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Characteristics of vacuum consolidation
Caractéristique de la consolidation sous vides

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ABSTRACT

The characteristics of vacuum consolidation of soft clay soils are discussed. The results of laboratory odometer tests indicate that applying a vacuum pressure generally causes less settlement than applying a surcharge load of the same magnitude. It is demonstrated by both laboratory tests and theoretical analysis that in cases where the bottom of a soft clayey deposit is free draining, application of a vacuum pressure will cause less consolidation settlement than an equivalent surcharge load because of the drainage boundary effect. For this type of subsoil condition it is suggested that if vacuum consolidation is combined with the use of prefabricated vertical drains (PVDs) for ground improvement, the PVDs should not penetrate the entire clay layer. An equation for calculating the optimum penetration depth has been derived. In the field, vacuum consolidation causes inward lateral displacement while an embankment load will generally cause outward lateral displacement of the underlying soil. The combination of vacuum pressure with embankment loading can therefore substantially reduce preloading-induced lateral displacement of the subsoil. A full scale field test combining vacuum pressure with embankment load conducted at Bangkok, Thailand, and the corresponding analysis results are presented briefly to illustrate the effect of vacuum pressure loading on lateral displacements in the subsoil.

RESUME

Les caractéristiques de la consolidation des sols mous argileux sont discutées. Les résultats des essais de laboratoire oedométriques indiquent que l'application d'une dépression engendre généralement moins de tassement que l'application d'une surcharge de même amplitude. Il est démontré par les essais de laboratoire et des analyses théoriques que au cas où le fond d'une déposition molle argileuse soit de drainage libre, l'application d'une dépression va causer moins de tassement dû à la consolidation qu'une surcharge équivalente à cause des effets des conditions de drainage. Pour ce type de condition de multicouche il est suggéré que si la consolidation sous vides est combinée avec l'utilisation des drains verticaux préfabriqués (DVP) pour l'amélioration du terrain, les DVP ne doivent pas traverser l'ensemble de la couche argileuse. Une équation permettant de calculer la profondeur de pénétration optimale a été dérivée. En place, la consolidation sous vides provoque des déplacements latéraux vers l'intérieur alors qu'un remblai provoque en général des déplacements latéraux vers l'extérieur des sols de fondation. La combinaison de la dépression avec le chargement par remblai peut donc réduire de façon considérable le déplacement du sol du au pré-chargement. Un essai en vraie grandeur combinant la dépression avec le chargement par remblai a été effectué à Bangkok, Thaïlande, et les résultats d'analyse correspondant sont présenté brièvement pour illustrer l'effet du chargement par dépression sur les déplacements latéraux des sols de fondation.

1 INTRODUCTION

Vacuum consolidation is a well established method of ground treatment (e.g., Kjellman, 1952). It has advantages over embankment loading, e.g., no fill material is required, construction periods are generally shorter and there is no need for heavy machinery. In addition, the vacuum pressure method does not put any chemical admixtures into the ground and consequently it is an environmentally friendly ground improvement method. Although several field applications had been reported (e.g., Bergado et al., 1998;), some important questions relating to the technique have yet to be answered definitively. For example, issues such as whether the vacuum pressure can induce the same settlement as a surcharge load of the same magnitude, and the effect of drainage boundary conditions on vacuum consolidation, have not yet been fully addressed. Furthermore, vacuum consolidation is normally combined with other ground improvement measures such as the installation of prefabricated vertical drains (PVD), and in this case the optimum penetration depth of the PVDs needs to be identified.

In this paper, the characteristics of vacuum consolidation are discussed. Firstly, the results of laboratory odometer consolidation tests with both vacuum pressure and surcharge load are presented and compared. The effect of drainage boundary conditions on vacuum consolidation is investigated. Secondly, the response of soft ground in terms of the lateral displacements induced under vacuum pressure and embankment loading are compared and discussed. Finally, the results of a full scale field test embankment on soft Bangkok clay, combining vacuum pressure with embankment loading, are presented briefly to support the proposition that there are distinct advantages in combining the two techniques.

2 ODOMETER BEHAVIOR

A series of laboratory odometer tests were conducted under vacuum pressure and surcharge load in order to investigate the mechanism of vacuum consolidation. In the field, the achievable vacuum pressure is about 60 to 80 kPa, so the loading applied during these tests was 80 kPa for both surcharge load and vacuum pressure. The equipment used was a Maruto Multiple Odometer Apparatus. Each sample was 60 mm in diameter and typically 20 mm in thickness. The soil tested was reconstituted Ariake clay, which was pre-consolidated under a pressure of 30 kPa. The physical properties of the sample are listed in Table 1. For each test condition, two parallel tests were conducted to check for repeatability. It has been confirmed that the scatter was small.

For clarity, only one set of results is reported for each test presented here.

Table 1: Physical properties of the soil sample

Soil particles (%)			Unit weight γ_t (kN/m^3)	Water content W (%)	Liquid limit W_l (%)	Plasticity limit W_p (%)	Void ratio e_0
Clay (<5μm)	Silt	Sand					
31.0	67.8	1.2	13.9	97.1	116.6	57.5	2.32

2.1 *Comparison of results for vacuum and surcharge loading*

The settlement versus time curves for samples with one-way drainage are compared in Fig. 1 for the cases of vacuum loading and surcharge loading. It can be seen that the final settlement under vacuum pressure is about 80% of that under surcharge load, but the times to reach 50% of the final settlement are almost the same. Although the tests were conducted under odometer conditions, vacuum pressure tends to apply an isotropic consolidation pressure to the soil sample and consequently there was some horizontal straining of the sample. After the test when taking off the confining ring it was observed that the soil samples loaded by vacuum pressure had separated from the confining ring, which is a direct evidence of horizontal strain in the sample.

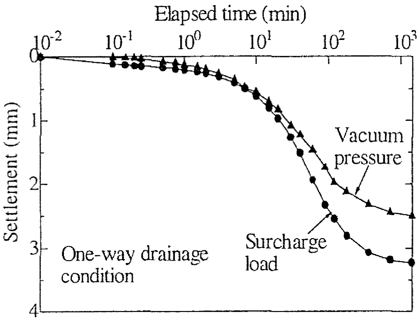


Figure 1. Comparison of the settlement-time curves

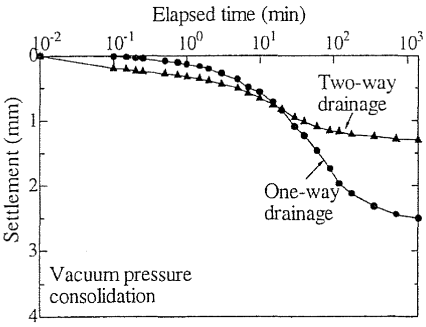


Figure 2. Drainage boundary condition effect of vacuum consolidation

From elasticity theory, the ratio between the vertical strain during 1D consolidation (ε_{v1D}) and the vertical strain during isotropic consolidation (ε_{viso}) is as follows:

$$\frac{\varepsilon_{viso}}{\varepsilon_{v1D}} = \frac{1-\mu}{1+\mu} \qquad (1)$$

where μ = Poisson's ratio. Assuming $\mu = 0.3$, implies that $\varepsilon_{Viso} / \varepsilon_{v1D} = 0.54$. However, the behavior of clay is certainly not perfectly elastic and vacuum consolidation does not induce ideal isotropic consolidation, so that Eq. (1) only provides a qualitative explanation for the difference between the outcomes of vacuum and surcharge load consolidation. It is noted that under ideal 1D conditions (no horizontal strain) a vacuum pressure will induce the same settlement as a surcharge load of the same magnitude. However, in the laboratory as in the field, under vacuum pressure a strict 1D condition can not be maintained and for this reason application of a vacuum pressure will induce less settlement than a surcharge load of the same magnitude.

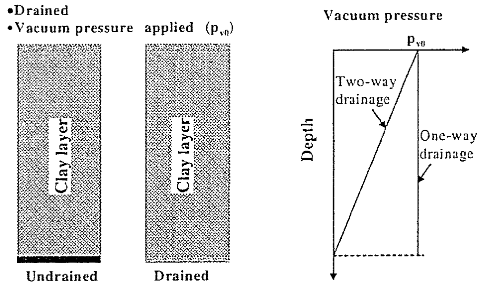
2.2 *Effect of drainage condition*

For one-dimensional (1D) consolidation problems there are normally two types of drainage boundary conditions, viz., one-way drainage and two-way drainage. In the case of an embankment load applied to the soil surface, the final settlement for these two drainage conditions may not differ much (theoretically they should be identical), but the settlement rate for two-way drainage will usually be much higher than that for one-way drainage. However, in the case of vacuum consolidation, these two drainage conditions should (theoretically) result in quite different final settlements but the same settlement rates.

Laboratory odometer tests were also conducted for the two-way drainage condition and the results are compared with those for one-way drainage in Fig. 2. Practical difficulties were experienced in conducting the test under two-way drainage conditions with only a vacuum pressure. Because of the tendency for isotropic consolidation a gap was induced between the soil sample and the confining ring, and consequently the vacuum pressure could not be effectively applied. The test results for two-way drainage shown in Fig. 2 were obtained by combining 20 kPa surcharge load with 60 kPa vacuum pressures, giving a total consolidation pressure of 80 kPa. It can be seen that the total settlement in the case of two-way drainage is about half the settlement under one-way drainage. Under vacuum pressure, theoretically, the rate of consolidation for one-way drainage and two-way drainage should be the same (will be explained in following section). However, in Fig. 2, the time to reach 50% of total settlement for two-way drainage is short then that of one-way drainage. It is considered that the rate under 20 kPa surcharge is higher and also even with applying 20 kPa surcharge load, with the progress of consolidation, possibly there was gap between soil sample and the confining ring occurred and reduced the effect of vacuum pressure (the total settlement is less than theoretical value). The effect of drainage boundary on vacuum consolidation can be explained as follows.

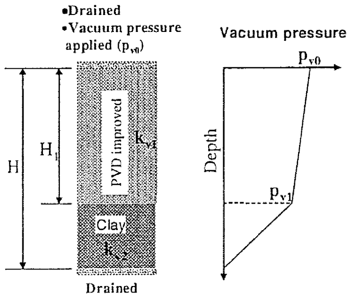
As shown in Fig. 3, a vacuum pressure (suction) is applied at the top surface of the clay layer while drainage is still possible from the same top boundary. For a given amount of vacuum pressure, the final vacuum pressure distribution in the clay layer will be uniform for the case of one-way drainage, as illustrated in Figs. 3(a) and 3(c). However, in the case of two-way drainage (Fig. 3(b)), at the bottom of the clay layer the excess pore pressure is fixed at zero and effectively no vacuum pressure can be applied at this boundary. For a uniform layer with two-way drainage, the vacuum pressure distribution at steady state will be linear with the maximum value at the surface and zero at the bottom (Fig. 3 (c)). In this case, Darcy's law implies that the steady state condition will involve uniform upward water flow through the clay layer. It is obvious therefore that vacuum consolidation involving two-way drainage should result in less settlement than one-way drainage. With regard to the degree of consolidation, it is well known that theoretically for similar drainage conditions the degree of consolidation for both rectangular and triangular initial excess pore pressure distributions is the same. In the case of vacuum consolidation, for both one-way and two-way drainage conditions, actually, water can only be drained out from the top surface and the drainage length is the same.

The above argument is made on the assumption that the clayey deposit is uniform. In an actual case, the deposit may not be uniform. Under these circumstances the final vacuum pressure distribution within a deposit with two-way drainage may not be a straight line and, indeed, its shape will depend on the relative values of the hydraulic conductivities of the individual layers. For steady upward water flow in a layered deposit the following conditions must be satisfied in order to maintain the continuity of the flow:



(a) One-way drainage soil profile (b) Two-way drainage soil profile (c) Vacuum pressure distribution

Figure 3. Vacuum pressure distribution within the ground



(a) Soil profile (b) Vacuum pressure distribution

Figure 4. Illustration of vacuum consolidation with PVD improvement

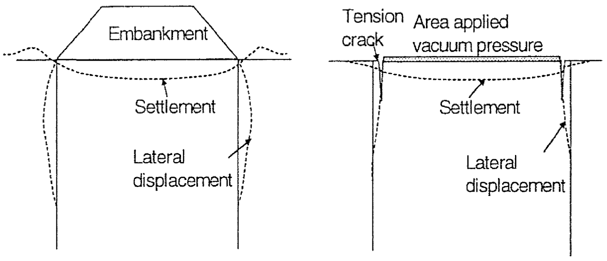


Figure 5. Lateral deformation of subsoil

$$i_1 k_{v1} = i_2 k_{v2} = \cdots = i_i k_{vi} \tag{2}$$

where i_i and k_{vi} = the hydraulic gradient and hydraulic conductivity of the ith layer, respectively. As can be seen from Eq. (2), a layer with a lower hydraulic conductivity must have a higher hydraulic gradient to maintain continuity of the flow.

In most field applications of vacuum consolidation, the subsoil drainage is improved by installation of prefabricated vertical drains (PVDs). For cases where the clay is underlain by a sand layer, the PVDs should only partially penetrate the clayey layer to avoid the two-way drainage condition. The remaining, unpenetrated portion of the clay layer serves as a semi-impermeable barrier (Fig. 4). The possible long-term vacuum pressure distribution within the layers is also illustrated in Fig. 4. Determination of the optimum penetration depth of the PVDs is an important practical question. In this case the optimum penetration depth means the depth at which the clay layer will exhibit the largest consolidation settlement under a given surface vacuum pressure. It is relatively easy to demonstrate that the optimum depth H_1 is as follows:

$$H_1 = \left(\frac{k_{v1} - \sqrt{k_{v1} k_{v2}}}{k_{v1} - k_{v2}} \right) H \tag{3}$$

where k_{v1} and k_{v2} = the vertical hydraulic conductivities of layers 1 and 2, respectively, and H = the thickness of the soft clayey deposit. Chai *et al.* (2001) proposed a method to calculate the equivalent vertical hydraulic conductivity of PVD-improved subsoil, which can be used to evaluate the value of k_{v1}, i.e., the mass vertical hydraulic conductivity of the PVD improved zone:

$$k_{v1} = \left(1 + \frac{2.5 l^2}{\mu D_e^2} \frac{k_h}{k_v} \right) k_v \tag{4}$$

$$\mu = \ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s} \ln(s) - \frac{3}{4} + \pi \frac{2 l^2 k_h}{3 q_w} \tag{5}$$

where D_e = the diameter of unit cell (containing a PVD and its improvement area), $n = D_e/d_w$ (d_w is the diameter of the drain), $s = d_s/d_w$ (d_s is the diameter of smear zone), k_h and k_s = the horizontal hydraulic conductivities of the natural soil and the smear zone, respectively, k_v = the vertical hydraulic conductivity of the natural soil, l (= H_1) = the drainage length of the PVDs, and q_w = the discharge capacity of the PVDs.

3 FIELD BEHAVIOR

3.1 *Lateral displacement*

Embankment loading will not only cause settlement of the soft subsoil but also generally outward lateral displacement (Fig. 5(a)). This lateral displacement is mainly caused by the shear stresses induced by the embankment load, and if these shear stresses are big enough they will cause shear failure within the subsoil. By contrast, the vacuum pressure technique tends to apply an isotropic consolidation pressure to soft subsoil. The isotropic consolidation will induce settlement and inward lateral displacement (Fig. 5(b)). This kind of inward deformation may cause some surface cracks around the improvement area, but normally there is no possibility of general shear failure.

3.2 *Advantage of combining vacuum pressure with embankment load*

In situations where existing structures are adjacent to the preloading area, both outward lateral movement of the treated area induced by embankment loading and inward lateral deformation induced by vacuum pressure are undesirable. In order to avoid or minimize lateral deformations during the preloading period, it is possible to combine embankment loading with application of a vacuum pressure. Assuming plane strain loading conditions and equating the outward lateral deformation due to embankment loading with the inward lateral deformation due to vacuum pressure, the following equation can be obtained from elasticity theory:

$$\Delta\sigma_{fill} = \left(\frac{1 - 2\mu}{\mu} \right) \Delta\sigma_{vac} \tag{6}$$

where $\Delta\sigma_{fill}$ = the vertical stress increment due to embankment fill, and $\Delta\sigma_{vac}$ = the isotropic stress increment due to the vacuum pressure. In the field, the response of the ground is not elastic and vacuum consolidation is not an idea isotropic consolidation, and therefore Eq. (6) only provides a rough estimate of the ratio between embankment load and vacuum pressure to minimize lateral subsoil displacement for applications which combine the use of the vacuum pressure technique with embankment preloading.

3.3 *A field trial of combining vacuum pressure with embankment load*

Two full scale test embankments combining vacuum pressure with embankment loads were constructed on soft Bangkok clay (Bergado et al., 1998). Results for one of the test embankments and predictions of plane strain finite element (FEM) analysis are briefly presented here to demonstrate the benefit of combining vacuum pressure with an embankment load.

The test embankment had a base area of 40 m by 40 m and top area of 16 m by 16 m with a height of 2.5 m. Prefabricated vertical drains (PVDs) were installed to 12 m depth from the ground surface in a triangular pattern with a spacing of 1.0 m. The thickness of the soft soil layer is about 15.0 m (Bergado et al., 1998).

Figure 6 compares measured and predicted surface settlements on the embankment centerline together with the history of the vacuum pressure application and embankment fill construction. The analysis simulated the field data well. Also, the results of FEM analysis show that the vacuum pressure increased the surface settlement significantly. Figure 7 depicts the lateral displacement profiles of the ground at the end of the embankment construction. In this case, the analysis predicts a smaller value than the measurement. The results of FEM analysis indicate that if no vacuum pressure is applied but 2.5 m of fill is constructed, the maximum lateral displacement can be more than 100 mm. By combining vacuum pressure with the fill load, the lateral displacement is reduced to about 20 mm.

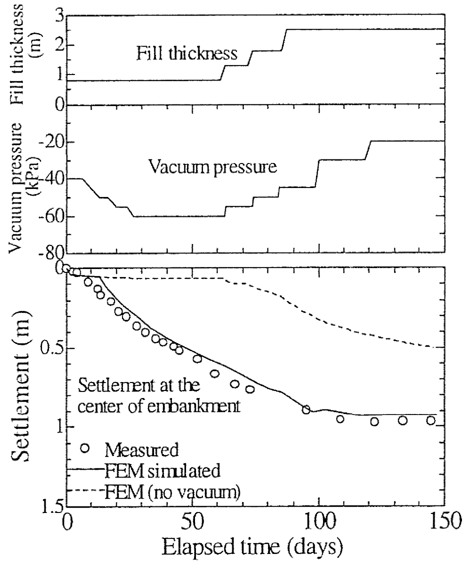


Figure 6. Surface settlement with construction history

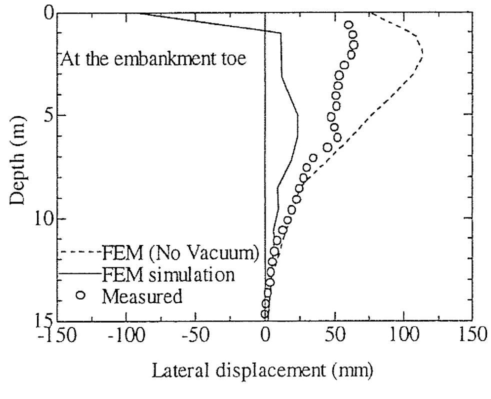


Figure 7. Comparison of the lateral displacement at the embankment toe

As indicated in Fig. 6, after placing the embankment fill, vacuum pressure was gradually reduced. It was possibly due to air leakage through defects in the "air tight" sheeting. Without embankment fill over the sheeting, leaks can be more easily detected and repaired. For the case of an embankment placed on top of the sheeting, it is difficult to detect and repair any defects in the sheeting. One of the methods to avoid this problem is combining vacuum pressure with use of capped prefabricated vertical drains (C-PVD), as described by Chai *et al.* (2003). Using C-PVD, there is no need to use an air sealing sheet. The vacuum pressure is applied to each C-PVD through a drainage (air and/or water) hose.

4 CONCLUSIONS

Some important characteristics of vacuum consolidation have been discussed using laboratory odometer test results, analysis and field data.

(1) Laboratory odometer test results indicate that vacuum pressure intends to apply an isotropic consolidation condition to the soil sample and results in less settlement than an equivalent surcharge load. For the conditions tested, the settlement caused by vacuum pressure is about 80% of that induced by the corresponding surcharge load.

(2) The drainage boundary conditions have a significant effect on vacuum consolidation. In cases of two-way drainage, vacuum pressure treatment will generally cause less consolidation settlement of the clay than an equivalent embankment load. For this kind of subsoil condition, if vacuum consolidation is combined with the use of prefabricated vertical drains (PVDs), the PVDs should not penetrate the entire clay layer. An equation for calculating the optimum penetration depth has been presented.

(3) In the field, vacuum consolidation will induce inward lateral displacement of the subsoil while embankment loading will generally induce outward lateral displacement. It is possible to reduce or minimize the lateral displacement of subsoil by combining vacuum pressure with an embankment load. The results of a field trial in Bangkok, Thailand, support this argument.

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REFERENCES

Bergado, D. T., Chai, J.-C., Miura, N. and Balasubramaniam, A. S. 1998. PVD improvement of soft Bangkok clay with combined vacuum and reduced sand embankmentpreloading. *Geotechnical Engineering*, Southeast Asian Geotechnical Society, 29(1), 95-121.

Chai, J.-C., Shen, S.-L., Miura, N. and Bergado, D. T. 2001. Simple method of modeling PVD improved subsoil. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(11), 965-972.

Chai, J.-C., Miura, N., Nomura, T. and Yoneya, H. 2003. Vacuum consolidation of soft clayey subsoil using cap-drain. *Proceedings of 18th Geosynthetics Symposium*, Japan Branch, International Geosynthetics Society, 18, 231-236 (in Japanese).

Kjellman, W. 1952. Consolidation of clayey soils by atmospheric pressure. *Proceedings of a Conference on Soil Stabilization*, Massachusetts Institute of Technology, USA, 258-263.

Tang, M. and Shang, J. Q. 2000. Vacuum preloading consolidation of Yaoqing airport runway. *Geotechnique*, 50(6): 613-623.