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A Study on Consolidation Analysis Solution in Deep Soft Ground Improved by Plastic Board Drain Method

PBD공법이 적용된 대심도 연약지반에 대한 압밀분석해에 관한 연구

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ABSTRACT : It is very important to determine the consolidation rate of ground, depending on the progress of time in applying this vertical drain method. Various consolidation analysis solutions capable of forecasting the consolidation rate are being proposed at the moment. However, the degree of consolidation measured from site, has a considerable different from the degree of consolidation which was obtained by the analysis of vertical drain consolidation. This study aims at assessing the applicability and verfication of each consolidation analysis solution by comparing and analyzing the degree of consolidation measured in the field and the degree of consolidation based on the theoretical equation for the analysis of the consolidation of Hansbo, Onoue, Zeng and Xie used as the consolidation analysis solution before the beginning of construction, on the basis of monitored field results and site investigation data as to the deep soft ground in Busan area applied by PBD method.

Keywords : Vertical drain method, Consolidation analysis solution, Deep soft ground, Degree of consolidation

요 지 : 연직배수공법의 적용시 시간경과에 따른 지반의 압밀도를 판단하는 것은 매우 중요하다. 이에 압밀속도를 예측하는 여러 압밀분석해들이 제안되고 있다. 하지만, 실제 현장에서의 압밀속도는 연직배수재의 압밀해석에 의한 값과 상당한 차이를 나타내고 있다. 본 논문에서는 PBD공법을 적용한 부산지역의 대심도 연약지반에 대한 압밀종료시점의 현장계측자료 및 지반조사 자료를 바탕으로 시공 전 압밀분석해로 사용되고 있는 Hansbo, Onoue, Zeng과 Xie의 압밀분석 이론식의 압밀도와 현장에서 계측된 압밀도를 상호 비교, 분석하여 각 압밀분석해의 적용성과 타당성을 평가하였다.

주요어 : 연직배수공법, 압밀분석해, 대심도연약지반, 압밀도

1. Introduction

As there is a soaring demand for industrial sites and residential sites amid fast economic growth, it is urgent to secure large land through the 'Coastal Dredging & Reclamation' because of domestic geographical property. However, the coastal foundation has a very poor ground conditions, composed of marine clay, silt soil, sand soil, which may result in poor support or sinking of structures such as ports, airports and bridges, and shear deformation, and so forth.

Though various ground improvement methods have been applied in order to resolve these problems, and prevent the premature sinking and improve the strength. Recently, PBD method, one of the vertical drain methods, is used most commonly to shorten consolidation time.

The present study has been carried out about PBD method, and reported that the ground disturbance related to installing drain, smear effect, well resistance, may affects consolidation rate.

However, the value which is obtained by consolidation analysis of vertical drain that considers only these influential factors, makes a difference from reality, and researches for influential factors have been conducted. Meanwhile, it is considered to have a close relationship with the vertical drain layer(sand mat) which discharges the consolidation water of vertical drain, and its effect on the sand mat resistance has been studied(Korean Geotechnical Society, 2005).

In particular, the existing consolidation analysis equation needs to be carefully applied because marine soil of Busan is not only deep depth which exceeds 40 m but also is composed of double-layered soft ground which has different

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in-situ sedimentation. In this paper, the average degree of consolidation, which is obtained by the consolidation analysis equations of Hansbo, Onoue, Zeng and Xie on the basis of field monitoring data and ground survey data in Busan to which PBD method was applied.

The average degree of consolidation which was measured in the field were compared and analyzed, and the reasonability of each consolidation analysis solution was evaluated.

2. Theoretical Background

2.1 Hansbo's Consolidation Analysis One Space Solution

Hansbo (1979) derived the interpretative, simple and convenient solution, considering both smear zone and drain resistance at the certain depth in the soil layer and the consolidation at z, $U_h(T_h)$ while quoting the convenient process of derivation suggested by Kjellman (1937).

$$U_h(z,T_h) = 1-\exp\left(\frac{-8T_h}{F}\right) \tag{1}$$

Where, $F = F(n) + F(s) + F(w)$

$F(n) = \ln\left(\frac{d_e}{d_w}\right) - \frac{3}{4}$: factor by the interval of drain

$F(s) = \left(\frac{k_h}{k_s} - 1\right)\ln\frac{d_s}{d_w}$: factor by the smear effect

$F(w) = \pi z(2H-z)\frac{k_h}{q_w}$: factor by the drain resistance

$T_h = \frac{c_h\ t}{d_e^2}$: time coefficient of horizontal direction

k_h/k_s : reduction rate of coefficient of permeability by disturbance(= η)

q_w : water passing capacity of drain(discharge capacity) ($=\pi d_w^2 k_w$)

d_s/d_w : diameter ratio of smear zone (= S)

H : length of drain

d_e : the radious of influence circle

d_s : the radious of smear zone

C_h : horizontal coefficient of consolidation

K_h : horizontal permeability coefficient

K_s : permeability coefficient of smear zone

K_w : permeability coefficient of vertical drain

Hansbo (1979) model is considered reality by assuming that the smear zone's subsoil is compressible in comparison to the solution of Barron (1948), but still assumes that the compressibility of smear zone is identical with the undisturbed zone.

2.2 Onoue's Consolidation Analysis Solution

Onoue (1988) proposed a general and simple equation as $U_h(T_h)$ considering of the drain resistance using a variation of Barron (1948)'s equation in order to consider both well resistance and smear zone.

$$U_h = 1-\exp[-8T_h/(F(n')+0.8L)] \tag{2}$$

Where, $F(n') = \frac{(n')^2}{(n')^2-1}ln(n') - \frac{3(n')^2-1}{4(n')^2}$

$n' = nS^{\eta-1}$, $n(=d_e/d_w)$: Interval ratio

$L = \frac{32}{\pi^2}\frac{k_h}{k_w}\left(\frac{H}{d_w}\right)^2$: coefficient of drain resistance

$T_h = \frac{c_h\ t}{d_e^2}$: time coefficient of horizontal direction

t : consolidation time

H : thickness of clay layer

k_h/k_s : reduction rate of coefficient of permeability caused by disturbance (= η)

d_s/d_w : diameter ratio of smear zone (= S)

2.3 Zeng and Xie's Consolidation Analysis One Space Solution

Zeng and Xie (1989) proposed the approximate solution of governing equation based on the technique same as the assumed condition of Hanbo (1979) for the radial drain which considers the drain resistance and smear effect of the overall inter-penetrated drain.

$$\overline{U_r} = 1-\exp(-\beta_r t) \tag{3}$$

Where, $\beta_r = 8c_h/(F+\pi G)/d_e^2$

$F = \ln\left(\frac{n}{S}\right) + \frac{k_h}{k_s}ln(S) - \frac{3}{4}$

$G = \frac{k_h}{k_w}\left(\frac{H}{d_w}\right)^2$: coefficient of drain resistance

H : length of drain

k_h/k_s : reduction rate of coefficient of permeability caused by disturbance (= η)

d_s/d_w : diameter ratio of smear zone (= S)

k_w : permeability coefficient of vertical drain

3. Field Condition and Monitoring Status

3.1 Field Location and Section

The land for north container (CY section) under construction area where the 0-0 wharf of Busan New Port, selected as the field measurement site, is located in the sea in front of "Yongwon-dong, Jinhae-si, Gyeongsangnam-do", and has well-developed raise coasts formed by orogeny, as well as small and large islands to the south. To the east, Noksan National Industrial Complex is located. the poor subsoil is composed of deep soft ground whose thickness of In-situ ground layer (subsoil with less than 15 inch N value) ranges from approximately 40.1 to 45.7 m (average by zone) where the consolidation settlement happens, and Table 1 shows the distribution of layer's thickness by zoning and major soil characteristics of In-situ ground.

3.2 Layer Condition and Soil Characteristics

The layer in the region where the field measurements were carried out is composed of sand layer (reclaimed layer, sand mat), deposited layer (clay layer, sand gravel) and Bedrock. The sand layer at the top is as thick as 4.1 to 4.7 m. This layer is the upper drain layer for the subsoil improvement and the cover for the operability of equipment composed of fine sand, and N value ranges from 5/30 to 37/30. The sediment layer at the top contains some shells and sand as marine sediment layer, and is classified into silt clay layer. The depth distribution of layer ranges from 4.6 to 53.7 m, and the thickness ranges from 28.3 to 46.3 m. Meanwhile, the N value is between 2/30 and 11/30.

The sediment layer at the bottom is the sand layer mixed with sand and gravel. The depth distribution ranges between 42.2 and 56.1 m, and the thickness of layer is between 2.4 and 2.8 m. the N value is between 5/30 and 35/30.

Table 1. Major characteristic value of in-situ ground clay (EJ-TECH, 2004)

permeability		Zone 1	Zone 2	Remarks
specific gravity (G_s)		2.72	2.72	Z : Depth (m) (based on GL)
void ratio (e)		1.52	1.69	Z : Depth (m) (based on GL)
water content ratio ($w:\%$)		56	62	Z : Depth (m) (based on GL)
saturation unit weight ($\gamma_w : t/m^3$)		1.74	1.70	Z : Depth (m) (based on GL)
1st compression coefficient (C_c)	S1 layer	0.56	0.61	re-compression coefficient (C_r) : $C_r/C_c = 0.15$ applied 2nd compression coefficient (C_α) : $C_\alpha/C_c = 0.033$ applied
	S2 layer	0.86	1.03	
	S3 layer	0.77	0.92	
	S4 layer	0.3	0.3	
vertical consolidation coefficient ($C_v : 10^{-3} cm^2/\sec$)		0.42	0.38	Z : Depth (m) (based on GL)
horizontal consolidation coefficient ($C_h : 10^{-3} cm^2/\sec$)		0.97	0.87	Z : Depth (m) (based on GL)
coefficient of permeability ($k_v : 10^{-8} cm/\sec$)		$8.38 \times e^{-0.0081z}$	$4.41 \times e^{-0.0629z}$	horizontal permeability coefficient : $K_h = 2.3k_v$

Table 2. Soil characteristics of clay (Dong-Ah Geotech, 2003)

Characteristics of soil quality \ Type		Zone 1	Zone 2
physical property	USCS	CH, CL	CH, CL
	#200 sieve passage weight percentage (%)	83～100	83～100
	liquid limit, w_L (%)	40.8～98.7	35.2～93.8
	natural water content ratio, w_n (%)	37.7～72.1	34.0～70.8
	plasticity index, I_p	19.3～65.8	15.0～63.9
	unit weight, $\gamma_t(tf/m^3)$	1.56～1.86	1.57～1.89
property of consolidation	preconsolidation stress, $P_c(kg/cm^2)$	0.25～5.5	0.41～3.00
	Compression index, C_c	0.27～1.08	0.26～1.04

4. Comparative Analysis and Degree of Consolidation

4.1 Comparative Analysis of the Degree of Consolidation by Consolidation Analysis Solution

Vertical drain method to expell water in the soil is used commonly, with the Pre-loading method, to improve the soft ground, and consolidation rate of subsoil is predicted through the consolidation analysis solution, such as Hansbo, Onoue, Zeng and Xie, before the construction. Many researchers are proposing empirical values for effective diameter of drain, range of smear zone, permeability coefficient of smear zone, obtained by experiments, which are necessary when solving the consolidation solution.

In this paper, Hansbo, Onoue, Zeng and Xie's consolidation analysis solution were applied to forecast the values proposed by Hansbo (1987) and Park (1994) from the perspective of consolidation speed, estimate the average degree of consolidation accordingly, and compare that with the real average degree of consolidation, so as to figure out the characteristics of consolidation analysis solution and evaluate the feasibility. Table 3 shows the values proposed by Hansbo (1987) and Park (1994).

4.2.1 Degree of Consolidation by Hansbo (1987)

Figs. 1 shows the relationship between the average degree of consolidation and the actually measured average degree of consolidation to the ground improvement zone, when the empirical value proposed by Hansbo (1987) was applied to

Table 3. Proposed value of consolidation analysis solution

Type	Value proposed by Hansbo (1987)				Value proposed by Park (1994)			
	dw (cm)	ds (mm)	ks (m/s)	H (m)	dw (cm)	ds (mm)	ks (m/s)	H (m)
A1	3.324	30	7.25×10^{-8}	37.72	6.016	41.25	9.18×10^{-8}	37.72
B1	3.324	30	7.12×10^{-8}	44.21	6.016	41.25	9.02×10^{-8}	44.21
C1	3.324	30	7.16×10^{-8}	42.55	6.016	41.25	9.06×10^{-8}	42.55
D1	3.324	30	7.74×10^{-8}	20.7	6.016	41.25	9.80×10^{-8}	20.7
E1	3.324	30	2.34×10^{-8}	46.4	6.016	41.25	2.94×10^{-8}	46.4
F1	3.324	30	2.30×10^{-8}	50.3	6.016	41.25	2.90×10^{-8}	50.3

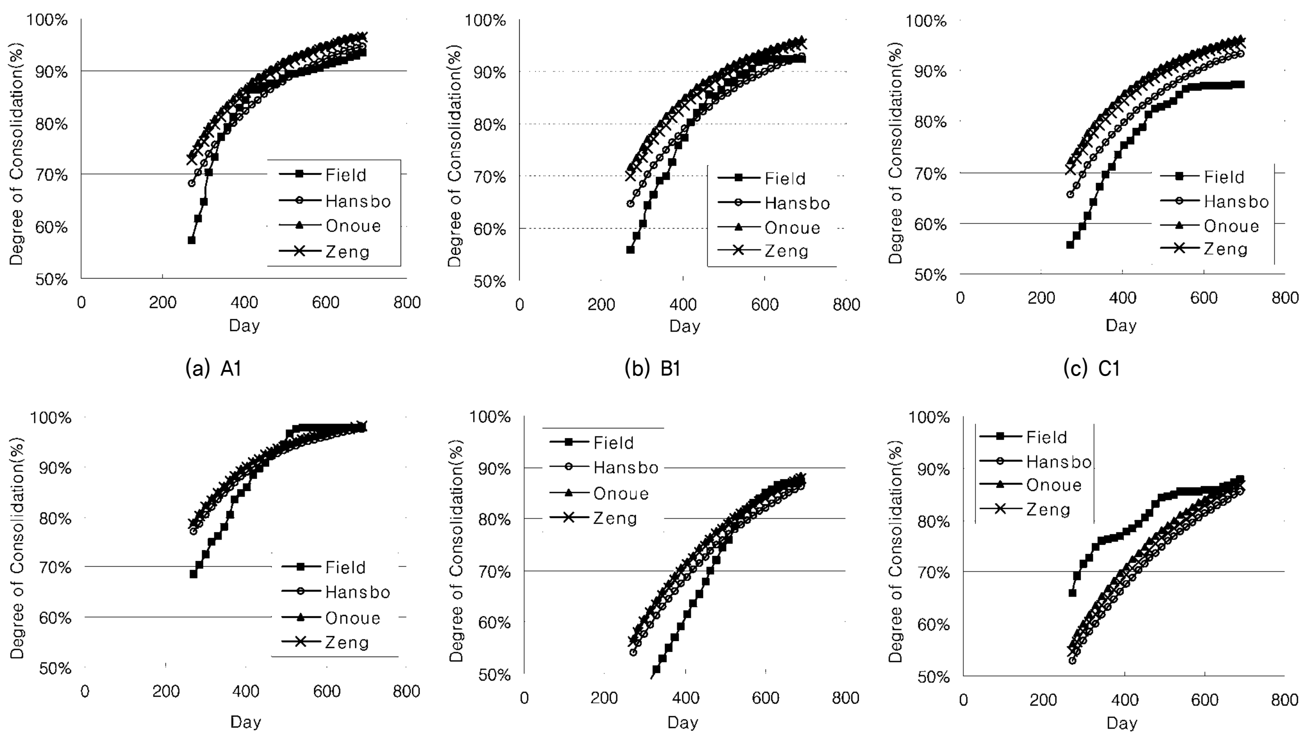

Fig. 1. Variation in degree of consolidation long time

each consolidation analysis solution.

Change in the degree of compression, depending on the passage of time by the value that Hansbo proposed shown in Fig. 4.1.

Though all regions shows a great difference between the average degree of consolidation measured by consolidation analysis solution and the average degree of consolidation which is measured by the field monitoring in the initial stage of consolidation after the embankment, but both values were found to get closer to each other while the degree of consolidation reaches over 80%. The rate of error at each region is shown in Fig. 2.

Overvaluation was found in the region with narrow interval of drain among the Onoue solution and Zeng & Xie solution. And the undervaluation was found in the region with broad interval of drain in case of Hansbo solution. However, the error rate of all consolidation analysis solutions was found to be less than 1% in D1 region which has low depth, suggesting a closeness to the actually measured value.

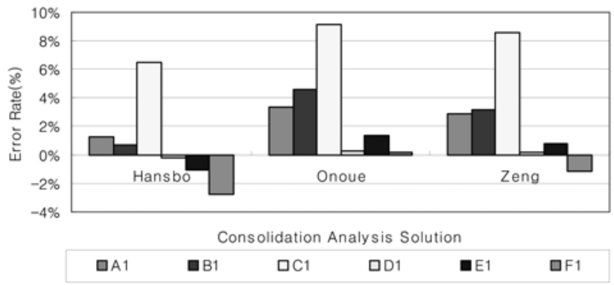

Fig. 2. Error rate of degree of consolidation

4.2.2 Degree of Consolidation Using Values Proposed by Park (1994)

Recently many studies are carried out in relation to the factors which affect the degree of consolidation under vertical drain method for domestic marine clay subsoil in the wake of the increased coastal reclamation and dredging works in Korea, and empirical values from various experiments have been proposed about the soft ground in Korea.

In response to that, the value proposed by Park (1994) was applied in order to analyze the average degree of consolidation, which was compared with the actually measured degree of consolidation and analyzed. The results of comparative analysis were shown in Fig. 3.

All regions, except D1 region, which had a low depth showed a great difference not only in the inchoate stage of consolidation but also at the finishing point of consolidation, and was found to be overvalued. Hansbo's consolidation analysis solution showed better approximation than the other

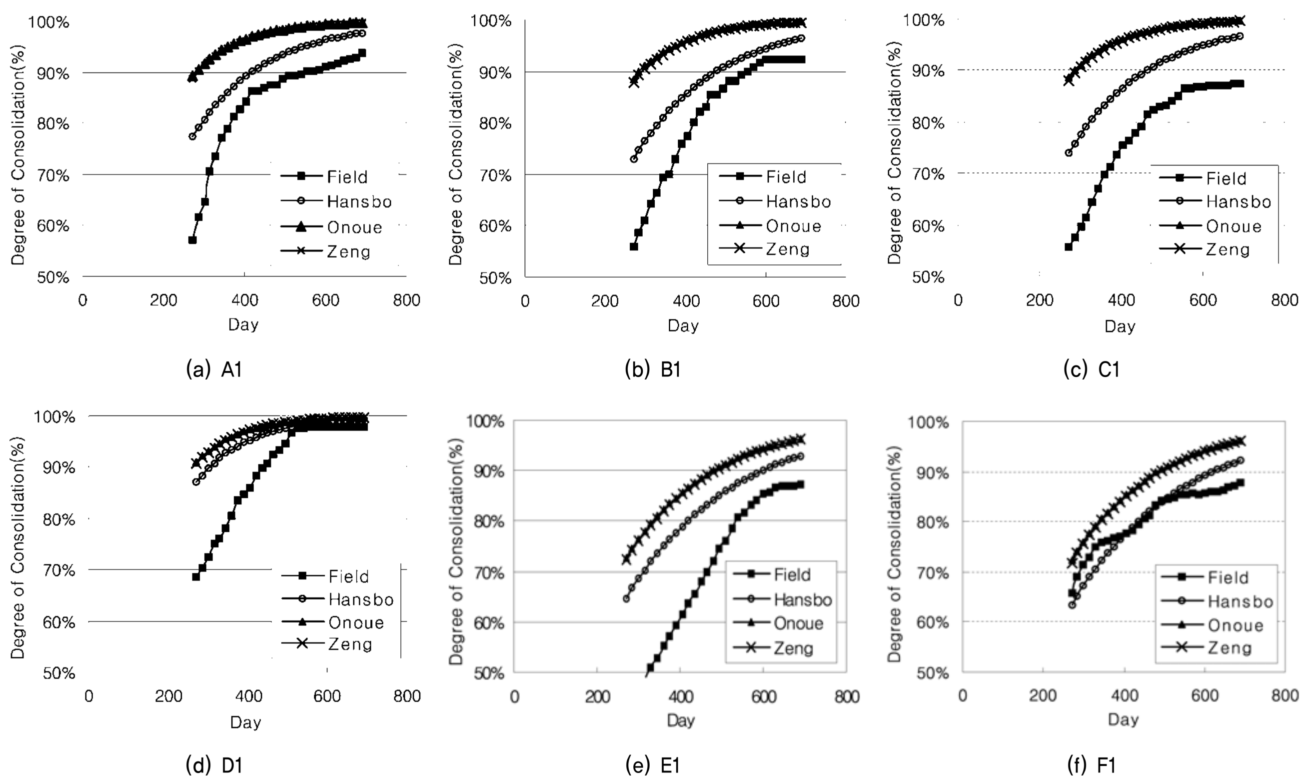

Fig. 3. Variation in degree of consolidation along time, by the value that Park proposed

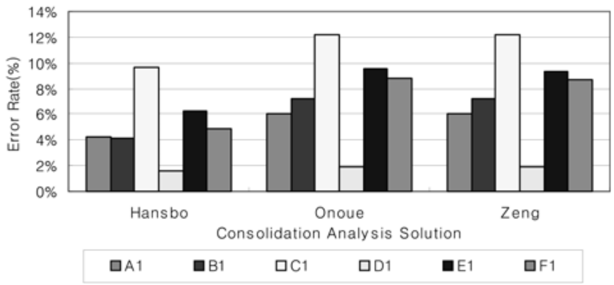

Fig. 4. Error rate of degree of consolidation, on the regions by the value that Park proposed

two consolidation analysis solutions, and was found to be also overvalued in regions where the concreting interval of drain is broad unlike the consolidation analysis solution which uses the value proposed by Hansbo. Fig. 4 shows the error rate on the regions.

All regions, except D1 which has a low depth, showed an error rate over 5%, and 3 places, which account for half of all regions, showed a difference from the actually measured degree of consolidation close to 10%, when the equation of Onoue and Zeng and Xie was applied. This suggests that Onoue solution and Zeng and Xie solution which use the value proposed by Park are not appropriate when interpreting the vertical drain method for the poor subsoil in Busan that has a deep depth. And the average degree of consolidation based on the value proposed by Park showed a great difference in the region with broad concreting interval, compared to the average degree of consolidation based on the value proposed by Hansbo which displays smaller difference in the region with broad installing interval of drain.

5. Conclusion

The comparison and analysis between the average degree of consolidation which was predicted by using the consolidation analysis solution on the basis of the field monitoring data and subsoil investigation data at the finishing point of consolidation and the average degree of consolidation which was actually measured in the field are as follows:

(1) For the empirical value which was proposed previously for the effective diameter of drain and smear zone, the empirical value proposed by Hansbo (1987) was found to show higher accuracy than the empirical value proposed by Park (1994) when all consolidation analysis solution were applied, and in particular, it is considered reasonable to apply the value proposed by Hansbo (1987) in the region which has broad installing interval of drain.

(2) Though there was a considerable difference in the range of error rate, depending on the regions, the analysis of the average degree of consolidation indicates that the actually measured average degree of consolidation and the degree of precision were found in the following order: Hansbo's solution, Zeng snd Xie's solution, Onoue's solution.

(3) Though it was relatively close to the average degree of consolidation that was actually measured in the regions that the average degree of consolidation was over 80%, it was difficult to derive the correlation depending on the zone. This may be because the value of horizontal consolidation coefficient for subsoil was not accurately estimated

It is considered to be necessary to determine the variation in the consolidation analysis solution which ensues from the variation in soil parameters and the resulting applicability by varying different values of horizontal permeability coefficient and horizontal consolidation coefficient range to compute the degree of consolidation, and comparing with the actually measured value, in order to draw more quantitative conclusion.

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