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Sensitivity analysis related to the phenomena of consolidation delay by construction work using prefabricated vertical drain method in deep-soft clay deposits

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ABSTRACT: In soft clay deposits, consolidation delay occurs due to various factors when consolidation method of construction by prefabricated vertical drain is applied. We have examined Well Resistance, Smear Effect, and construction management (come-out phenomena of drain board, perpendicularity) which are the effective factors that greatly influence consolidation delay in lower layers. And it was discovered that, when consolidation method of construction by prefabricated vertical drain is applied in deep-soft clay deposits, not only mechanical reasons such as Well Resistance or Smear Effect but also constructional reasons such as the come-out phenomena of drain board or perpendicularity affected consolidation delay.

1 INTRODUCTION

The development in soft ground has been, recently, propelled for the efficient use of land. However, various problems have occurred because the engineering properties of the ground are complex, the intensity is weak, and the transformation of subsidence is tremendous. Soft ground is composed of clay, silt fine-grained soil, and loose sand. These come from the alluvium layer which is accumulated in the alluvial plains, coastal landfills, and valleys. The bedding or fertility of the ground is fairly different according to the creating environment of topography.

In soft ground, subsidence and stability problems occur according to the weight of embankment and structure. The subsidence of soft ground is determined as a relative relation of the loaded state, the construction speed of embankment, and the order of construction, etc. That is why a thorough analysis on the engineering properties of the ground and necessary countermeasures are strongly needed for a safe and economic design and management. However, even if delicate numerical analysis techniques are used to analyze consolidation behavior of soft ground where the drain is installed, the actual phenomenon that occur in soft ground are quite different from planned measurements. This is because of the uncertainty caused by disproportion and anisotropy.

Especially, when consolidation method of construction by prefabricated vertical drain is applied in deep-soft clay deposits, unlike planned measurements, consolidation delay occurs in lower layers due to various factors. This causes several problems. Therefore, this study will compare Well Resistance and Smear Effect which are the effective factors that greatly influence consolidation delay in deep-soft clay deposits when prefabricated vertical drain is applied. The study will be done through virtual construction simulation and it will measure the relative importance by interpreting quantitatively the effect of each factor.

2 BASIS THEORY ABOUT PREFABRICATED VERTICAL DRAIN

2.1 *Consolidation theory of vertical drain*

Vertical drain method holds its purpose to consolidation theory and the security of ground intensity.

Consolidation theory reports that the time needed for the consolidation of soft clay ground is in proportion to the square of drain length. And the horizontal permeability coefficient (K_h) of the ground is bigger than that of the vertical (K_v). The purpose is to obtain ground intensity by installing a fixed-space drain with a perpendicular direction into the ground. This causes accelerated consolidation and increased strength.

2.2 *Element that influence in the consolidation speed*

The element which influences the exclusion speed and the time spent in processing consolidation, excluding pore water in the ground, can be regarded with the theory Hansbo (1979) suggests. The effective factor that influences horizontal consolidation speed and the equation concerning the estimation of consolidation degree are given as equ (2.1)–(2.7).

$$\mu_s = F(n) + F(s) + F(w) \tag{2.1}$$

$$t = d_e^2 \times \frac{T_h}{c_h} \tag{2.2}$$

$$T_h = U_s \times \ln \frac{1}{1 - U_h} \tag{2.3}$$

$$U_h = 1 - \exp \frac{-8T_h}{\mu_s} \tag{2.4}$$

Where, d_e = Equivalent diameter of soil cylinder
c_h = Horizontal coefficient of consolidation
U_h =Average degree of horizontal consolidation
T_h =Time factor

$F(n)$, $F(s)$, $F(w)$ represent the spacing of the drain, the smear zone effect and the well resistance effect, respectively.

$$F(n) = \ln\left(\frac{d_e}{d_w}\right) - \frac{3}{4} \tag{2.5}$$

$$F(s) = \left(\frac{k_h}{k_s} - 1\right) \cdot \ln \frac{d_s}{d_w} \tag{2.6}$$

$$F(w) = \pi \cdot z \cdot (2H - z) \cdot \frac{k_h}{k_w} \tag{2.7}$$

2.3 *Well Resistance*

Well Resistance is the factor that deteriorates perpendicular drain ability as consolidation is being processed in the drain-installed ground. The main factors that produce Well Resistance are the quality decline in the drain, the lengthiness of the drain, the largeness of lateral confining pressure, the bending or folding of the drain when subsidence is augmented, and the accumulation of fine-grained soil that passes through the filter sleeve which reduces the sectional area necessary for the flow of channels. Hansbo stressed that a drain which has an infinite permeability with the direction of length does not exist. He suggested that if the existence of Well Resistance in the drain is ignored, it could turn out as an underrated design when installing the drain.

2.4 *Smear Effect*

When installing a drain, the penetration of the casing causes disturbance such as shear strains and displacement in the surrounding soil (Hansbo, 1960). The area where such disturbance occurs is known as Smear Zone. The disturbance is different according to the size and shape of the casing, the structure and type of the ground, and the installing method of the drain. Ground disturbance reduces consolidation coefficient, causing a decline in drain performance that was not considered during the actual designing. This delays the consolidation process. To minimize such effect of disturbance, the sectional area of the casing must be minimized. And it must have sufficient intensity in consideration to the resistance of the installation ground and the maintenance of perpendicularity. Regarding the extent of Smear Zone, researches have been done actively. However, most cases depend on an empirical method of estimating. Recently, there have been studies based on experimental results. They can be summarized as in the following table:

Table 1. Range of Smear Zone.

Division	Range of Smear Zone	Note
Hansbo (1987)	$d_s = 2 \cdot d_m$	d_s : Diameter of Smear Zone d_m : Diameter of Casing
Jamiolkowski (1981)	$d_s = \frac{(5 \sim 6) \cdot d_m}{2}$	
Park etc (1985)	$d_s = 1.5 \cdot d_m$	

3 LABORTARY TEST

3.1 *Large scale discharge capacity test with drain resistance*

Park Yeong Mok (2003) used two large-scale test devices to examine the discharge capacity of the drain fixed to the actual scale applied in field. A large-scale test device is composed of a large-sized steel cylindrical body (the structure is equivalent to that of a triaxial cell), an in-out jet water tank, a compressor, a water tank, and a water pump, etc. The drain is long in the large-scale test device. Because of this, the device was complemented so that the pressure corresponding to the waterhead could be applied to the inlet of the test device in case there is difficulty controlling the hydraulic gradient with the waterhead.

The test was carried out, changing the lateral pressure and hydraulic gradient, to examine the change within the range appropriate to site condition. The lateral pressure which corresponds to the depth installation on site was executed under the 3-type condition (1.0 kgf/cm^2, 2.0 kfg/cm^2, 4.0 kgf/cm^2). Also, the 3-type condition (0.2, 0.5, 1.0) was applied for the hydraulic gradient that changes according to the consolidation progress. The amount of air released from the compressor was regularly controlled and, then, was applied pressure by a regulator. Using the water inside the compressor, pressure was applied in

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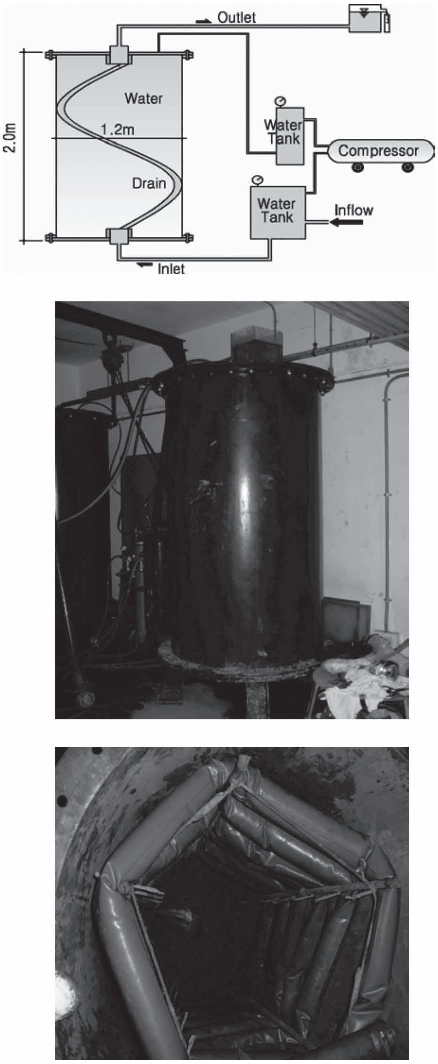

Figure 1. Large scale discharge capacity test with drain resistance.

the large-scale test device with water pressure. The hydraulic gradient was set to maintain a steady pressure using the regulator installed on the outside of the pressure device.

3.2 *Smear zone test*

Park Yeong Mok (2003) executed an experiment, modeling the installation method on site and manufacturing a model of the Smear Zone test device. In the upper part of the picture, the body of the Holland's dual-cone penetration test device was attached to install a mandrel. Then a two-dimensional Smear Zone test was in operation, using a semicylindrical steel mold which was 30 cm in diameter of the lower mold and 37 cm in height.

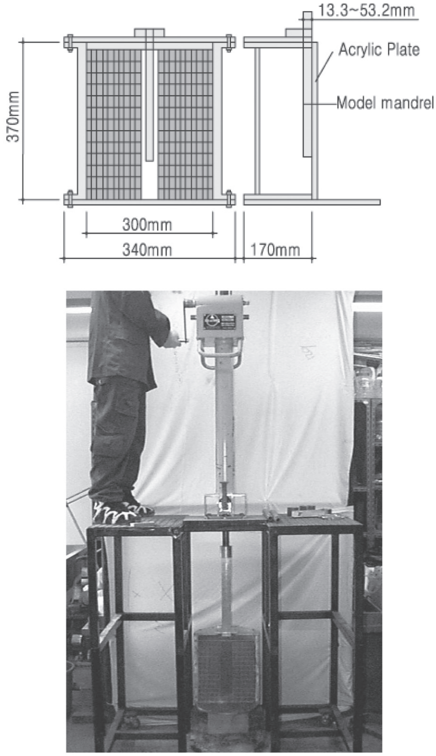

Figure 2. Smear Zone Test.

The mandrels used in this test are in the form of a circle with a closed lower department, rectangle, and square. Small- and large-sized mandrels were manufactured to compare the effect caused by the shape and size of the mandrel. The rectangular and square mandrels were manufactured, changing the long-short side ratio by converting the ratio into equal sectional areas of that of the circle.

4 RESULT

4.1 *Result of discharge capacity with large scale test*

Testing the lateral pressure was tested while steadily maintaining the hydraulic inclination (i = 0.5). The result was that the discharge capacity was 19.6 cm^3/sec when the lateral pressure was 1.0 kfg/cm^2 and 5.6 cm^3/sec when 4.0, decreasing 28% as the pressure increased four times. Testing under the same conditions but changing the hydraulic inclination, the discharge capacity was 5.6 cm^3/sec when the lateral pressure was 4 kfg/cm^2 (i = 1.0) and 3.8 cm^3/sec when i = 0.5, decreasing 68% in capacity. Testing the discharge capacity by changing the bending phenomena of drain into erection, free deformation (20% free bending), and 1 point folding, the discharge capacity was 34.0 cm^3/sec in erection, 27.8 cm^3/sec in free deformation and 19.6 cm^3/sec in 1 point folding.

In this study, the result of the large-scale discharge capacity test with drain resistance was converted into delay ratios, calculating 90% consolidation period. The majority of the effective factor of Well Resistance interacted complexly and consolidation delay occured about 1.4 times more.

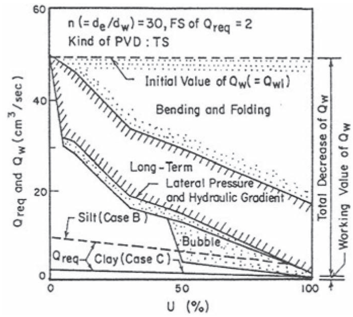

Figure 3. Consolidation delay with Well Resisitance.

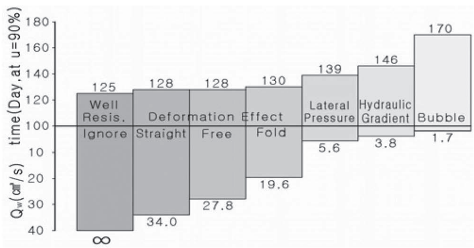

Figure 4. Well Resistance estimation by effect factor.

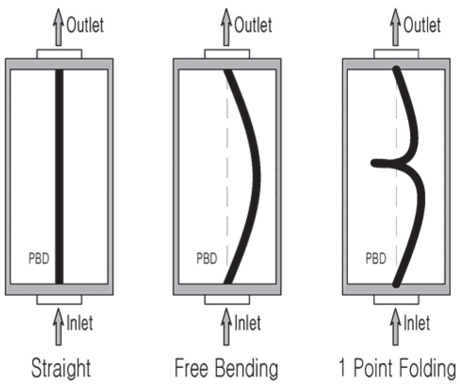

Figure 5. Shape of PBD.

4.2 *Result of Smear Zone*

Apprehending, with a laboratory test, the range of Smear Zone which influences the consolidation speed of prefabricated vertical drain method, the result was: the sizes (ds/dm) of Smear Zone based on the shape of the mandrel were circle 2.53, square 3.45, rectangle 2.78, and diamond 1.80, indicating 2.64 on average. In this study, consolidation delay occurred 1.8 times more when $d_s/d_m = 3$, $k_s/k_h = 0.5$ were applied.

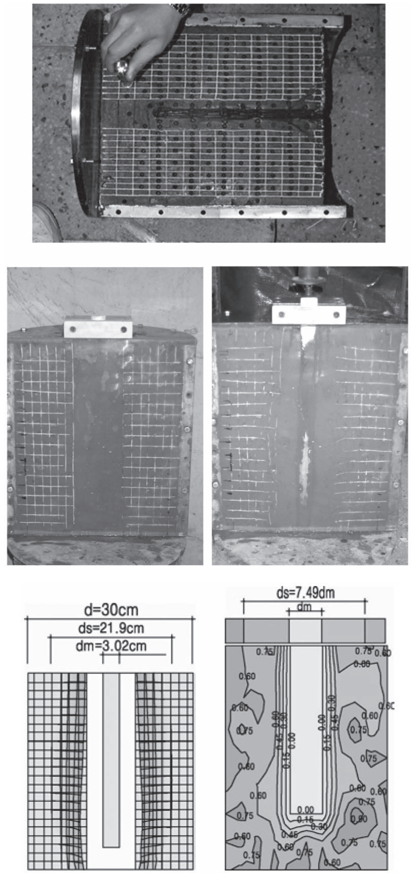

Figure 6. Shape of Mandrel Installing Before·After.

5 CAUSE OF CONSOLIDATION DELAY IN THE CONSTRUCTION

5.1 *Perpendicularity of PVD*

5.1.1 *Consolidation delay of perpendicularity defectiveness of PVD*

In deep-soft clay deposits, the possibility of consolidation delay exists when the clay stratum gets thicker even if a precise construction was carried out. Although it is stated in specifications to manage

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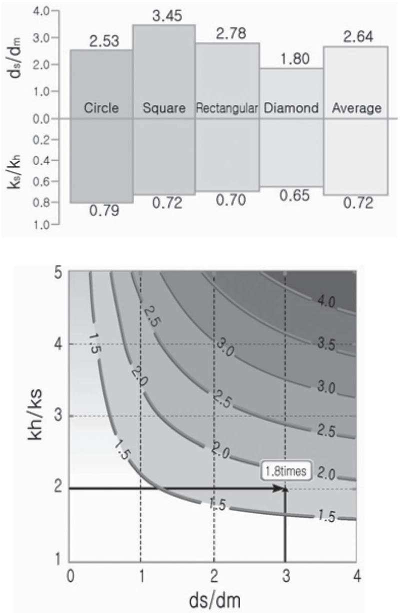


Figure 7. Smear Effect by Mandrel Shape.

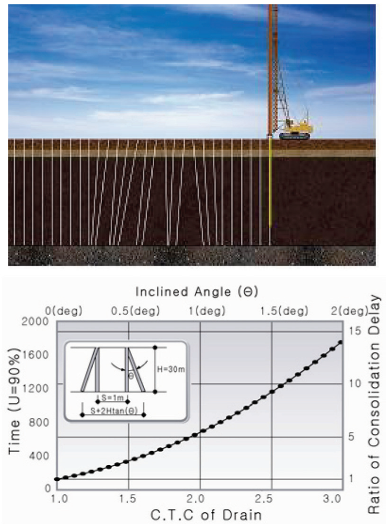


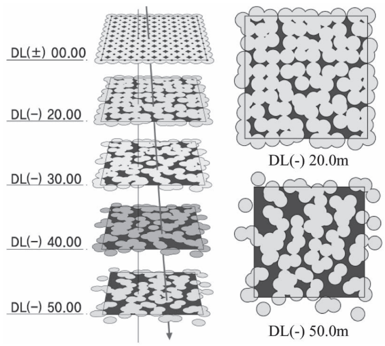
Figure 8. Happen to come out phenomena of drain board.

perpendicularity between 1-2°, the drain intervals in lower parts can widen to maximum 2 m if the depth of the clay stratum exceeds 30 m. If this happens, the distance of horizontal drain increases and consolidation delay occurs. Examining this situation, the period of such consolidation delay was calculated to be 5 times to, maximum, 15 times more.

However, this is the worst case. Therefore, to examine such effects, the possibility of consolidation delay of the ground and the distribution of PVD installed in lower parts was examined in this study by executing a virtual construction simulation.

5.1.2 *Virtual construction simulation*

Sensitivity analysis was carried out by using Monte Carlo method to estimate major factors that affect consolidation delay in the construction process. The condition of the simulation brought about random numbers within construction error 2° of perpendicularity. The slope angle brought about random numbers within 360°. The results are as showed in (Fig. 9). It was proved that non-improvement section does not lineally increase according to depth. This is because the installed drain infiltrates into the area of the drain nearby when the depth deepens.



Installing depth (m)	Average Area of unimprove
(–)20.0	7.60
(–)30.0	15.40
(–)40.0	23.20
(–)50.0	28.30

Figure 9. Result of virtual construction simulation by depth.

The result showed that as the installation depth deepened, the non-improvement area ratio increased. And in an installation depth of more than 50 m, the non-improvement area ratio was more than about 28.3%. These results show that the probability of consolidation delay that was calculated to be 5–15 times more, i.e., the worst case, has a low probability of happening. However, defective perpendicularity is a very important cause that can result in consolidation delay.

5.2 *Come out phenomena of PVD*

When installing prefabricated vertical drain in deep-soft clay deposits, the come-out phenomena of PVD, the coming out of the drain as the mandrel draws out, can occur in certain sections. Counting consolidation time, it was calculated that consolidation delay occurred partially 2-7 times more when the come-out phenomena occured for 1-2 m.

6 CONCLUSION

The relative importance of the effective factors of consolidation delay in lower layers, when consolidation method of construction by prefabricated vertical drain is applied in deep-soft clay deposits, was examined through virtual construction simulation. The results can be summarized as the following:

1. In the large-scale discharge capacity test with drain resistance, the majority of the effective factors of Well Resistance interacted complexly and caused consolidation delay about 1.4 times more in 30 m depth.
2. In the Smear Zone test, consolidation delay occurred about 1.8 times more although there was a difference based on the shape of the mandrel.
3 When executing consolidation method of construction by prefabricated vertical drain in deep-soft clay deposits, consolidation delay occurred partially about 5-15 times more in lower parts as the drain was installed 1-2° slantingly.
4. When executing consolidation method of construction by prefabricated vertical drain in deep-soft clay deposits, consolidation delay occurred partially about 2-7 times more in lower parts as the come-out phenomena of 1-2 m occurred.
5. When propelling consolidation in deep-soft clay deposits by using prefabricated vertical drain, not only mechanical reasons such as Well Resistance or Smear Effect but also constructional reasons such as the come-out phenomena of drain board or perpendicularity affected consolidation delay.

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