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Laboratory Test and Field Study of Soft Ground Improvement Effect by Using Various PVDs

실내실험과 현장실험을 통한 다양한 PVD의 연약지반개량효과

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ABSTRACT

The advantages of prefabricated vertical drains over conventional sand drains include their relatively low costs, less disturbance to the soil mass, the easinees of installation, and their flexibility which ensures the integrity of the drains during installation. This study tested the change of discharge capacities with respect to the hydraulic gradients for each lateral pressure. From the test results, as increases the overburden pressure, the clay soil is being consolidated, and also lateral pressure to the PVD specimen is increased. Therefore, the discharge capacity is decreased. The size of opening space in the core of PVDs is proportionally related to the discharge capacity. The numerical analysis was performed with utilizing computer simulation with considering field conditions. The results of numerical analysis are compared well with the field measurements.

요 지

인공연직배수재는 일반적인 샌드드래인에 비하여 비용 절감, 지반 교란의 최소화, 시공성 및, 시공 중에 발생될 수 있는 배수재의 변형을 최소화하는 유연성을 지니고 있다. 본 연구에서는 실내실험을 통하여 측압과 동수경사에 따른 여러형태 PVD의 통수능을 도출하였다. 시험결과는 압밀된 점토에 대한 과압력이 증가하였으며, 또한 PVD 공시체의 측압도 증가하였다. 이는 측압이 증가함에 따라 통수능이 감소됨을 나타내고 있으며, PVD 코어의 공극크기는 통수능과 비례관계에 있음을 보여준다. 현장조건을 고려하여 시뮬레이션을 통한 침하량에 대한 수치해석을 수행한 결과 현장계측한 침하량과 유사하게 나타났다.

Keywords **:** Prefabricated vertical drains, Soft clay, Discharge capacity, Field measurements

1. INTRODUCTION

Soft soil as a problem with low bearing capacity and large excess settlement due its low shear strength, high water content, and large time dependent deformations such as consolidation and creep. The main objective of vertical drain method is to accelerate the consolidation process so as to obtain the primary settlement in a shorter period of time and to increase the shear strength of soft ground. The advantages of prefabricated drains over conventional sand drains include their relatively low costs, less disturbance to the soil mass, the easinees of installation, and their flexibility which ensures the integrity of the drains during installation. Prefabricated drains can be installed at much faster rates than those of sand drains which makes more attractive to practical engineers. PVDs are also relatively adaptable and can be used in a variety of commonly encountered field conditions.

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Application of vertical drains is one of the most popular and effective methods of improvement of soft soil properties in South-Asian countries. This method can be applied by construction companies in Kazakhstan while constructing buildings on soft saturated soils of the coasts of Caspian and Aral seas, and also in cities of Kazakhstan because of high ground water table and underflooding of ground by flood and surface waters (Fig. 1).

2. LABORATORY DISCHARGE CAPACITY TEST

For settlement analysis a silty clay soil used which collected from Song-Do city coast, Republic of Korea. The geotechnical engineering properties of the soil as determined from the laboratory tests are tabulated in Table 1.

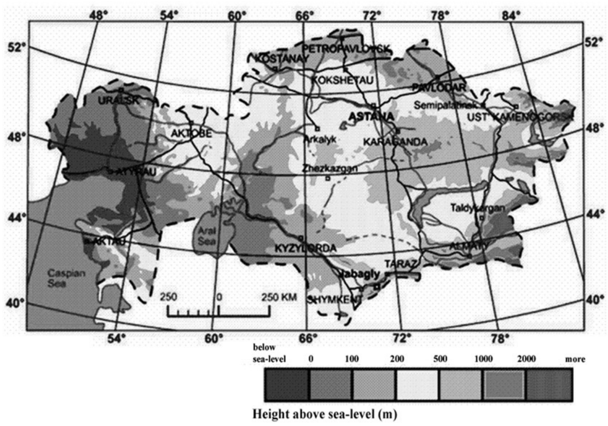


Fig. 1. Geographical map of the Republic of Kazakhstan

Six types of PVDs were tested, these PVDs have different structures (Table 2). Type A, B are plastic board

Table 1. Geotechnical engineering properties of clay

Properties	Item	Value
Physical, properties	Moisture content (w, %)	59.5
	Specific gravity (G_s)	2.7
	Liquid limit (LL, %)	35.1
	Plastic limit (PL, %)	22.5
	Plasticity index (PI, %)	12.6
	Flow index (FI, %)	10.6
	Initial void ratio (e_0)	1.48
	Saturated unit weight (γ_t, kN/m^3)	17
Compaction properties	Maximum dry unit weight (γ_d, kN/m^3)	15.6
	Optimum moisture content (w_{opt}, %)	25.5
Consolidation properties	Compression index (C_c)	0.32
	Remolded compression index (C_r)	0.0032
	Rate of strength increase (S_u/P_0')	0.279
	Coefficient of vertical consolidation (C_v, cm^2/s)	1.56×10^{-4}
	Coefficient of horizontal consolidation (C_h, cm^2/s)	0.003
	Vertical permeability (k_v, cm/s)	8.36×10^{-8}
	Horizontal permeability (k_h, cm/s)	1.09×10^{-7}
	Overconsolidated ratio (O.C.R.)	1.12

Table 2. Physical properties of PVDs

Types of PVDs		Quality of material	Standard weight of core and filter	Width (mm)	Thickness (mm)	Area of core space, mm^2	Permeability of filter, k (cm/sec)
Type A	Core	Polypropylene	60 g/m	100 ± 0.5	4 ± 0.5	400	1.3×10^{-2}
	Filter		140 g/m^2				
Type B	Core	Polypropylene	120 g/m	100 ± 0.5	4 ± 0.5	400	1.3×10^{-2}
	Filter		140 g/m^2				
Type C	Core	Polypropylene	80 g/m	100 ± 0.5	5	500	1.0×10^{-2}
	Filter		140 g/m^2				
Type D	Core	High-Density Polyethylene	138.3 g/m	32 (OD)	23.5 (ID)	803.84	2.8×10^{-1}
	Filter	Polypropylene	159.3 g/m^2				
Type E	Core	Polypropylene	112.2 g/m	95 ± 0.5	Over 6.5	617.5	1.0×10^{-2}
	Filter		140 g/m^2				
Type F	Core	polypropylene	128.5 g/m	102.1	6.45	658.5	1.1×10^{-2}
	Filter		140 g/m^2				

drains (PBD, Fig. 2), consisting of flexible flow path grooves on both sides along its length and nonwoven polypropylene geotextile with weight of core and filter 60 and 120 g/m, respectively.

Type C is a cylindrical board drain with longitudinal channel (CBD) with core of polypropylene. Type D is a plastic cylindrical drain (PCD) which is consisting of cylindrical shape core (high-density polyethylene) enveloped by filter. Type E is a plastic board drain with X-core (X-PBD). Type F is a plastic board drain with double core (D-PBD). The physical properties of the PVDs are given in Table 2.

Drain properties of six types of PVDs are described in Table 3. The total length of drains os about 90cm with the width of 10cm and the thickness of PVDs is varied. The equivalent drain diameter is approximately 6.4~6.9 cm. While the discharge capacities in the laboratory are about 3.43~4.70 m^3/day.

The change of discharge capacities with respect to the hydraulic gradients for each lateral pressure are shown in Fig. 3. From the test results shown in the figures, as

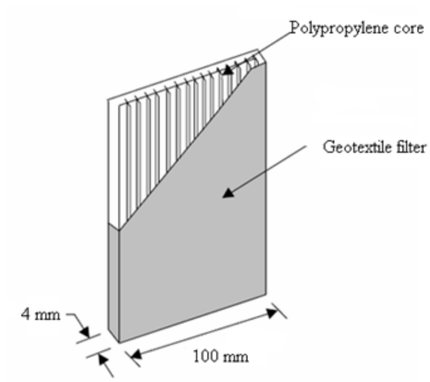


Fig. 2. Sketch of a prefabricated vertical drain

increases the overburden pressure, the clay soil is being consolidated, and also lateral pressure to the PVD specimen is increased. Therefore, the discharge capacity is decreased. From the physical properties of various PVDs which described in Table 2, the size of opening space in the core of PVDs is proportionally related to the discharge capacity.

3. NUMERICAL ANALYSIS FOR CONSOLIDATION SETTLEMENT

For each type of PVDs, the lateral earth pressure of 100 kN/m^2 was applied with the hydraulic gradient (i) of 1.0, the permeability ratio (k_h/k_s) is equal to 2.0, and the pattern of installation is 1.0.

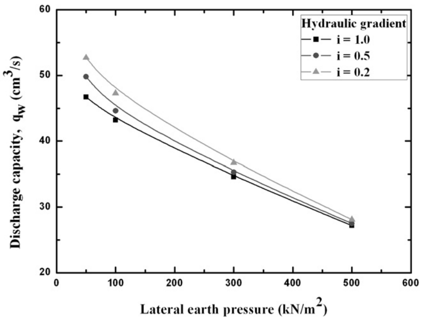
The numerical analysis of prefabricated vertical drains was performed using computer program PVD-SD version 2.3 (Chai and Bergado, 2000) for calculating the 1-D consolidation of soft clay ground improved with PVD. The soil parameters used in the numerical analysis to predict the consolidation settlement with the PVDs improved ground for each soil layer are tabulated in Table 4.

Where, C_h and C_v are horizontal and vertical coefficients of consolidation, respectively. C_c is the compression index and e_0 is the initial void ratio of soft clay. The value of M in Cam clay theory is chosen as 1.2 in this case. The drain parameter named LDRIN is 0 for without PVD and 1.0 with PVD inclusion in the soft ground.

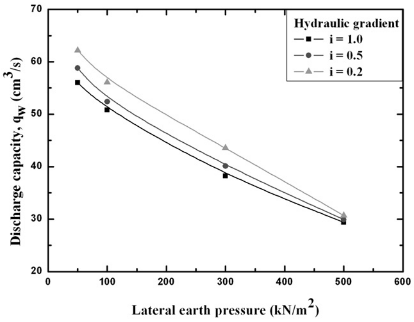
A number of input conditions such as degree of consolidation, ground water table, surcharge load, vacuum

Table 3. Drain properties for various PVDs

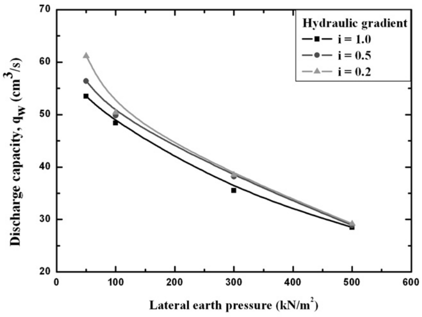
Type of drain	Length (m)	Width (cm)	Thickness (mm)	Equivalent drain diameter, d_w (m)	Diameter of smear zone, d_s (m)	Discharge capacity, q_w (m^3/day)
Type A	0.9	10	4	0.0662	0.1986	3.732
Type B	0.9	10	4	0.0662	0.1986	4.389
Type C	0.9	10	5	0.0662	0.1986	4.182
Type D	0.9	Ø3.2	-	0.0320	0.0960	4.691
Type E	0.9	9.5	6.5	0.0646	0.1938	3.430
Type F	0.9	10.2	6.45	0.0690	0.2070	4.691



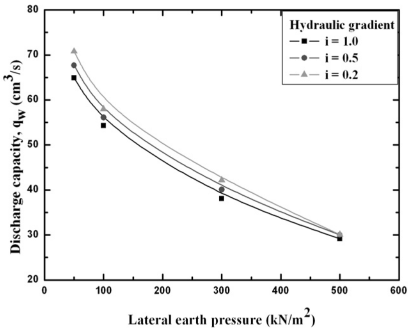
(a) Type A - PBD 60g



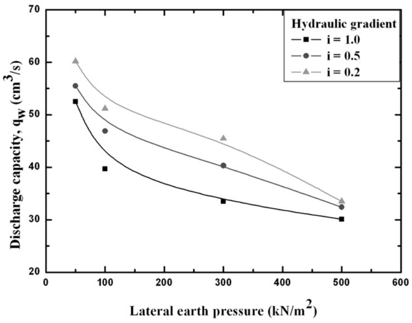
(b) Type B -PBD -120g



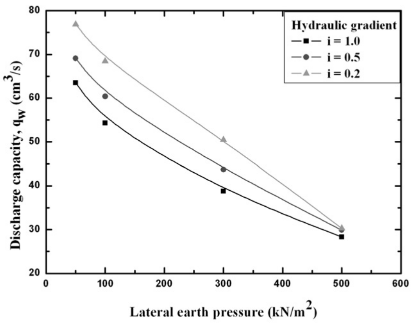
(c) Type C - CBD



(d) Type D - PCD



(e) Type E - X-PBD



(f) Type F - D - PBD

Fig. 3. Variation of discharge capacity with lateral pressure

Table 4. The soil parameters for each layer

Soil No.	Thickness of the layer, H (m)	C_h (m^2/d)	C_v (m^2/d)	Unit weight of the soil (kN/m^3)	C_c	e_0	M	OCR	LDRIN
1	5	0.026	0.00135	17.0	0.32	1.48	1.2	1.12	1

pressure, consolidation time, drainage condition, and the number of loading steps for numerical analysis were provided as described in Table 5.

Based the predicted consolidation settlement shown in Fig. 4, regardless of PVD type, the most of consolidation settlement occurs during the time period of 50days. The consolidation settlement is practically remained constant after preloading period of 100 days. The behaviour of consolidation settlement by numerical analysis is pretty much agreed with the degree of consolidation shown in

Table 5. Input conditions for numerical analysis of consolidation settlement

Items	Input parameters
Required degree of consolidation (%)	90
Ground water level (m)	2.5
Surcharge load (preloading, kPa)	40.0
Vacuum pressure applied at ground surface (kPa)	20
Total time (days)	365
Bottom drainage condition	one way
Number of load step	20

Fig. 5. However, the settlement prediction for PVD Type D is somewhat lower value in the early stage than those of other types. Because it has a cylindrical core shape and it can retard the dissipation of the pore water pressure. This phenomenon is illustrated in the consolidation process as shown in Fig. 5 as well.

The settlement and consolidation behaviour predicted by numerical modelling is well predicted with the past field observation of many ground improvement projects in the region of Incheon coastal area.

4. FIELD MEASUREMENT FOR PVD IMPROVED GROUND

The settlements of improved ground with six different types of prefabricated vertical drains are predicted by using computer program PVD-SD version 2.3 (Chai and Bergado, 2000) and compared with the field observation .

Field settlement of improved ground was conducted on

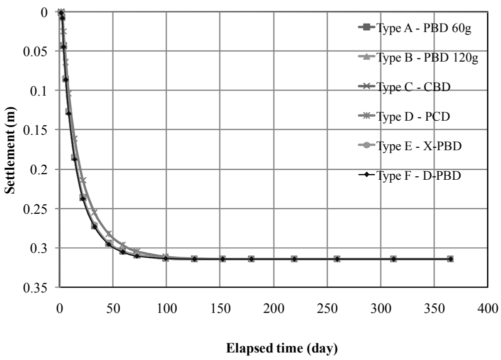


Fig. 4. Predicted consolidation settlement with elapsed time for various PVDs installed ground

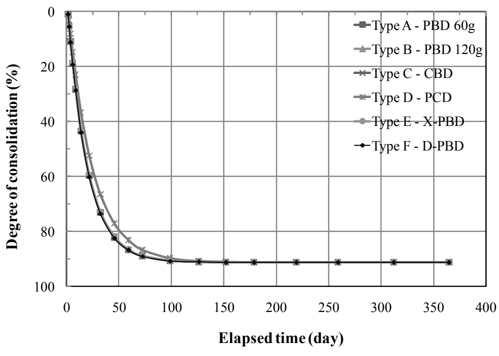


Fig. 5. Degree of consolidation with elapsed time for various PVDs installed ground

Song-Do site. New Song-Do City is located at 35 km west of Seoul on a reclamation land along Incheon's waterfront, and connected to Incheon International airport by Incheon Bridge. The field monitoring on the prefabricated vertical drains improved subsoil was carried out on Song-Do new campus site of the University of Incheon. The effectiveness of prefabricated vertical drains for ground improvement was investigated.

The pressure of preloading is equivalent to the 2.48 m soil height with the moisture unit weight of soil, 16.13 kN/m^3. The material of the preloading is mixed soil between the dredged soil and waste lime which is the by product of chemical factory. The preloading (surcharge load) applied in this study takes into account weight of pavement thickness for road and the prospective traffic load. The allowable settlement for road is normally limited as 10cm. Therefore, the future settlement in this case will be minimized with the elimination of present settlement by using combined techniques the preloading and PVD. The thickness of sand mat is approximately 25cm and it is placed below the preloading to drain the water out horizontally which is extruded out via PVD. The cross section of the ground improvement work with PVDs is shown in Fig. 6. The vertical settlements (s) were measured by the settlement plate (S) at 3 locations with the embedment depth of 20cm below original ground surface. The lateral displacement (δ) was also monitored with using the inclinometer. The vertical consolidation settlements shown in Fig. 7 is based on the field measurement of settlement plate No.2 (SP2).

The computed settlement results shown in Fig. 7 are

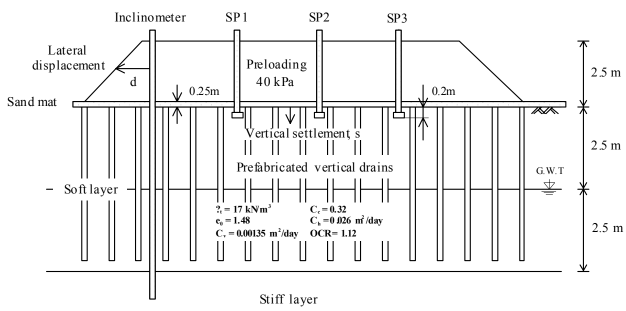


Fig. 6. Cross section of the ground improvement work with PVDs

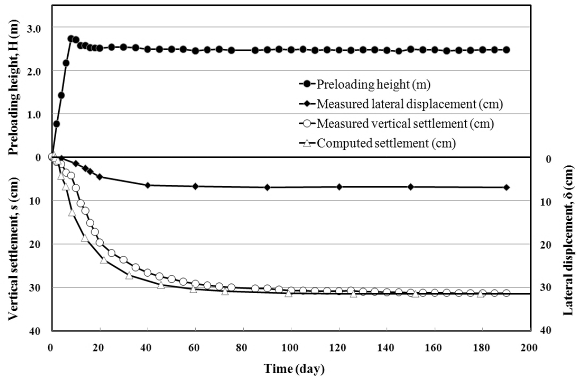


Fig. 7. Comparison between measured settlement SP2 and computed settlements

obtained from Fig. 2 for PVD Type A. At the initial stage, the computed results are somewhat larger than the measured values. At the final loading stage, the computed settlements are slightly larger than the measured results as well. The maximum settlement was 31.4cm for 126 days by the computer program, the settlement was 31.3 cm for 170 days by measured results. The results of numerical analysis indicates that the settlement level in Song-Do area is very much similar than those of field measurement in Incheon Bay Area.

The finite element procedure shows very good numerical stability characteristics and is used for analysis of 1-D consolidation clay. The measured and computed settlements are illustrated in Fig. 7. The settlements computed by using the one-dimensional consolidation theory are well agreed with measured (observed) settlements.

The stability control monitoring technique for the PVD improved ground under the preloading process was performed by following the stability chart proposed by Matsuo and Kawamura (1977) with the field measurement of vertical settlement and lateral displacement. In Fig. 8, q is the preload per unit area causing displacements s and δ for anyloading stage and q_f is the failure load per unit area. The lateral displacement occurred with respect to the vertical settlement is approximately within the ratio of 0.13~2.5 and hence at all times it is well below the stability control limit line as shown in Fig. 8. Most of vertical settlement and δ/s ratios from the field observation fell below the line of q/q_f = 0.7.

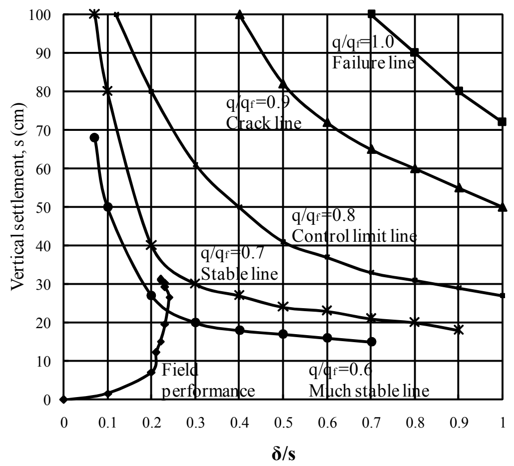


Fig. 8. Stability control by Matsuo and Kawamura method (1977) for PVD improved ground

5. CONCLUSIONS

Laboratory test were conducted to determine the discharge capacity for various PVDs. The numerical analysis was also performed with utilizing computer simulation with considering field conditions. The results of numerical analysis are compared well with the field measurements. Based on the economic efficiency analysis (Shin E.C. et al., 2008), laboratory discharge test numerical analysis, and field observation, the following conclusions are drawn.

1. The standard banded type of PVD (Type A) is the most suitable and economical vertical drain for clayey soils in the ground improvement work.
2. Using PVDs are shortening the consolidation settlement time required such that final construction can be completed in a reasonable time with minimal post construction settlement.
3. The field measured settlement shows a good agreement with comparison of the numerical analysis.
4. The numerical analysis for prediction of consolidation settlement on PVD improved ground is pretty accurate, and hence design and construction efficiency is greatly improved.
5. The stability of preloading embankment with PVD installed soft ground is effectively controlled by using the method of Matsuo and Kawamura (1977).

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