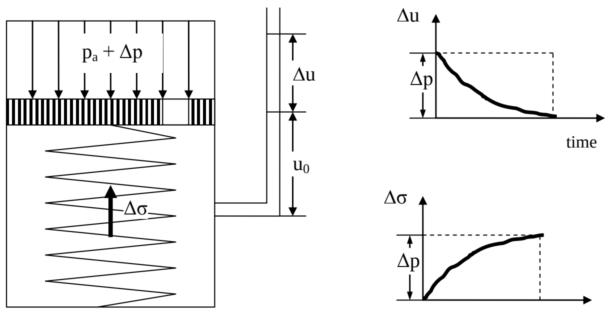
preloading method can still be effective for soil that is much deeper than 10 m below the ground surface. Practical considerations in promoting the effective use of the vacuum preloading method are discussed.

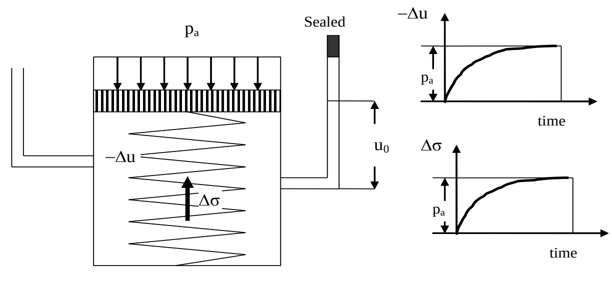
## MECHANISMS OF VACUUM LOADING

The consolidation process of soil under surcharge load has been well understood and can be illustrated using the spring analogy as shown in Fig. 1(a). For the convenience of explanation, the pressures in Fig. 1 are given in absolute values and $p_a$ is the atmospheric pressure. As shown in Fig. 1a, the instance when a surcharge load, Δp, is applied, it is the excess pore water pressure that takes the load. Therefore, the initial excess pore water pressure, Δu, is the same as the surcharge Δp. Gradually, the excess pore water pressure dissipates and the load is transferred from water to the spring (i.e., the soil skeleton) in the model shown in Fig. 1(a). The amount of effective stress increment equals to the amount of pore water pressure dissipation, Δp – Δu (Fig. 1(a)). At the end of consolidation, Δu = 0 and the total gain in the effective stress is the same as the surcharge, Δp (Fig. 1(a)). It should be noted that the above process is not affected by the atmospheric pressure, $p_a$.




$$u_0 = p_a$$
$$\Delta\sigma = p_a + \Delta p - (u_0 + \Delta u) = \Delta p - \Delta u$$

(a)



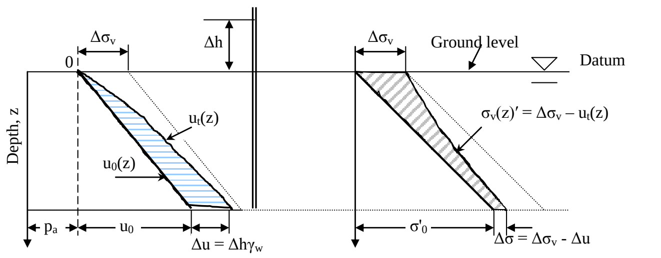

$$u_0 = p_a$$
$$\Delta\sigma = p_a - (u_0 - \Delta u) = \Delta u$$

(b)

Fig. 1 Spring analog of consolidation process (a) under fill surcharge; (b) under vacuum load

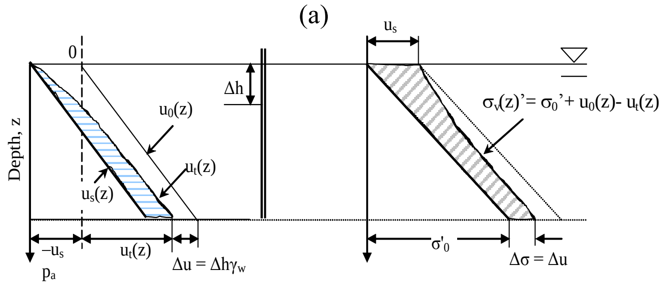
The mechanism of vacuum preloading can also be illustrated in the same way using the spring analogy shown in Fig. 1(b). When a vacuum load is applied to the system shown in Fig. 1(b), the pore water pressure in the soil reduces. As the total stress applied does not change, the effective stress in the soil increases. The instance when the vacuum load, –Δu, is applied, the pore water pressure in the soil is still $p_a$. Gradually the pore pressure is reducing and the spring starts to be compressed, that is, the soil skeleton starts to gain effective stress. The amount of the effective stress increment equals to the amount of pore water pressure reduction, Δu, which will not exceed the atmospheric pressure, $p_a$, or normally 80 kPa in practice.

For an idealised soil profile with the water table and a single drainage boundary at the ground level, the distributions of pore water pressure and effective stress with depth at a given time during consolidation can be plotted in Fig.s 2(a) and 2(b) for surcharge and vacuum preloading respectively. Under surcharge load, the effective stress equals to $\Delta\sigma_v - u_t(z)$, where $\Delta\sigma_v$ is the surcharge and $u_t(z)$ is the excess pore water pressure. As the pore water pressure increases with depth, the effective stress decreases with depth as shown in Fig. 2(a). Under vacuum load, the effective stress equals to




Pore water pressure change Effective stress change

(a)




Pore water pressure change Effective stress change

(b)

$u_0(z)$ = hydrostatic pore water pressure profile
$\sigma_v(z)'$ = effective stress at time t
$u_t(z)$ = excess pore water pressure at time t
$u_s(z)$ = suction line
$\sigma_0'$ = initial effective overburden stress

Fig. 2 Pore water pressure and effective stress changes (a) under fill surcharge and (b) under vacuum load

$\sigma_0' + u_0(z) - u_t(z)$, where $\sigma_0'$ is the initial effective overburden stress, $u_0(z)$ is the hydrostatic pore water pressure, and $u_t(z)$ is the pore water pressure. When the vacuum pressure is applied from the ground level, $u_t(z)$ is smallest at the top. Therefore, the effective stress will be the highest at the top (Fig. 2b). It should be pointed out that in the case of vacuum preloading, the increment in effective stress cannot exceed 98 kPa, although the effective stress in the soil can be higher than 98 kPa.

Although the mechanism of vacuum preloading are similar to that surcharge loading as explained above, the stress states imposed in the two loading conditions are different. The vacuum load causes an equal amount of changes in the vertical and horizontal stresses, whereas the surcharge load imposes an unequal amount of changes in the vertical and horizontal stresses which are controlled by stress distribution.

## DIFFERENCE BETWEEN WATER LIFTING USING VACUUM AND VACUUM PRELOADING

Water lifting by vacuum and vacuum preloading are two different processes and the mechanisms involved are different. The effective depth for vacuum preloading is different from the maximum depth for water lifting, that is, the maximum depth that water can be lifted using a vacuum pump.

### Maximum Depth for Water Lifting using Vacuum

Water lifting is a process to overcome the gravity of water to be lifted. For water lifting using a vacuum pump installed at the ground level, the maximum depth, $h_w$, is less than 10 m. This is because the maximum uplift pressure for a water column is only one atmospheric pressure, which is equivalent to a water column of 10 m high, as illustrated schematically in Fig. 3. The force equilibrium condition of a water column is shown in Fig. 3. For an uplift pressure of $p_a$, equilibrium is reached when $\gamma_w h_w = p_a$, where $\gamma_w$ is the unit weight of water. Therefore, the maximum depth cannot exceed $h_w = p_a/\gamma_w$.

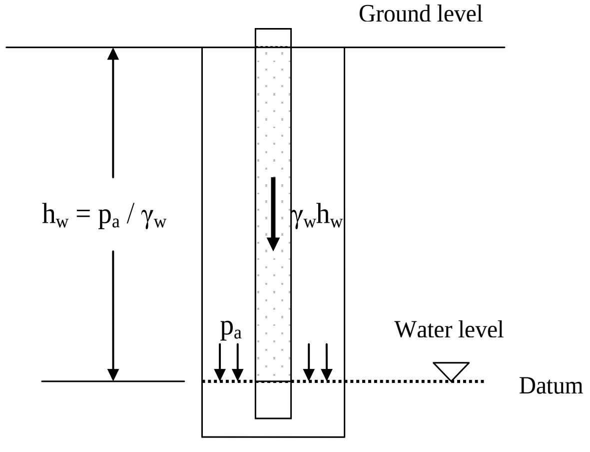



Fig. 3 Force and total head analysis for the water column to be lifted by vacuum during dewatering

Another way to examine the conditions that control water lifting is to analyse the total head difference between the ground level and the water level at the bottom. In Fig. 3, when the datum is chosen as the water level at the bottom, then the total head at the datum level is the same as the pressure head. In terms of absolute pressure, the pressure head at the bottom is related to the atmospheric pressure as $p_a/\gamma_w$. At the ground level, the pressure head is zero, or nearly zero because of the application of the vacuum pressure. Then the total head at the ground level is the same as the elevation head, $h_w$. For water to flow upward, the total head at the ground level has to be smaller than the total head at the bottom, that is, $h_w < p_a/\gamma_w$. Therefore, the maximum depth has to be smaller than 10 m.

### Effective Depth for Vacuum Preloading

At the hydrostatic condition, the total head at every point in the soil is the same. Under surcharge load, the change in the excess pore water pressure will cause the pressure head in the soil to change. As shown in Fig. 2(a), the total head difference between the bottom and the ground level can be calculated as $\Delta h = \Delta u/\gamma_w$, where $\Delta u$ is the amount of excess pore water pressure. Under this total head difference, water will flow up to the ground level. The flow of water is controlled by the amount of excess pore water pressure, not the depth. In general, the direction of water flow can be either up, down, or horizontal, depending on the hydraulic gradient, that is, the excess pore water pressure difference.

Similarly, under vacuum load, the pore water pressures in the soil will change. The changes in the pore water pressures will lead to changes in the total head in the same way as for surcharge loading. For the case shown in Fig. 2(b), when the datum is chosen to be at the ground level, the total head at the ground level is $-u_s/\gamma_w$ and the total head at the bottom is $-\Delta u/\gamma_w$[3]. Thus the total head difference between the bottom and the ground level is $|u_s - \Delta u|/\gamma_w$, where $u_s$ is the suction in the soil at the bottom level. Under this total head difference, water will flow toward the ground level. Therefore, the flow of water is controlled by the amount of suction, not the depth.

[3] The pressure head = $(u_0(z) - \Delta u)/\gamma_w = z - \Delta u/\gamma_w$ , the elevation head = z. The total head is the sum of the pressure head and the elevation head.

It can be concluded from the above analysis that for both surcharge and vacuum preloading, the flow of water in soil is controlled by pore water pressure changes. This is completely different from the mechanism of water lifting. On the other hand, it needs to be pointed out that consolidation is controlled by the effective stress change caused either by an increase in total stress (in the case of surcharge) or by a decrease in pore water pressure (in the case of vacuum preloading). Under surcharge load, the effective depth is controlled by the surcharge load distribution in soil. Under vacuum load, the effective depth depends on the depth that the vacuum pressure can be distributed. This, in turn, depends on the well resistance of the well used to distribute vacuum and the screen resistance. Here the well resistance refers to the vacuum pressure loss along the vacuum distribution channel (the well) and the screen resistance refers to the vacuum pressure loss when the vacuum pressure is transmitted through the filter used for the well. Prefabricated vertical drains (PVDs) are often used as wells to distribute vacuum pressure. Nowadays good quality PVDs can offer a discharge capacity that is high enough for the well resistance to be practically neglected (Chu et al. 2004). In this case, the vacuum pressure can be transmitted to a depth as deep as the PVD can reach and the effective depth of vacuum preloading will be as deep as the drain.

## MODEL TESTS

To demonstrate the consolidation process of soil under vacuum load and the difference between water lifting and vacuum preloading, a model is set up as shown in Fig. 4. The model consists of a 300 mm in diameter Perspex cylinder with 4 pistons connected in series by 4 springs. The pistons were perforated with many 3 mm in diameter holes except the top one. The pistons were designed in a way to keep the friction between the pistons and the cylinder to be small. The cylinder was 1 m tall. The distances between the pistons were 200 mm. Four standpipes with the top sealed were also used as shown in Fig. 4. A vacuum pump was used to apply vacuum pressure through a vacuum pressure chamber, as shown in Fig. 4.

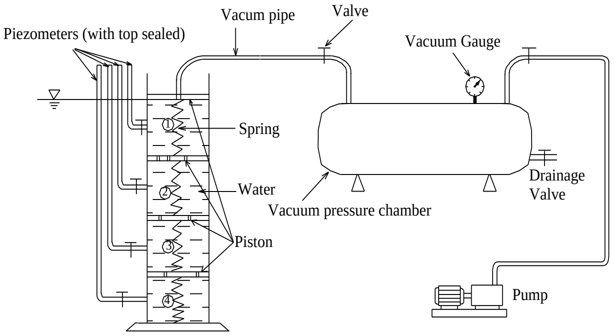



Fig. 4 Arrangement for model test for vacuum consolidation

In one of the model tests, a constant vacuum pressure of 2.5 kPa was applied. For water lifting using a 2.5 kPa vacuum pressure, the maximum depth is only 0.25 m. If the mechanism of vacuum preloading is the same as that for water lifting, the vacuum load should only be effective to a depth of no more than 0.25 m. This was not the case in the model test. The model showed that after the application of the vacuum pressure, the pistons started to move down one after another from the top until equilibrium was achieved. The settlement versus time curve measured for every piston is shown in Fig. 5. It can be seen from Fig. 5 that every layer moved down, or in other words, every spring was compressed. Fig. 5 also shows that at the first 2 to 3 mins, only the 1$^{st}$ and 2$^{nd}$ layers moved and the 3$^{rd}$ and 4$^{th}$ layers only settled subsequently. Therefore, there was a vacuum distribution period for vacuum pressure to be distributed from the ground surface to the deeper layers. This distribution period has also been observed in the field. The initial and final positions of the pistons are given in Fig. 6. The compressibility and the corresponding force in each spring at the equilibrium position are given in Table 1. Please note that the spring constants were not the same due to the random variation in the springs. Taking into the friction between the piston and the cylinder and the errors in the measurement into consideration, the forces developed in each spring are comparable. This is an indication that the vacuum preloading is equally effective in every depth. Therefore, the effective depth of vacuum preloading is not related to the maximum depth for water lifting. The model test also suggests that the depth where the vacuum can be transmitted is not related to the magnitude of the vacuum pressure and if there is no well resistance, the magnitude of the vacuum pressure will be the same everywhere in the soil. Therefore, to increase the effective depth of vacuum preloading, vertical drains with sufficiently high discharge capacity and filter permeability should be used to reduce vacuum pressure loss along the drain.

Table 1 Compressibility and the Force in Each Spring in the Model

| Spring | Compressibility (mm) | Spring constant (N/mm) | Force in the spring (N) |
|---|---|---|---|
| 1 (Top) | 12.5 | 122.0 | 1525 |
| 2 | 16.5 | 94.3 | 1556 |
| 3 | 12.0 | 122.5 | 1470 |
| 4 (Bottom) | 14.0 | 116.3 | 1624 |

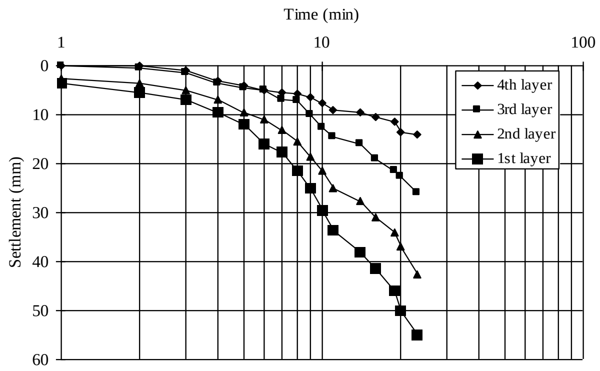



Fig. 5 Settlement against time curves measured for each layer

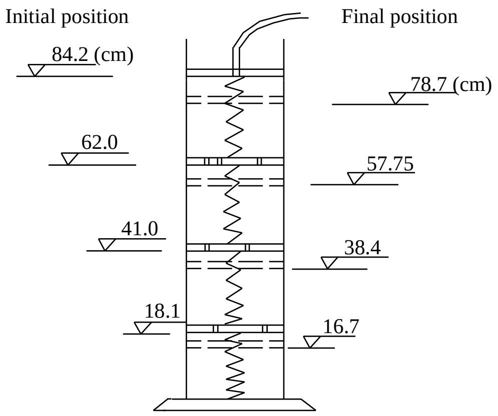



Fig. 6 Initial and final positions of the pistons in the model

The above model test was repeated by blocking the holes on the piston at the bottom so that the vacuum pressure could not be transmitted to the section below this piston. In this case, this piston did not move. This observation verifies the common believe that if there is no vacuum pressure there will be no consolidation.

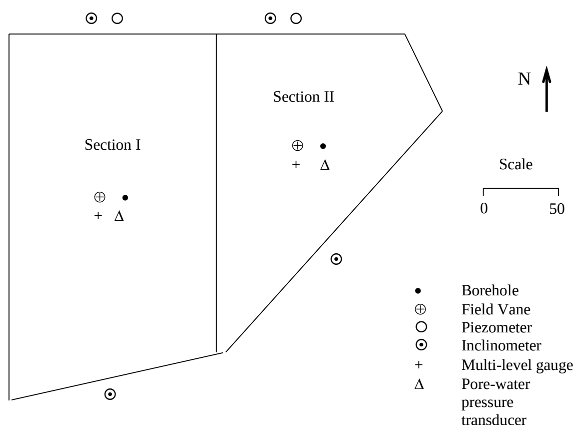
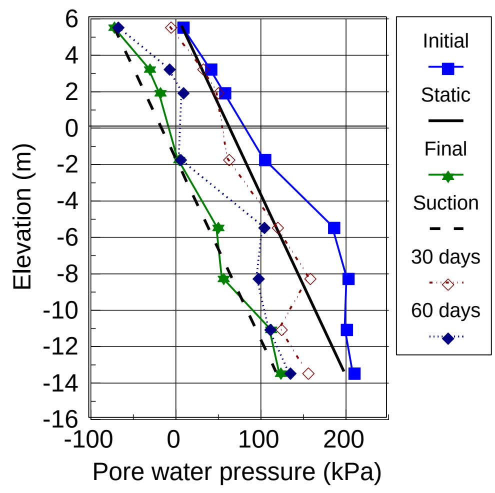



Fig. 7 Project site and plan view of instrumentation for Case I

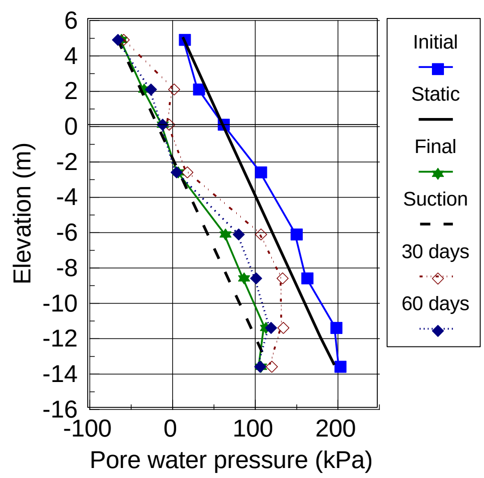
## CASE STUDIES

### Case I: Soil Improvement for an Oil Storage Station

This case has been presented in detail in Chu et al. (2000). Therefore, only the data relevant to the discussion will be reproduced here. The project was to construct an oil storage station near the coast of Tainjin, China, on a site that was recently reclaimed using clay slurry dredged from the seabed. The site for the oil storage station is shown in Fig. 7. It covered a total area of approximately 50,000 m$^2$. For the purpose of soil improvement, the site was divided into two sections: Section I of 30,000 m$^2$ and Section II of 20,000 m$^2$, as shown in Fig. 7. The soil profile consisted of a 6 m thick very soft consolidating slurry clay layer followed by a 16 m soft silty clay layer which overlaid a stiff sandy silt layer. The soil in both layers was very soft and the water contents of the soils were higher than the liquid limit at




(a)




(b)

Fig. 8 Pore water pressure distributions versus depth at different times(a) at Section I, (b) at Section II most locations. More details on the soil profile and soil properties are presented in Chu et al. (2000). Vacuum preloading together with vertical drains was adopted to improve the two layers of soil clay. Vertical drains were installed on a square grid at a spacing of 1.0 m to a depth of 20 m. Corrugated flexible pipes (100 mm diameter) were laid horizontally in the sand blanket to link the drains to the main vacuum pressure line. The pipes were perforated and wrapped with a permeable fabric textile to act as a filter. Three layers of thin membrane were laid to seal each section. Vacuum pressure was applied using vacuum pumps. For more information on the soil improvement procedure, see Chu et al. (2000). A vacuum pressure of 80 kPa was applied continuously for 125 to 145 days and the total settlement achieved was nearly 1 m. Field instruments were installed in both sections (Fig. 7) at various elevations (Chu et al 2000) to monitor the pore water pressure changes, settlements and lateral displacement developments during the entire consolidation process. These included surface settlement plates, deep settlement gauges, water stand pipes, pore pressure transducers and inclinometer.

Using the pore water pressure data measured at different depths (Chu et al. 2000), the initial and final pore water pressure distribution profiles together with the hydrostatic pore water pressure line and the suction line are plotted versus depth in Fig.s 8(a) and 8(b) for Sections I and II respectively. The suction line is plotted for a uniform suction of 80 kPa. The initial pore water pressures were greater than the hydrostatic pore water pressure as the subsoil was recently reclaimed and was still undergoing consolidation. The pore water pressure distributions at 30 and 60 days are also plotted in Fig.s 8(a) and 8(b) to illustrate the pore water pressure dissipation processes. It can be seen that the final pore water pressure distribution is very close to the suction line throughout the entire depth. The suction at the bottom of the drain, i.e., at elevation of -14 m, was as high as 80 kPa. This confirms that it is the vacuum pressure that causes the consolidation. It also suggests that there was no or little reduction in the suction along the drains. The data also indicate that the vacuum preloading method was effective throughout the entire soft clay layer of 20 m. The effectiveness of the vacuum preloading through the entire soft clay layer can also be seen from the settlement monitoring data shown in Fig. 9 and the field vane shear strength profile shown in Fig. 10 for Section II. Similar observations were made for Section I as reported by Chu et al. (2000). It can be seen from Fig. 9 that there was settlement at every elevation to a depth of nearly 20 m below the ground surface. At the end of the vacuum preloading, the degree of consolidation achieved was about 90% (Chu et al. 2000).

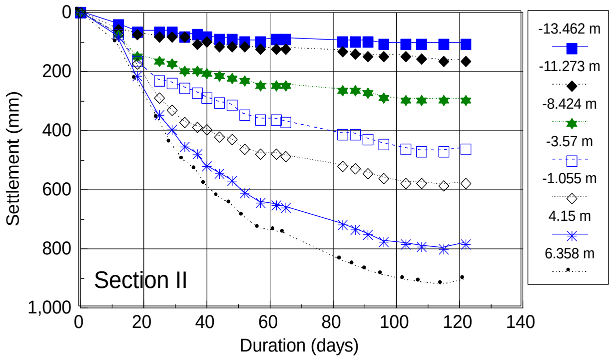



Fig. 9 Settlement measured at different depths against duration at Section II

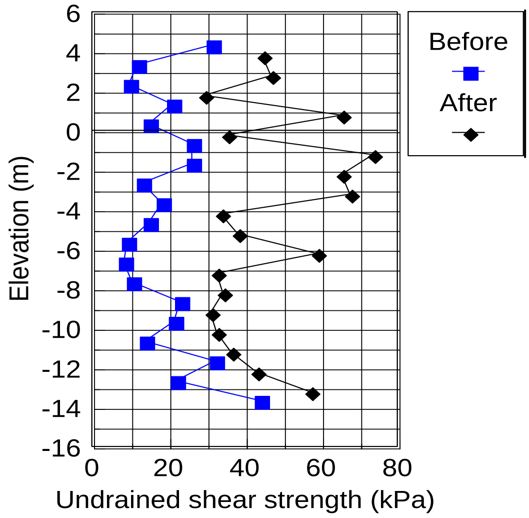



Fig. 10 Field vane shear strength profiles measured before and after vacuum preloading at Section II

The field vane shear strength has increased by 2 to 3 folds, as shown in Fig. 10. Therefore, the vacuum preloading method was effective throughout the entire depth of 20 m where PVDs were installed.

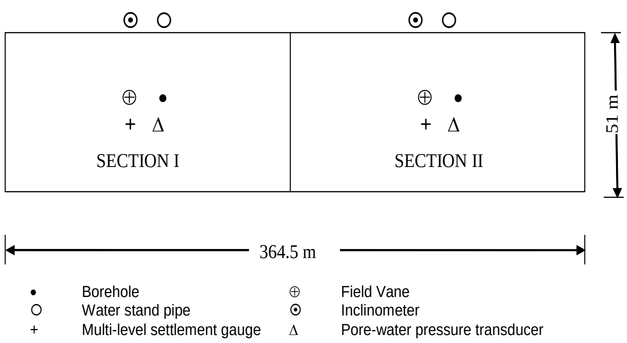



Fig. 11 Project site and plan view of instrumentation for Case II

Case II: Soil Improvement for Road Construction

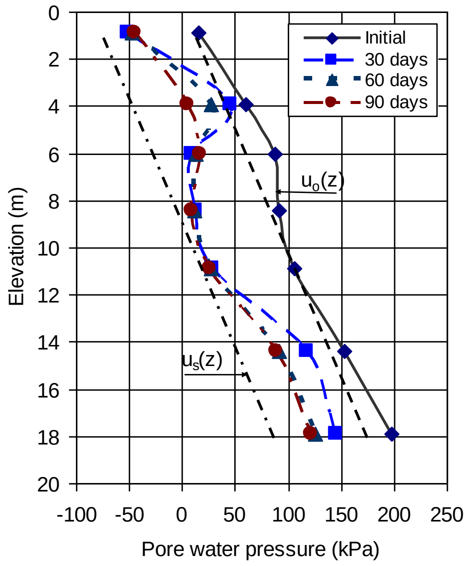
This case is taken from Yan and Chu (2003). The project concerned the construction of a road on a 20 m thick soft clay layer in Tianjin, China. Similar to the first case, the top 5 to 6 m of the clay layer was reclaimed recently using clay slurry dredged from seabed. The rest 14 to 15 m was original seabed clay.

The vacuum preloading method was adopted in this project for soil improvement. The section of the road to be improved is schematically shown in Fig. 11. It was 364.5 m long and 51 m wide. For the convenience of construction, the site was divided into two sections. A vacuum pressure of 80 kPa was applied continuously for 90 days. For the other detail of this project, see Yan and Chu (2003). Based on the pore water pressures monitored at different depths, the pore water pressure distributions with depth at durations of 30, 60, and 90 days are shown in Fig.s 12(a) and 12(b) for both Section I and Section II. The initial pore water pressure profile, $u_o(z)$, and the suction line, $u_s(z)$, are also plotted in Fig.s 12. The initial pore water pressures were greater than the hydrostatic pore water pressure, indicating that before soil improvement, the subsoil was still under consolidation. The pore water pressure variations shown in Fig.s 12 have indicated again that the vacuum preloading method is effective in soil much deeper than 10 m. It is noted that the dissipations of pore water pressure within the soil layers from 3 to 5 m and 14 to 18 m were slower. This is because the soils at those two layers had much smaller permeability compared with the soils in other depths.

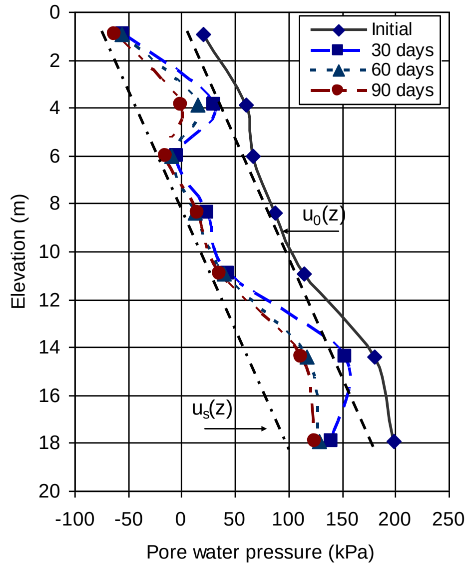
Similar cases where the vacuum preloading method has been successfully adopted to improve soft clay layers of more than 10 m deep can also be found in the cases reported in Choa (1990), Bergado et al. (1998), Tang and Shang (2000) and Yan and Chu (2005).

## CONCLUSIONS

In this paper, the mechanisms of water lifting using vacuum and vacuum preloading are explained. The differences between the effective depth for vacuum preloading and the maximum depth for water lifting using vacuum are discussed. A simple model and two case studies were used to demonstrate that the effective depth of vacuum preloading can be much more than the 10 m. The model tests have shown that the effective depth of vacuum preloading is related only to the depth where vacuum pressure can be transmitted, and is not related to the magnitude of the vacuum pressure applied. The maximum depth for water lifting using vacuum, on the other hand, is controlled by the vacuum pressure applied. As the maximum vacuum pressure can only be 98 kPa, the maximum depth for water lifting can only be within 10 m. To increase the effective depth for vacuum preloading, vertical drains with sufficient high discharge capacity and filter permeability should be used to reduce the vacuum pressure loss along the drains.




(a)




(b)

Fig. 12 Pore water pressure distribution versus depth at different duration (a) at Section I, (b) at Section II

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