Evaluation of Vertical Drain-enhanced Radial Consolidation with Modified Analytical Solution

Évaluation de la consolidation radiale améliorée par des drains verticaux par une solution analytique modifiée

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ABSTRACT: The installation of vertical drains accelerates the consolidation process by reducing the drainage path and predominating horizontal flow within the soft deposits. However, the radial consolidation of the vertical drain installed into the soft ground is governed by the permeability of a smear zone. Modification of Hansbo's analysis is proposed to analyze the degree of consolidation on a horizontal plane by considering the properties of the soil within the smear zone in this study. A parametric study is carried out to investigate the effects of the soil properties on the proposed analysis. The proposed equation is observed to be relatively insensitive to the uncertainty of the horizontal permeability ratio between the undisturbed and smear zones. The validity of the proposed analysis is examined by comparison with the settlement data from a field measurement. It is revealed that the proposed analysis provides a reliable prediction on the consolidation rate of soft ground installed PVD.

RÉSUMÉ : L'installation de drains verticaux accélère le processus de consolidation en réduisant les chemins de drainage et d'écoulements horizontaux prédominant dans les dépôts mous. Toutefois, la perméabilité de la zone d'influence détermine le degré de la consolidation radiale induite par les drains verticaux installés dans les sols mous. Une modification de l'analyse de Hansbo est proposée dans cette étude pour analyser le degré de consolidation dans un plan horizontal en considérant les propriétés du sol dans la zone d'influence. Une étude paramétrique est notamment menée pour étudier les effets des propriétés du sol sur l'analyse proposée. L'observation montre que l'équation proposée est relativement insensible à l'incertitude du rapport entre perméabilités horizontales entre les zones non perturbées et les zones d'influence. La validité de l'analyse proposée est examinée par comparaison avec les données de tassement d'une mesure sur site. Il s'est révélé que l'analyse proposée fournit une prévision fiable sur le taux de consolidation des drains verticaux installés dans les sols mous.

KEYWORDS: Permeability, Radial consolidation, Smear zone, Vertical drain

1 INTRODUCTION

The radial consolidation flow into the vertical drain induces a reduction in the flow channel and an increase in flow rate approaching the drain. It causes that the hydraulic head is dramatically decreased as the distance to the drain decreases. Therefore, the permeability of drain and soil near the drain control the rate of consolidation by the vertical drain. Since the permeability of drain is generally designed to be larger enough than that of soil, it is known that the well resistance is negligible if the discharge capacity exceeds the required discharge capacity (Holtz et al. 1987, Lo 1991). On the other hand, the installation of vertical drains induces a soil disturbance in the vicinity of the mandrel. The disturbed zone, called smear zone, is an area where has reduced permeability and increased compressibility comparing with an undisturbed soil. Reduced permeability in the disturbed zone governs the rate of consolidation, because the hydraulic head loss in soil near the drain further increases when the permeability decreases.

Many researchers insisted that the soil adjacent to the drain is remolded, and several researches were investigated the smear effect by obtaining the permeability of the distrubed zone from the permeability of remolded clay (Tavenas et al. 1983, Bergado et al. 1991, Hird and Moseley 2000, Sathananthan and Indraratna 2006). In this study, modification of Hansbo's solution is proposed to evaluate the degree of radial consolidation, considering the consolidation characteristics of remolded clay. Characterisitcs of the modified solution are discussed, in comparison with Hansbo's solution. And the consolidation settlement predicted by the modified solution is comprared with measured settlement data in the field.

2 MODIFIED ANALYTICAL SOLUTION

Hansbo's (1981) solution has been widely used to evaluate the consolidation behavior with vertical drain. It is simple and accurate as compared with other rigorous solutions and numerical analysis (Onoue 1988, Lo 1991). According to Hansbo (1981), the average degree of radial consolidation ($\overline{U}_r$) by vertical drain is

$$\overline{U}_r = 1 - \exp(-8T_h / \mu_s) \quad (1)$$

where, $\mu_s = \ln(d_e/d_w)+(k_h/k_s-1)\ln(d_s/d_w)+\pi \cdot z(2L-z)(k_h/q_w)-0.75$, T_h is a time factor ($= c_h \cdot t/d_e^2$), c_h is the coefficient of horizontal consolidation in the field, d_e is the circular diameter influenced by the drain, d_w is the drain diameter, k_h is the coefficient of horizontal permeability in the undisturbed zone, k_s is the coefficient of horizontal permeability in the disturbed zone, d_s is the disturbed zone diameter, L is the drainage path length, and q_w is the drain discharge capacity.

Hansbo's analysis is based on the horizontal flow characteristics of the undisturbed zone (k_h or c_h) to evaluate the radial consolidation. However, it is difficult to obtain due to the anisotropy of permeability and difference between laboratory and field measurement values (Bergardo et al. 1991, Chai and Miura 1999).

The consolidation characteristics of the disturbed zone are homogeneous and isotropic due to the disturbance (Lo 1991). To analyze the radial consolidation based on the consolidation characteristics of disturbed zone, Hansbo's solution is modified in this study. Since Hansbo's solution assumes an equal vertical strain, the ratio of horizontal permeability between the undisturbed and disturbed zones (k_h/k_s).

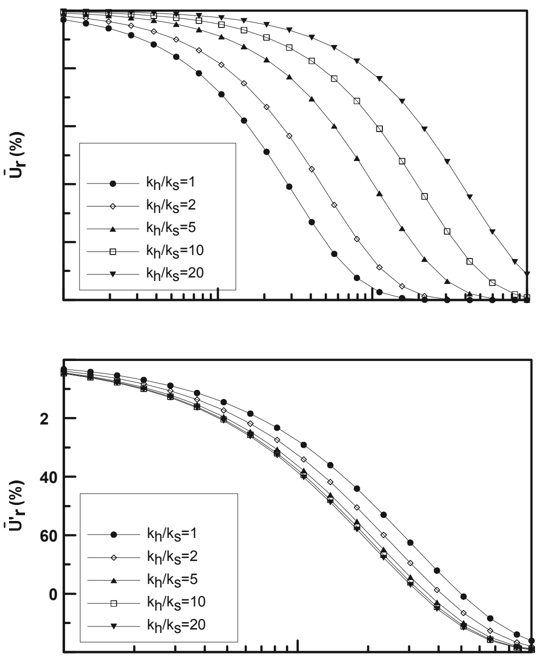

Figure 1. Effect of k_h/k_s on the degree of consolidation: (a) Hansbo's method, (b) Proposed method

is the same as the consolidation coefficients ratio between the undisturbed and disturbed zones (c_h/c_{hs}). By using this condition, rearranged the average degree of radial consolidation ($\overline{U'}_r$) is

$$\overline{U'}_r = 1 - \exp(-8T_{hs} / \mu'_s) \qquad (2)$$

where, $\mu'_s = \ln(d_s/d_w)+[\ln(d_e/d_s)+\pi \cdot z(2L-z)(k_h/q_w)-0.75]/(k_h/k_s)$, T_{hs} is a time factor based on c_{hs}.

The permeability reduction in the disturbed zone, frequently represented as k_h/k_s, is important factor for the vertical drain-enhanced consolidation. The effect of k_h/k_s on the analysis results is investigated both Hansbo's solution and modified solution. Figure 1 shows the effect of k_h/k_s on $\overline{U}_r - T_h$ and $\overline{U'}_r - T_{hs}$ curves. Other factors are maintained as a constant value (d_e/d_w=25, d_s/d_w=5), and well resistance is ignored.

As shown in Figure 1(a), the rate of consolidation by Hansbo's method is continuously retarded with increasing in k_h/k_s. However, the consolidation rate by proposed method (Figure 1(b)) is slightly speeded up and finally converged with increasing in k_h/k_s, because the rate of vertical drain-enhanced consolidation is governed by the permeability of disturbed zone (Basu and Prezzi 2007).

3 APPLICATION (BUSAN NEW-PORT SITE)

The consolidation behavior in Busan New-port site is analyzed to verify the proposed analysis. The rate of consolidation settlement is evaluated by Hansbo's solution and modified solution, and these results are compared with observed settlements in field.

3.1 *Soil properties of clay layers*

The profiles of clay layer properties (Busan New-port) are shown in Figure 2. The natural water content (w_n) and liquid limit (w_L) vary 35~75% and 40~80%, respectively. The plastic limit (w_p) exists in relatively narrow range from 20 to 30%.

Table 1. Void ratio and compression index of each clay layer

Property	Layer 1		Layer 2		Layer 3	
	U	R	U	R	U	R
e_L	1.81		2.22		1.35	
e_0	1.65	1.32	1.95	1.46	0.94	0.78
C_c	0.84	0.46	1.04	0.57	0.57	0.34
c_v (10^{-4} cm^2/sec)	7.1	3.8	13.0	4.8	22.0	5.0

Note. U: undisturbed clay, R: remolded clay

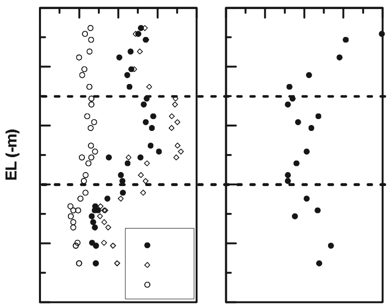

Figure 2. Profiles of soil properties

Although OCR at shallow depth is slightly larger than 1, the clay layers can be presumed normally consolidated. Busan clay can be divided into upper and lower clay layers based on EL -30m.

3.2 *Consolidation properties of each clay layer*

In this study, the clay layers of Busan New-port are divided into 3 layers for the consolidation analysis based on the soil properties. The consolidation tests were carried out for 50 samples for the natural clay and 3 samples for the remolded clay to figure out the consolidation characteristics of clay layers. Table 1 shows the void ratio, compression index (C_c) and coefficient of consolidation (c_v) representing the each clay layer.

3.3 *Extent of the disturbed zone*

In this study, several assumptions are made to evaluate the extent of the disturbed zone: 1) the soil adjacent to the drain is completely remolded. Therefore, the void ratio of the clay adjacent to the drain is the same as that of the remolded clay at the same effective stress level; 2) the void ratio reduction due to the disturbance around the drains occurs faster than the consolidation settlement under a surcharge load. Therefore, ground settlement that occurred without applying the surcharge load is mainly caused by the void ratio reduction due to the disturbance; 3) the extent of the disturbed zone and the variation of the void ratio within the disturbed zone are a invariable property with depth; 4) the shape of disturbed zone is a circular cross section. With these assumptions, the extent of the disturbed zone is evaluated from measured ground settlement, which occurred in the interval between PVD installation and a surcharge loading.

Burland (1990) suggested that the e-log σ'v relation for the remolded clay:

$$e_r = e_L (A - B \log \sigma'_v) \qquad (3)$$

where, e_r is the void ratio of the remolded clay, e_L is the void ratio at the liquid limit, σ'_v is a vertical effective stress (kPa), and A and B are constants. For Busan clay, the values of A and B are 1.224 and 0.256, respectively (Hong 2011). Therefore, the void ratio reduction (Δe) due to the disturbance can be evaluated from the liquid limit and the natural water content.

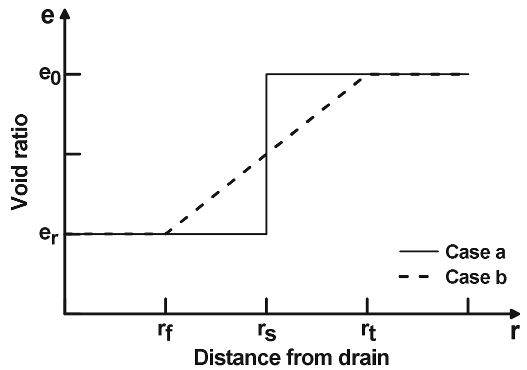

Figure 3. Variations of void ratio in disturbed zone

Figure 3 shows two possible variations of the void ratio with radial distance from the center of the drain. Case a assumes a constant permeability or void ratio within the disturbed zone (r_s). However, most studies (Onoue et al. 1991, Indraratna and Redana 1998, Shin et al. 2009) were consistently insisted a decrease in the permeability or the void ratio within the disturbed zone, although there are some differences in shape of variation (e.g. linear, bilinear, and parabolic). To consider variation of the permeability or the void ratio within the disturbed zone, case b assumes that the void ratio linearly increases from the value equal to e_r at the outer boundary of the fully disturbed zone (r_f) to the initial void ratio (e_0) of the undisturbed soil at the outer boundary of the transition zone (r_t). For cases a and b, the volume changes due to the disturbance induced by PVD installation can be expressed as:

$$\Delta V = \pi \cdot r_s^{\,2} \cdot H \cdot \Delta e/(1+e_0) \qquad \textit{Case a} \quad (4)$$

$$\Delta V = \pi \cdot [(r_f^{\,2} + r_f \cdot r_t + r_t^{\,2})/3] \cdot H \cdot \Delta e/(1+e_0) \quad \textit{Case b} \quad (5)$$

where, Δe is the void ratio reduction due to the disturbance, and H is the thickness of the target clay layer.

Figure 4 shows the ground elevation and total ground settlement during the entire period of the improvement. The measured settlement that occurred between the PVD installation and surcharge loading is 85.6 cm. This ground settlement could be occurred by the two reasons: 1) void ratio reduction within the disturbed zone; and 2) consolidation settlement in the undisturbed zone due to the sand mat. The consolidation settlement in the undisturbed zone is calculated as 13.8 cm by using Zeng and Xie's solution (1989). Therefore, the ground settlement caused by the void reduction within the disturbed zone is 71.8 cm.

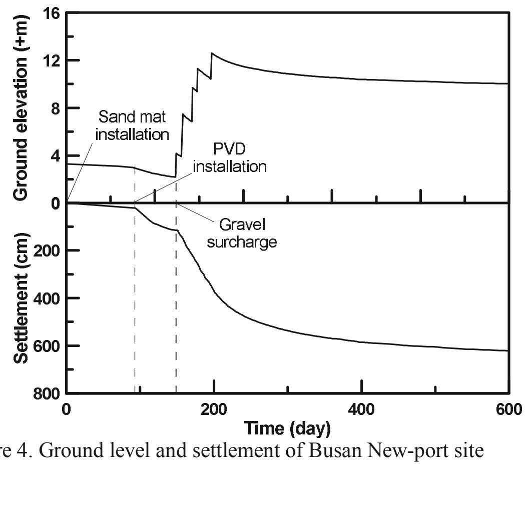

Figure 4. Ground level and settlement of Busan New-port site

Table 2. Analysis conditions

Case	Analytical condition	
	Hansbo's method	Proposed method
1	No disturbance, $c_h = c_v$	No disturbance, $c_h = c_v$
2	$c_h = c_v$ in disturbed zone, $c_h = 2c_v$ in undisturbed zone	No disturbance, $c_h = c_{hs}$
3	$c_h = c_v$ in undisturbed zone, $k_h/k_s = 2.5$	$c_h = c_{hs}$ in disturbed zone, k_h/k_s or $k_h/k_f = 2.5$
4	$c_h = c_v$ in undisturbed zone, $k_h/k_s = 5.0$	$c_h = c_{hs}$ in disturbed zone, k_h/k_s or $k_h/k_f = 5.0$
5	$c_h = c_v$ in undisturbed zone, $k_h/k_s = 10.0$	$c_h = c_{hs}$ in disturbed zone, k_h/k_s or $k_h/k_f = 10.0$

The extent of the disturbed zone (r_s) for case a is easily calculated as 21.6 cm based on 71.8 cm of the ground settlement. However, it is hard to calculate the values of r_f and r_t for case b because both r_f and r_t values are variables. For the linear spatial variation, previous studies suggested that the r_f is approximately 1.0~1.6r_m (Onoue et al. 1991, Hird and Moseley 2000, Sharma and Xiao 2000), where r_m is the equivalent radius of the mandrel. In this study, since the r_f is assumed to be 1.0r_m (8.0 cm), calculated value of r_t is 4.1r_m.

3.4 *Consolidation analysis*

The consolidation rate of Busan New-port is predicted using both Hansbo's method and proposed method. To evaluate effect of consolidation properties, parametric study is performed for a set of different conditions, as shown in Table 2. In case of proposed method, two possible permeability variations within disturbed zone are considered. Based on the PVD property, d_w=6, d_e=135cm, and q_w=15cm^3/sec are used for analysis.

Figure 5 shows the rate of consolidation settlement predicted by both Hansbo's method and proposed method, and the measured settlement for the layer located above EL -30 m. The average degree of consolidation ($\overline{U}$) is calculated by using Carillo's suggestion (1942), and then the consolidation settlement is calculated by considering the non-linear relationship between the consolidation settlement and the degree of consolidation.

As shown in Figure 5(a), Hansbo's analysis for cases 1 and 2 overestimate the settlement rate compared with the measured one because the coefficient of horizontal consolidation in the disturbed zone is assumed to be the same as c_v. All cases do not fit well with the measured settlement. To obtain the best result by Hansbo's analysis, it is necessary to know proper values of c_h and k_h/k_s. However, the suitable k_h/k_s ratio appears to vary with the assumed c_h value.

Proposed analysis (Case a) results show in Figure 5(b). The settlement rate at a certain time is underestimated to compare with the measured settlement, since the extent of disturbed zone is evaluated relatively large compared with the real condition due to an assumption for a constant permeability or void ratio within the disturbed zone. Basu et al. (2006) suggested the simplified μ_s for the linear spatial variation in disturbed zone (Case b). Using this suggestion, the settlement rate for case b is calculated by the proposed method, as shown in Figure 5(c). Case 4 (k_h/k_f = 5.0) is well matched with measured settlement within 100 days, and then case 3 (k_h/k_f = 2.5) shows good agreement with the measured settlement after 100 days. Since the typical value of c_h/c_v could be larger than 1.0 in nature, the k_h/k_f is presumed larger than 3.0, based on the consolidation test results. The slightly underestimation of the settlement rate predicted with the presumed k_h/k_f value may occur due to the difference in the surcharge schedule. In the analytical solution,

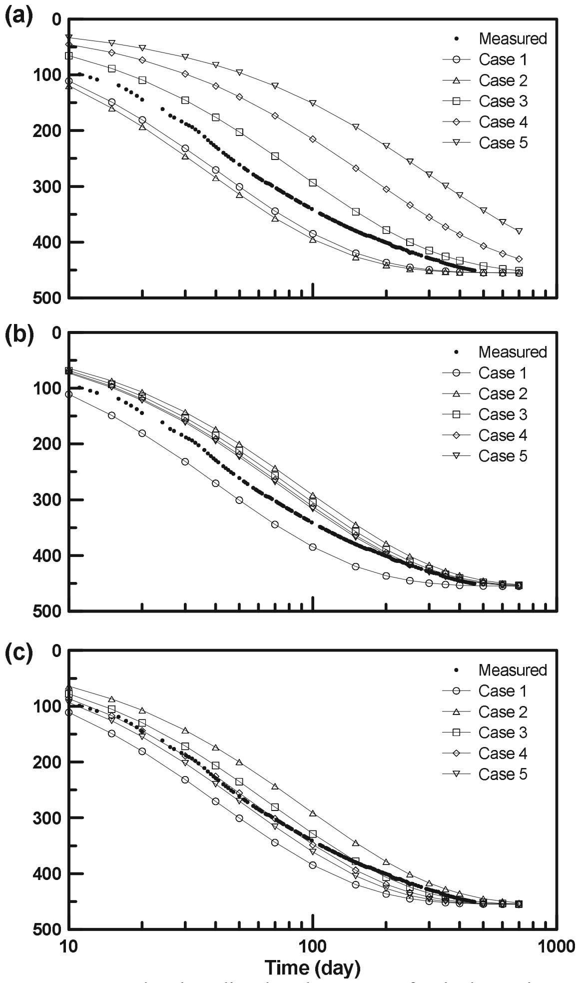

Figure 5. Measured and predicted settlement rate for the layer above EL -30m: (a) Hansbo's method, (b) Proposed method with case a, (c) Proposed method with case b

the surcharge load is assumed to be applied all at once, while, in the field, the surcharge load is applied incrementally.

4 CONCLUSION

In this study, the radial consolidation enhanced by the vertical drain is discussed with the analytical method existed, and the modified solution is suggested. Through parametric study and comparison between the calculated and measured settlement rates, the results are summarized as follows.

As the degree of disturbance increases, Hansbo's analysis shows that the time factor T_h increases for a certain degree of radial consolidation. However, the time factor for proposed analysis (T_{hs}), which corresponds to a certain degree of radial consolidation, slightly decreases as the degree of disturbance increases. Furthermore, proposed analysis gives the almost identical $\overline{U'}r - T_{hs}$ curves when the k_h/k_s value becomes larger than 20.

For Busan New-port site, the extent of the disturbed zone is evaluated using two possible void ratio variations within the disturbed zone. When a constant permeability or void ratio within the disturbed zone is assumed, the extent of the disturbed zone r_s is estimated to be $2.7r_m$. For the linear spatial variation within the disturbed zone, the extent of the transition zone r_t is estimated to be $4.1r_m$ with the same equivalent radius between fully disturbed zone and mandrel ($r_f = 1.0r_m$).

The settlement rate predicted by the proposed analysis is well matched with the measured field settlement when the k_h/k_f ratio is 2.5 with a linear spatial distribution of the permeability within the disturbed zone. The proposed method has advantages to evaluate the extent of disturbed zone and it is less influenced by the disturbance effect than Hansbo's method.

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