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Vacuum Preloading Methods: An Update

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ABSTRACT: It has been more than 60 years since the concept of vacuum preloading was proposed. The vacuum preloading method has been evolving. There have been considerable improvements in the techniques as well as new applications. In this paper, several vacuum preloading methods including some new variations are introduced. The advantages and disadvantages of each method are compared. Technical issues such as improvement depth, vacuum pressure distribution in soil, and evaluation of degree of consolidation for soil under vacuum consolidation are discussed. A case history using a combined vacuum and fill surcharge preloading method for soft soil improvement is also used to illustrate the changes in the pore pressure versus depth profiles and the application of the method to calculate degree of consolidation using pore water pressure distributions.

1. INTRODUCTION

Vacuum preloading is one of the most commonly used soil improvement methods for soft clay. This method has been successfully used in a number of countries for land reclamation or soil improvement works (Holtz 1975; Chen and Bao 1983; Choa 1990; Bergado et al. 1998; Chu et al. 2000; 2009b; Chai et al. 2006; 2008). Sand drains and recently prefabricated vertical drains (PVDs) have been used to distribute vacuum load and discharge pore water (Bo et al. 2003; Chu et al. 2004). A vacuum load of 80 kPa or above can be applied and maintained as long as it is required. When a higher surcharge load is required, a combined vacuum and fill surcharge can be applied. Compared with the fill surcharge method for an equivalent load, the vacuum preloading method is cheaper and faster (Chu et al. 2000). The vacuum preloading method has also been incorporated in the land reclamation process when clay slurry dredged from seabed is used as fill material for land reclamation. As the clay slurry fill is too soft for fill surcharge to be applied, the vacuum preloading method is ideally used for the consolidation of the clay slurry. Thousands of hectares of land have been reclaimed in Tianjin and Wenzhou, China, using this method. When the reclaimed land is subsequently used for industrial and infrastructure developments, the vacuum preloading method is used again to improve the foundation soil that consists of a layer of consolidated slurry fill and the underlying seabed marine clay (Chu et al. 2000; Yan and Chu 2003).

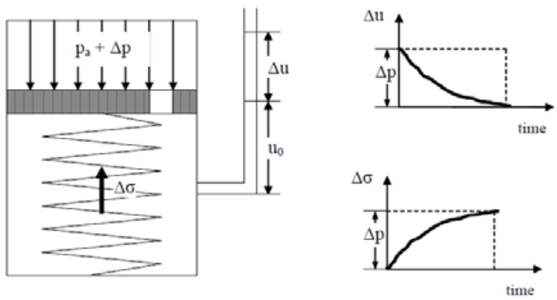
In this paper, the mechanism of vacuum preloading is explained by examining the pore water pressure and effective stress changes in both fill surcharge and vacuum preloading cases. Several vacuum preloading methods including some new variations are introduced. The advantages and disadvantages of each method are compared. Discussions on the effective depth of the vacuum preloading method and methods to estimate the degree of consolidation are also made.

2. MECHANISMS

The principles and mechanism of vacuum preloading have been well explained in the literature, e.g., Kjellman (1952), Holtz (1975), and Chu et al. (2000). To assist in explaining the interpretations adopted later for the case studies, the pore water pressure and effective stress change processes in both fill and vacuum preloading cases are examined as follows.

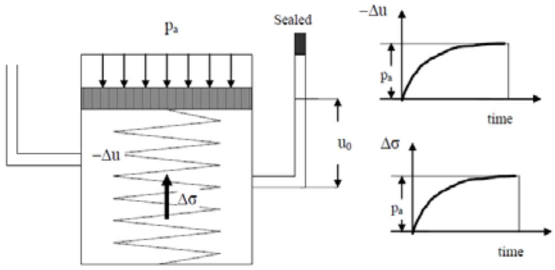
The consolidation process of soil under surcharge load has been well understood and can be illustrated using the spring analogy as shown in Figure 1(a). For the convenience of explanation, the pressures in Figure 1 are given in absolute values and p_a is the atmospheric pressure. As shown in Figure 1(a), the instance when a surcharge load, Δp, is applied, it is the excess pore water pressure that takes the load. Therefore, for saturated soil, the initial excess pore water pressure, Δu_0, 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 Figure 1(a). The amount of effective stress increment equals to the amount of pore water pressure dissipation, $\Delta p - \Delta u$ (Figure 1(a)). At the end of consolidation, $\Delta u = 0$ and the total gain in the effective stress is the same as the surcharge, Δp (Figure 1(a)). It should be noted that the above process is not affected by the atmospheric pressure, p_a.

The mechanism of vacuum preloading can also be illustrated in the same way using the spring analogy as shown in Figure 1(b). When a vacuum load is applied to the system shown in Figure 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, $-\Delta u$, 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 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.



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

(a)



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

(b)

Figure 1 Spring analog of consolidation process
(a) under fill surcharge; (b) under vacuum pressure

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 Figures 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 Figure 2(a). Under vacuum load, the effective stress equals to $\sigma_0' + u_0(z) - u_t(z)$, where σ_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 (Figure 2(b)). 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. It will be shown in the case study that the above simplified model depicts well the pore water pressures change process in soil under vacuum preloading.

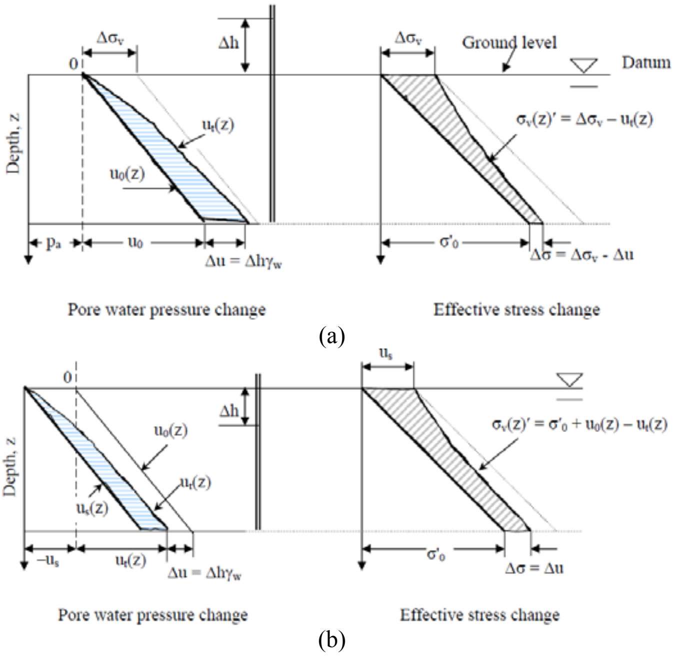


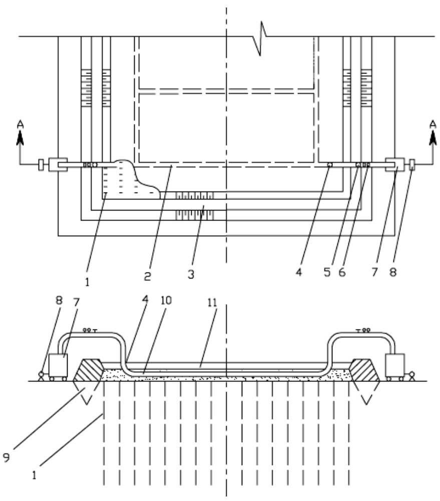
Figure 2 Pore water pressure and effective stress changes (a) under fill surcharge and (b) under vacuum load

3. VACUUM PRELOADING SYSTEMS

3.1 Membrane System

When the ground is very soft or when the fill surcharge has to be applied in stages to maintain the stability of the fill embankment, the vacuum preloading method becomes a good alternative. Vacuum preloading is also used when there is no fill or the use of fill is costly, when there is no space on site to place the fill and when slurry or soft soil is used as fill for reclamation. The idea of vacuum preloading was proposed by Kjellman in 1952. Since then, the vacuum preloading method has evolved into a mature and efficient technique for the treatment of soft clay. This method has been successfully used for many soil improvement or land reclamation projects all over the world (Holtz 1975; Chen and Bao 1983; Cognon 1991; Bergado et al. 1998; Chu et al. 2000; Chu and Yan, 2005b, Indraratna et al. 2005; 2011; Yan and Chu, 2003, 2005).

The schematic arrangement of the vacuum preloading system adopted in China is shown in Figure 3. PVDs are normally used to distribute vacuum load and discharge pore water. The soil improvement work using the vacuum preloading method is normally carried out as follows. A 0.3 m sand blanket is first placed on the ground surface. PVDs are then installed on a square grid at a spacing of 1.0 m in the soft clay layer. Corrugated flexible pipes (50 to 100 mm diameter) are laid horizontally in the sand blanket to link the PVDs to the main vacuum pressure line. The pipes are perforated and wrapped with a nonwoven geotextile to act as a filter layer. Three layers of thin PVC membranes are laid to seal each section. Vacuum pressure is then applied using jet pumps. The size of each section is usually controlled in the range of 5,000 to 10,000 m^2. Field instrumentation is an important part of the vacuum preloading technique, as the effectiveness of vacuum preloading can only be evaluated using fielding monitoring data. Normally piezometers, settlement gauges and inclinometers are used to measure the pore water pressure changes, the settlement at ground surface and/or different depths in the soil and the lateral displacement. More details are presented in Chu et al. (2000; 2005b) and Yan and Chu (2003; 2005).



1, drains; 2, filter piping; 3, revetment; 4, water outlet; 5, valve; 6, vacuum gauge; 7, jet pump; 8, centrifugal pump; 9, trench; 10, horizontal piping; 11, sealing membrane.

Figure 3 Vacuum preloading system used in China (after Chu et al. 2000)

In Europe, the Menard Vacuum Consolidation system has been developed in France by Cognon (1991). The details of this system can be found in Varaksin and Yee (2007). The general principle following this method is presented in Figure 4. The uniqueness of this system is the dewatering below the membrane which permanently keeps a gas phase between the membrane and the lowered water level. Therefore, the Menard Vacuum Consolidation system adopts a combined dewatering and vacuum preloading methods to maintain an unsaturated pervious layer below the membrane.

The vacuum preloading method may not work well when the subsoil is inter-bedded with sand lenses or permeable layers that extend beyond the boundary of the area to be improved, such as the improvement of soft soil below sand fill for reclaimed land. In this case, a cut-off wall is required to be installed around the boundary of the entire area to be treated. One example is given in Figure 5 by Tang and Shang (2000), in which a 120 cm wide and 4.5 m deep clay slurry wall was used as a cut-off wall in order to improve the soft clay below a silty sand layer.

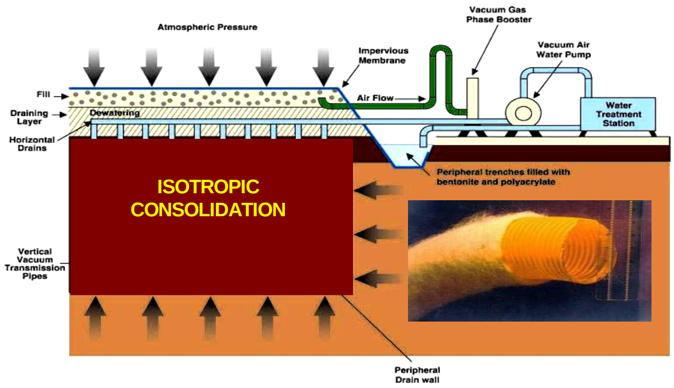


Figure 4 The Menard vacuum consolidation system (After Varaksin and Yee 2007)

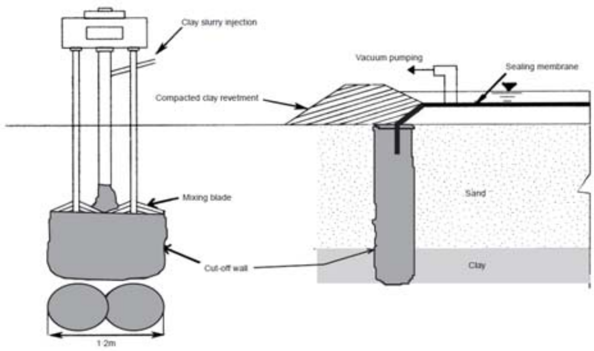
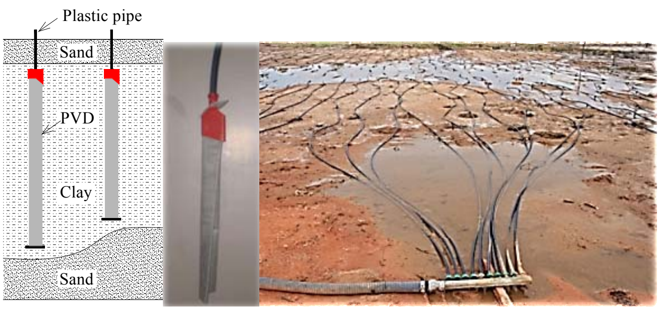


Figure 5 Use of cut-off wall for a vacuum preloading project (after Tang and Shang, 2000)

3.2 Membraneless System

However, installation of cut-off walls is expensive when the total area to be treated is large. One solution to this problem is to connect the vacuum channel directly to each individual drain. This so-called BeauDrain system has been developed in the Netherlands (Kolff et al. 2004). This method has evolved in the past few years and the one of the later version is shown in Figure 6. In this method, the top of each vertical drain is connected to a plastic pipe as shown in Figure 6(a) & 6(b). In this way, the channel from the top of the PVD to the vacuum line is sealed using the plastic pipe and thus go through a sand layer without causing leak in vacuum. A special connector as shown in Figure 6(b) is used for this purpose. The plastic pipes are connected directly with the vacuum line at the ground surface as shown in Figure 6(c).



(a) (b) (c)

Figure 6 BeauDrain vacuum preloading system (a) Concept; (b) Direct connection of PVD with plastic pipe for vacuum application; and (c) Connection of plastic pipes to a vacuum pump

Thus, a sand blanket and membranes as used in the conventional vacuum methods as shown in Figures. 3 and 4 are not required. This method has been used for the construction of the new Bangkok Suvarnabhum International Airport (Seah 2006; Saowapakpiboon et al. 2008) and other projects (Chai et al. 2008). One shortcoming of this method is that it is difficult to achieve a high vacuum pressure in soil. This could be caused by two factors. The first is the difficulty to ensure every drain is completely sealed. The second is the head loss in the sealed plastic pipe (see Figure 6(a)). This method also requires a more detailed soil profile as the length of each PVD has to be predetermined to match the depth of the clay layer at each PVD location. The production rate is also thus lower.

3.3 Low-level vacuum preloading system

Another method to do away with the membrane is to use the so-called low level vacuum preloading method (Yan and Cao 2005). This method is schematically illustrated in Figure 7. When clay slurry is used as fill for land reclamation, the vacuum pipes can be installed at the seabed or a level a few meters below the ground surface. In this way, clay slurry fill can be placed on top of the vacuum pipes. As clay has a low permeability, the fill material will provide a good sealing cap and membranes will not be required. However, this method is not problem-free. Tension cracks can develop on the surface when the top layer is dried. The vacuum pressure may not be distributed properly unless a drainage blanket is used at the level where the drainage pipes are installed or the individual drains are connected to the vacuum pipes directly. It is also difficult to install drainage pipes or panels underwater. Nevertheless, this method does not require the construction of inner dikes for subdivision and thus cuts down the project costs and duration substantially.

A similar approach has been adopted for a trial for undersea vacuum preloading in Holland (Karlsrud et al. 2007) where vacuum preloading was applied to consolidated seabed soft clay with a water depth of 15 m. The test confirms that vacuum consolidation can be an attractive means of improving soft seabed clays.

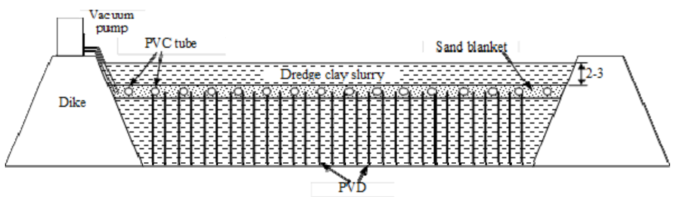


Figure 7 Low-level membraneless vacuum preloading method (After Chu et al. 2009)

3.4 Membrane System without sand blanket

Sand blanket is an important element of for vacuum preloading system with membrane. However, clean sand fill may not always be available or difficult to be placed. In this case, methods to connect PVDs directly to the vacuum pipes such as those shown in Figure 8 have been adopted so as to save the sand blanket. By connecting PVDs with vacuum pipes, the membranes can then be used without putting a layer of sand blanket. The method shown in Figure 8(a) may not work well all the time. The method to connect PVDs with the vacuum pipes through airtight connectors as shown in Figure 8(b) (Wang et al. 2016) can provide better performance. On the other hand, the requirements for the quality of PVDs will have to be more stringent. So far, there is no comparative study to compare the performance of the vacuum preloading method with sand blanket and that without sand blanket but with the methods shown in Figure 8 adopted. Further studies are required to establish a method that can offer the equal performance even without the use of sand blanket.

(a) (b)

Figure 8 Connecting PVDs directly to the vacuum pipes
(a) wrapping PVDs around vacuum pipes; (b) use of airtight connectors to connect PVDs with vacuum pipes
(after Wang et al. 2016)

3.5 Comparison of membrane and membraneless vacuum preloading system

The principal behind the membraneless system is the same as that for the membrane system. The membraneless system is particularly suitable to be used for sites with sandy soils overlaying the compressible soil layer. Furthermore, the boundary of vacuum preloading is no longer limited by the area of coverage of membranes. However, this method also has several disadvantages. For examples, it may be difficult to ensure every drain to work under the same vacuum pressure. The design vacuum pressure reported in the literature is mostly limited to 60 kPa. As there is no membrane and horizontal drainage blanket, the vacuum is only transmitted to the soil via vertical drains. Therefore, possible vertical consolidation may not take place. As a real case in Japan using the Beaudrain method, the measured vacuum pressure distribution versus depth is shown in Figure 9 (Chai et al. 2008). It can be seen that the measured vacuum pressure is nearly zero at the ground surface and at the tip of vertical drain which was next to the bottom impervious layer. The maximum vacuum pressure achieved was less than 60 kPa.

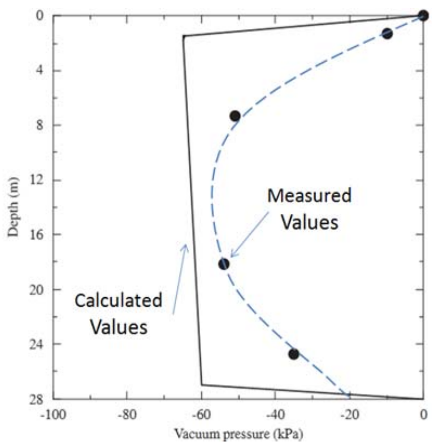


Figure 9 Vacuum pressure vs. depth using membraneless vacuum preloading method in Japan (modified after Chai et al. 2008)

3.6 Combined vacuum and fill surcharge preloading

One limitation of the vacuum preloading method is that the nominal vacuum pressure can only be 80 kPa. When higher surcharge is required, a combined vacuum and fill surcharge method can be adopted in which a fill surcharge can be applied after the soil has gained adequate strength under the vacuum load. One example is given in Figure 10 where 3.5 m of fill was placed after 80 kPa of vacuum pressure was applied for 1.5 months. The ground settlement versus time curve is also shown in Figure 10. For a detail description of the project, see Yan and Chu (2005).

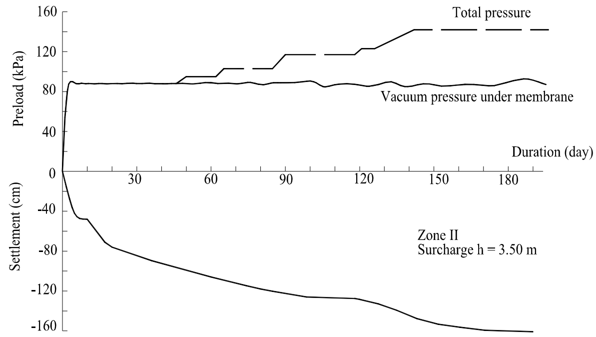


Figure 10 Combined vacuum and fill surcharge loading sequence and ground settlement for a soil improvement project
(after Yan and Chu 2005)

In this project, the pore water pressures at different depths were also measured and the pore water pressure distribution profiles are shown in Figure 11. It should be noted that with respect to the initial pore water pressure profile, there was an almost uniform reduction in the pore water pressure over the entire depth of 16 m at the end of consolidation. It is an indication that the well resistance was insignificant in this case. Within the first 30 days, there was a pore water pressure reduction of about 20 and 47 kPa at 3 and 16.5 m deep respectively. When the fill surcharge of about 60 kPa was applied at 45 days, the pore water pressure should have increased by 60 kPa. The pore water pressures measured at 60 days indicate a reduction of pore water pressure of 70 and 65 kPa at 3 and 16.5 m deep respectively. This is more than the pore water pressure reduction in the first 30 days! It implies that the consolidation under a combined load is more efficient than that under vacuum load alone. This could be partially attributed to the increase in hydraulic gradient after a positive increase in pore water pressure.

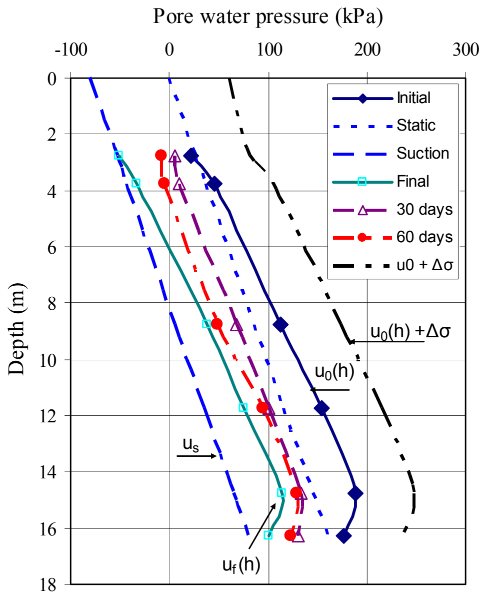


Figure 11 Pore water pressure distributions with depth at Section II
(after Yan and Chu 2005)

The combined vacuum and fill surcharge method offers several other advantages over either the vacuum or fill surcharge method alone. Firstly, it cuts down the construction time as the vacuum pressure can be applied relatively quickly and the subsequent fill surcharge can be applied much quicker too as the soil has been adequately consolidated under the vacuum load. Secondly, it provides a way to control the lateral displacement. Under vacuum pressure, an inward lateral displacement is created. On the other hand, under fill surcharge, the soil will move laterally outward. Lateral displacements are undesirable most of the time. If a loading program is designed properly, the vacuum and fill surcharge can be applied in a way to control the lateral displacement within a certain limit (Yan and Chu 2005). For this reason, this method is particularly suitable to be used when preloading has to be carried out near a retaining wall, an embankment or a dike. In situations such as the conditions shown in Figure 7, it also helps to reduce the construction cost as a smaller safety margin can be adopted for the dike. Thirdly, some laboratory tests have indicated that a combined vacuum and fill surcharge loading will be faster than the use of vacuum and fill alone (Liu et al. 2004). This is possible as vacuum creates an isotropic consolidation state and fill surcharge an anisotropic state. In theory, the soil will have a different stress-strain behavior when different stress paths are applied. This in fact helps to reduce some of the distortion deformation or settlement that would have incurred when working loads are applied to ground improved under vacuum preloading during the consolidation stage.

4. EFFECTIVE DEPTH OF VACUUM PRELOADING

Vacuum preloading is similar to dewatering using vacuum, as in both cases, water is pumped out from underground using a vacuum pump. As the maximum depth for dewatering 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. This is certainly not the case as the vacuum preloading method has been successfully used to treat soil of much deeper than 10 m in practice. This misconception is mainly due to a misunderstanding of the mechanism of vacuum preloading and the lack of explanation of the difference between dewatering and vacuum preloading in the literature. Dewatering 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 dewatering, that is, the maximum depth that water can be lifted using a vacuum pump.

4.1 Maximum depth for dewatering

Dewatering is a process to overcome the gravity of water to be lifted. For dewatering 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 Figure 12. The force equilibrium condition of a water column is shown in Figure 12. For an uplift pressure of p_a, equilibrium is reached when $\gamma_w h_w = p_a$, where γ_w is the unit weight of water. Therefore, the maximum depth cannot exceed $h_w = p_a / \gamma_w$.

Another way to examine the conditions that control dewatering is to analyse the total head difference between the ground level and the water level at the bottom. In Figure 12, 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/γ_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.

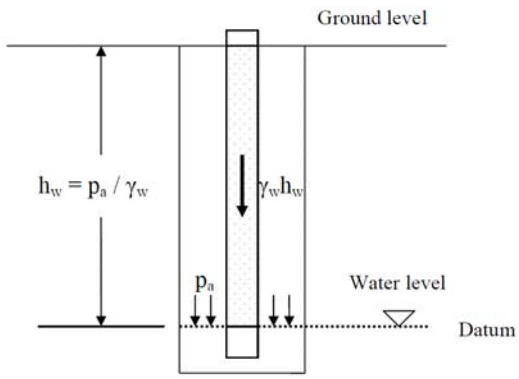


Figure 12 Force and total head analysis for the water column to be lifted by vacuum

4.2 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 Figure 2(a), the total head difference between the bottom and the ground level can be calculated as $\Delta h = \Delta u/\gamma_w$, where Δu 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 Figure 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 $-\Delta u/\gamma_w$. 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.

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 PVDs 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. 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.

5. PERFORMANCE EVALUATION

A soil improvement project using preloading is usually carried out until the required degree of consolidation is obtained. Assessment of the degree of consolidation of the soil therefore becomes one of the most important tasks for construction control. One of the most commonly adopted methods for assessing the degree of consolidation of soil is by means of field instrumentation using settlement or pore water pressure data. For this reason, field instrumentation is normally required to monitor settlements and pore water pressures at different elevations as well as ground water tables, lateral displacement, and earth pressure etc. Some of the commonly used instruments are described in Bo et al. (2003) and Arulrajah et al. (2009). Case studies and other instrumentation issues are discussed by many researchers (e.g., Bo et al. 2005, Indratnatna et al. 2005, Arulrajah et al. 2009). For projects using PVDs, in particular those use vacuum preloading, it is important to measure the pore water pressures at several depths in the soil to obtain a pore water distribution profile as shown in Figure 11 as this is the most effective way to visualize whether consolidation is progressing.

The degree of consolidation is normally calculated as the ratio of the current settlement to the ultimate settlement. However, for a soil improvement project, the ultimate settlement is unknown and has to be predicted. Although consolidation settlement can be estimated based on laboratory oedometer tests, the prediction by this method is normally not very reliable. Methods to estimate the ultimate settlement based on field settlement monitoring data are also proposed. Among them, the Asaoka's (1978) and hyperbolic (Sridharan and Rao 1981) methods are commonly used. Once the pore water pressures at different depths are measured during preloading, the initial and final pore water pressure distributions with depth can be plotted as shown in Figure 11 as an example. The typical pore water pressure distribution profiles for a combined vacuum and fill surcharge preloading case are shown schematically in Figure 13. Using Figure 13, the average degree of consolidation, U_{avg}, can be calculated as:

$$U_{avg} = 1 - \frac{\int [u_t(z) - u_s(z)]dz}{\int [u_0(z) - u_s(z)]dz} \tag{1}$$

and $u_s(z) = \gamma_w z - \sigma$, kPa

In Eq. 1, $u_0(z)$ = the initial pore water pressure at depth z; $u_t(z)$ = the pore water pressure at depth z at time t; $u_s(z)$ is the suction line, z = depth, γ_w = unit weight of water, and s = suction applied. The value of s is normally assumed to be 80 kPa. The integral in the numerator in Eq. 1 is the area between the curve $u_t(z)$ and the suction line $u_s(z)$, and the integral in the denominator the area between the curve $u_0(z)$ and the suction line $u_s(z)$.

As an example, the settlement and pore water pressure data presented in Figures 10 and 11 are used to estimate the degree of consolidation at the end of the preloading. Asaoka's method was applied to predict the ultimate settlements, S_∞, using the ground settlement data shown in Figure 10. The results are given in Table 1. Using the pore water pressure distribution profile shown in Figure 11 and Eq. (1), the average degree of consolidation was estimated and the value is given in Table 1. The degree of consolidation measured using the pore water pressure data is smaller than those by displacements. This is typical for the reasons explained by Chu and Yan (2005a; 2005b).

One concern of the method depicted in Figure 13 is that the random uncertainties in the pore water pressure measurements as the distance between the pore pressure transducers and the PVDs can affect the pore pressure distribution profile. This is true only when the depth of PVD is relatively short, say less than 5 m. This is because when a random variable varies over a long distance, the overall effect of the random variation over the entire distance reduced greatly due to a statistical property called spatial variance reduction (Vanmarcke 1977). This explains why the method illustrated in Eq. (1) has worked well for a number of projects (Chu et al. 2000; Chu and Yan 2005a; Yan and Chu 2005b; Chu et al. 2009).

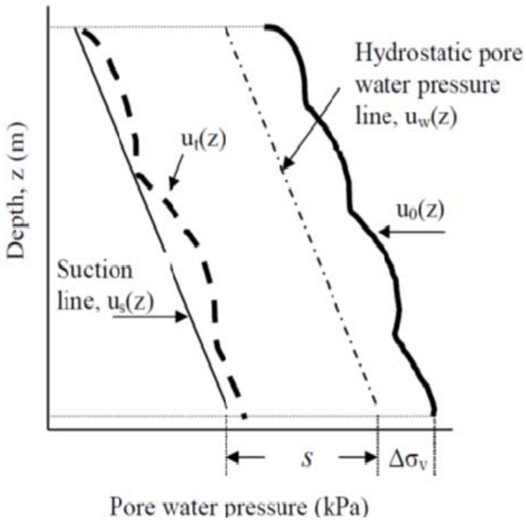


Figure 13 Schematic illustration of pore water pressure distributions versus depth under combined surcharge and vacuum load (After Chu and Yan 2005a)

Table 1 Ultimate settlement and Degree of consolidation estimated by different methods

Section	Asaoka's method		Based on Pore pressure
	S_∞ (m)	U_f (%)	U_f (%)
II	1.84	87	82

6. CONCLUSIONS

An overview and update on vacuum preloading methods and recent developments is presented in this paper. The main points discussed are summarized as follows:

(1) The vacuum preloading system normally requires membrane to be used to seal the soil to be consolidated, such as the China and Menard systems. Membraneless vacuum systems have also been developed. This includes the BeauDrain system in which each PVD is connected directly to the vacuum pump through plastic pipes and the low level vacuum preloading method.

(2) The combined vacuum and fill surcharge method offers several advantages over either the vacuum or fill surcharge method alone: (a) it cuts down the construction time, (b) it provides an effective way to control the lateral displacement, and (c) the rate of consolidation under a combined load may be faster than that under either vacuum and fill surcharge alone.

(3) Under vacuum load, the effective depth of vacuum preloading depends on the depth that the vacuum pressure can be distributed, which, in turn, depends on the well resistance of PVDs used to distribute vacuum and the screen resistance. Therefore, the quality of PVDs is important for vacuum preloading projects. With good quality of PVDs, the effective depth can be much more than 10 m.

(4) Monitoring of pore water pressure in soil is essential for vacuum preloading projects as the level of surcharge is dependent on the amount of pore pressure reduction in the soil. Using the pore water pressure versus depth distribution in the soil, the degree of consolidation can be calculated without calculating the ultimate consolidation settlement.

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