Deformation calculation of under-consolidated deposit induced by vacuum consolidation

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ABSTRACT: A method for calculating the consolidation deformation of under-consolidated deposits induced by vacuum pressure-caped prefabricated geosynthetics vertical drain (CPVD) method has been proposed and applied to a case history in Tokyo Bay, Japan. The method combines Terzaghi's one-dimensional (1D) consolidation theory and Hansbo's solution for vertical drain consolidation with the deformation analysis method for vacuum consolidation. Comparing the measured and the analysis results of the case history shows that the method simulated the field behavior reasonably well.

1 INTRODUCTION

A method of conducting vacuum consolidation without an air-tightening sheet at ground surface was developed (Chat et al. 2008), which uses a surface or/subsurface clayey soil layer as a sealing layer and applies vacuum pressure to each caped prefabricated geosynthetics vertical drain (CPVD) (vacuum pressure-drain method). The method is especially suitable for the case of consolidating a soft clayey deposit below sea level, such as the case in Tokyo Bay, Japan (Miyakoshi et al. 2007a, b).

Vacuum consolidation for reclaimed deposit often encounters the situation that the deposit is in an under-consolidated state. In this case, there is no well established method for calculating the ground deformation. Even the finite element method has a difficulty to simulate the correct initial effective stress in the ground. In this paper, a method has been proposed to calculate the settlement and lateral displacement of under-consolidated deposits induced by vacuum pressure-drain method and applied to the case history in Tokyo Bay, Japan.

2 CALCULATION METHODS

The proposed method combines Terzaghi's one-dimensional (1D) consolidation theory and Hansbo's (1981) solution for vertical drain consolidation with the deformation analysis method proposed by Chai et al. (2005) for vacuum consolidation.

2.1 Degree of consolidation

As illustrated in Fig. 1, the sealing layer with a thickness of H_1 and the bottom layer without CPVD (H_3) are mainly consolidated due to vertical drainage, and the middle layer (H_2) with CPVD is mainly consolidated by radial drainage of CPVD. It is proposed that the vertical drainage can be calculated by Terzaghi's one-dimensional (1D) consolidation theory under one-way drainage condition and the radial drainage can be evaluated by Hansbo's (1981) solution.

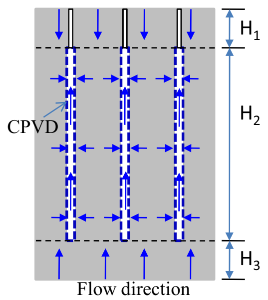


Figure 1 Drainage condition of vacuum pressure-CPVD method

2.2 Deformation calculation

For the settlement and the lateral displacement at the end of vacuum consolidation, the method proposed by Chai et al. (2005) is adopted. With the degree of consolidation and the settlement at the end of the vacuum consolidation are known, the settlement curve can be predicted. However, for estimating the initial effective stress in the ground, the factor of the deposit is in an under-consolidation state has to be considered, and the part of un-consolidated self-weight needs to be considered as part of load.

In both Terzaghi and Hansbo's solutions, the degree of consolidation is defined by the excess pore water pressure. For a clayey deposit, since the relationship between settlement and effective stress increment is logarithm, when the degree of consolidation (U) and therefore the effective stress increment ($\Delta\sigma'_v$) is known, the corresponding settlement (S) can be calculated by the following equation.

$$S = S_e \frac{\ln\left(1 + U \cdot \Delta\sigma'_{ve} /(U_e \sigma'_{vo})\right)}{\ln\left(1 + \Delta\sigma'_{ve} / \sigma'_{vo}\right)} \quad (1)$$

where S_e = settlement, U_e = degree of consolidation, and $\Delta\sigma'_{ve}$ = vertical effective stress increment at the end of consolidation respectively, and σ'_{vo} = initial effective vertical stress.

3 ANALYSIS OF A CASE HISTORY

3.1 *Brief description of the case history*

Two test sections were conducted with vacuum pressure-drain method in Tokyo Bay (Miyakoshi et al., 2007a, b). Section-A had an area of 60 m × 60 m and Section-B of 61.2 m× 61.2 m and the two sections were almost jointed together. The soil profile consists of a reclaimed clayey silt layer with a thickness of about 12 m at the surface. Below it is a thick clayey deposit of about 29 m underlain a sand layer. The most reclamation was made from 2003 to 2005 with a rate of about 3.5 m/year. The total unit weight (γ_t), compression index (C_c) and maximum consolidation pressure (p_c) before installing CPVD are shown in Fig. 2. It can be seen that the reclaimed layer was in a state of close to normally consolidated but the original clayey deposit was in an under-consolidated state. In the original deposit, the clay (grain size less than 5 µm) content was more than 50% and for the reclaimed layer, the sum of sand and silt contents was slightly more than 50%.

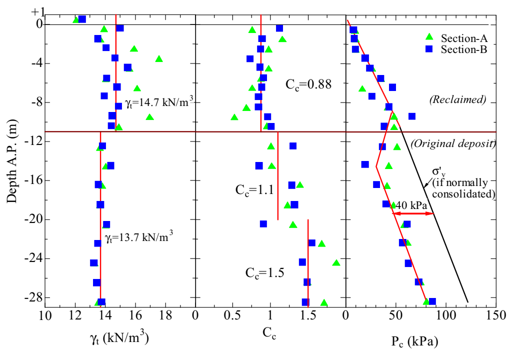


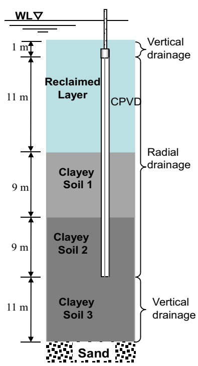
Figure 2 γ_t, C_c and P_c of the deposit (Measured data from Miyakoshi et al., 2007a)

Takeya et al. (2007) reported that for both the original clayey soil deposit and the reclaimed layer, the coefficient of consolidation (C_v) was about 0.012 m^2/day. However, from the information of grain size distribution and P_c values in Fig 2, it can be argued that the reclaimed layer might have a higher C_v value. In the analysis, it was assumed that C_v value for the reclaimed layer is twice of the value of the original clayey deposit.

CPVDs used at this site had a cross-section of 150 mm by 3 mm. At Section-A, CPVDs had a spacing of 2.0 m and 1.8 m for Section-B with a square pattern. For both the sections, CPVDs were installed to 30 m depth from the ground surface, and the sealing surface clayey soil layer had a thickness of about 1.0 m. The field installation started at the beginning of January 2006 in Section-A, and at the beginning of February 2006 in Section-B, and for the both sections, the durations of installation were about one month. The durations of after CPVD installation and before application of vacuum pressure were 5 and 4 months for Section-A and B respectively. Considering the half period of the installation as consolidation time, the partial self-weight consolidation periods before vacuum pressure application were about 165 and 135 days for Section-A and B respectively. From June 30, 2006, vacuum pressure of 80 – 90 kPa at the vacuum pump location was applied and lasted for 204 days. Surface and subsurface settlement gages, excess pore water pressure (vacuum) gages at the vacuum pump and at the ends of CPVDs, as well as inclinometer casings were installed to monitor the ground response.

3.2 *Analysis model and soil parameters*

The analysis model and soil parameters for each layer are shown in Fig. 3. The values of the initial void ratio (e_o) shown in Fig. 3 were calculated from the total unit weights (γ_t) by assuming the soil was 100% saturated and the density (ρ_s) of the soil particles was 26.5 kN/m^3. The parameters related to



γ_t (kN/m³)	C_c	C_v (m²/day)	e_o
14.7	0.88	0.024	2.41
14.7	0.88	0.024	2.41
13.7	1.1	0.012	3.28
13.7	1.5	0.012	3.28
13.7	1.5	0.012	3.28

For all layers, $C_h = 2C_v$

Figure 3 Consolidation analysis model

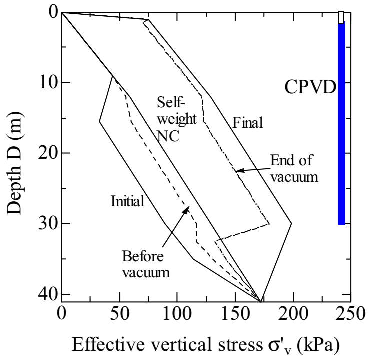


Figure 4 Effective vertical stress distribution at different stages for Section-A

CPVD consolidation are: diameter of drain, d_w = 75 mm; diameter of smear zone, d_s = 0.3 m; discharge capacity, q_w = 1.37 m^3/day; and the ratio, k_h/k_s = 2 (k_h and k_s are horizontal hydraulic conductivities of the natural ground and the smear zone, respectively). The value of q_w was assumed, and the value of k_h/k_s was back fitted to result partial self-weight induced settlement before vacuum pressure application close to the measured value for Section-A.

3.3 *Degrees of consolidation*

The ground deformation can be divided into 2 periods, i.e. Period-1, after CPVDs installation and before vacuum pressure application; and Period-2, during the vacuum consolidation. The analyses were also divided into these two-parts, i.e. for calculating the degree of consolidation during vacuum consolidation, the time origin was the start of the vacuum pressure which corresponding to zero degree of consolidation.

For CPVD improved zone, different C_h values were used for different layer, but the drainage length of CPVD was assumed as 29 m. It means that, for example, when calculating the degree of consolidation for Reclaimed Layer by Hansbo's solution, it was assumed that there is a layer with the properties of Reclaimed Layer and has a thickness of 29 m. The calculated degrees of consolidation are listed in Table 1.

3.4 *Settlement and lateral displacement*

Based on the measured data (Miyakoshi et al. 2007a), it was assumed that the final vacuum pressure at the cap location of CPVD (1.0 m below the ground surface) was 70 kPa and the values of vacuum pressure at the end of CPVDs was 69.3 kPa. Then with the initial effective vertical stresses (σ'_{vo}), which are equal to the P_c values in Fig. 2, and the degrees of consolidation in Table 1, the effective vertical stresses in the ground corresponding to different

Table 1. Calculated degrees of consolidation

Soil layer	Thickness (m)	Degree of consolidation, U (%)			
		After CPVD - before vacuum		Vacuum consolidation	
		A	B	A	B
Period (days)		165	135	204	204
Sealing layer	1	-	-	100	100
Reclaimed	11	84.8	85.6	90.4	94.7
Clayey soil 1	9	68.9	70	76.6	83.9
Clayey soil 2	9	68.9	70	76.6	83.9
Clayey soil 3	11	17.8	15.7	20.3	20.3

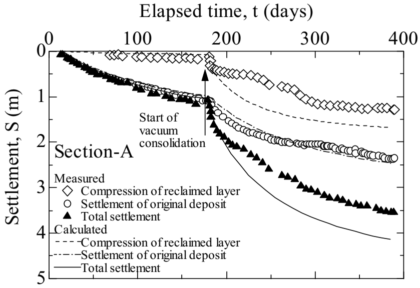
stages were calculated and for Section A, the results are depicted in Fig. 4.

Although there was lateral displacement after CPVD installation and before the vacuum pressure application, it was assumed that the consolidation induced by self-weight was 1D and only the settlement was calculated. To calculate the partial self-weight induced settlement-time curves before vacuum consolidations using Eq. (1), for Section-A, the initial stress (σ'_{vo}) is the line marked with "initial", and the stress increment at the end of the consolidation ($\Delta\sigma'_{ve}$) is the difference between the lines of "initial" and "before vacuum" in Fig. 4.

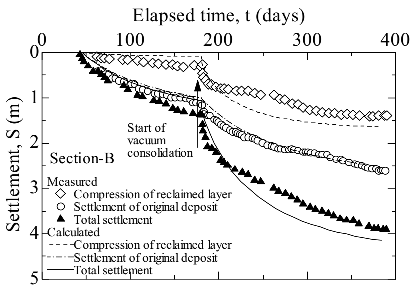
During vacuum consolidation, both settlement and lateral displacement were calculated. In this case, for Section-A, the initial stress (σ'_{vo}) is the line marked with "before vacuum", and the stress increment at the end of the consolidation ($\Delta\sigma'_{ve}$) is the difference between the lines of "before vacuum" and "end of vacuum" in Fig. 4. For calculating the lateral displacement, there is difference on assuming triaxial or plane strain deformation patterns in the ground (Chai et al. 2005). For the case considered, the improved area of each section was a square and close to triaxial state, but two sections were jointed together, and there was certain plane strain effect. In the analysis, it was assumed that the deformations are average values of triaxial and plane strain assumptions. The parameters used are: effective stress internal friction angle (ϕ') of 30°, cohesion (c') of 5 kPa, parameter for calculating earth pressure coefficient, β of 1.0, half width of the improved area B of 30 m for Section A and 30.6 m for Section B, and minimum settlement ratio, $\alpha_{\min}$ of 0.8 for triaxial and 0.85 for plane strain assumptions respectively (Chai et al. 2005).

The results are compared in Figs 5(a) and (b) for Section-A and B respectively. The calculation simulated the amount of compression of the original clayey deposit well for both sections, but over-estimated the compression of the reclaimed layer, especially for Section-A, and therefore the ground settlement. It is considered that the main reason may be the over-estimation of applied vacuum pressure in the layer near the ground surface. The vacuum pressure from the vacuum pump was only applied to the cap location of each CPVD, but in the analysis, it was assumed that the same value is applied everywhere at that depth.

For the lateral displacement at the edge of the improved area, only the values at the end of the vacuum consolidation were calculated and depicted in Fig. 6. The calculation yielded a reasonable simulation for the reclaimed layer which was in a close to normally consolidated state before the vacuum consolidation, but under-predicted the value of the original deposit which was in an under-consolidated



(a) Section-A



(b) Section-B

Figure 5 Settlement versus elapsed time curves (Measured data from Miyakoshi et al. 2007a)

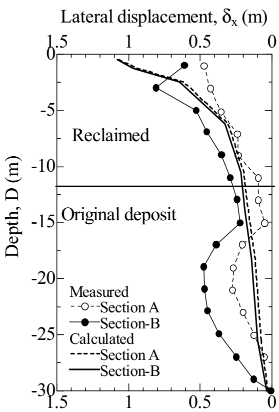


Figure 6 Comparison of lateral displacement (Measured data from Miyakoshi et al. 2007b)

state. Chai et al. (2008) reported the same tendency for a site in Yamaguchi, Japan, and suggested that the α_{min} value suggested by Chai et al. (2005) may be only applicable for a normally consolidated deposit, and for an under-consolidated deposit, a smaller α_{min} value may be used.

4 CONCLUSIONS

A method for calculating consolidation deformation of under-consolidated deposits induced by vacuum pressure-drain method has been proposed, and applied to a case history in Tokyo Bay, Japan.

Comparing the calculated values with the measurements indicates:

(a) The method simulated the settlement-time curves reasonably well.

(b) The calculated lateral displacement is less than the measured values for under-consolidated layer. A key parameter (α_{min}) estimated for normally consolidated deposit seems not applicable for under-consolidated case and further study is needed on this aspect.

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