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Effect of PBD to improve soft marine sedimentary ground

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Abstract : *The effect of plastic board drains (PBDs)on ground improvement was checked out considering three crucial factors: ground settlement, undrained shear strength, and residual water head. First, the settlement analysis including initial settlement induced by reclamation of sand mat was conducted by back calculation analysis with measured data. Its result showed that the PBDs used for this site worked well on improving soft ground. Secondly, the undrained shear strength was investigated by laboratory and in-situ tests including unconsolidated-undrained triaxial compression (UU) tests, unconfined compression tests, in-situ vane tests, and cone penetration tests. From the test results, they showed that the undrained shear strength of the improved ground by PBDs was significantly increased as well as the strength increasing ratio especially 10 ~ 15 m below the ground surface on site. Thirdly, the residual water head measurement from the in-situ dissipation test was found the same as the static water head, which indicated primary consolidation was completed and the effect of soil improvement with PBDs can be confirmed.*

Key words : *Shear Strength, Settlement, Soft Marine Clay, Plastic Board Drain (PBD)*

1. Introduction

Use of plastic board drain (PBD) as a vertical drain method for soft ground improvement has been commonly used in many countries. Usually, the plastic board drain consists of a filter and plastic core. The PBD method is used to accelerate consolidation of soft clay deposits and thus decrease the required time for consolidation (Barron, 1948; Hansbo, 1979; 1981). Many researches related to PBD method have been studied experimentally and theoretically on the factors of smear zone, well resistance, installation pattern, discharge capacity, material properties, and permeability, etc. (Yoshikuni and Nakanodo, 1974; Yoshikuni and Nakanodo, 1981; Onoue, 1988a; 1988b; Zeng and Xie, 1989; Holts et al., 1989; Chai and Miura, 1999; Kiyama et al., 2000; Kim et al, 2006; Basu and Prezzi, 2007). Although the previous these researches provided an understanding of PBD performance and factors affecting their function, there were few published studies on ground improvement effect of PBD using a field monitored data.

In this paper, thus, the improvement effect of plastic board drains in soft ground was examined using a filed data. Three crucial factors such as ground settlement, undrained shear strength, and residual water head were considered. The settlement analysis is a typical method to check ground improvement. However, in this paper, the settlement analysis including initial settlement induced by reclamation of sand mat was conducted by back calculation analysis with measured data. The improvement effect of PBDs was also assessed directly by using in-site tests such as CPT or other tests. To do this, before and after PBD installation, the undrained shear strength were investigated at laboratory tests including triaxial compression (UU) tests, unconfined compression tests and in-site tests including filed vane tests and cone penetration tests. In addition, the residual water head was checked by dissipation test after completion of surcharge removal to find out the state of excess pore water pressure.

2. Site Description

Busan new port container terminal is located in the west of Pusan city in Korea, which has been under construction Port since 1995. It is scheduled to be open fully in 2011. The purposes of this new port are to develop it into the hub port of northeast Asia and to overcome the shortage of existing port facilities in Busan. The phase 1-1 site at Busan new port is introduced to study the effect of Plastic Board Drains (PBDs) on ground improvement. The outline of Busan new port (Phase 1-1) construction is divided into three parts:

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quay wall construction, container yard construction, and the other such as revetment work and small craft wharf work. The PBDs were used in container yard construction to improve ground properties especially undrained shear strength and to accelerate consolidation of deposit ground (Korea Pusan New Port Company, 1997; 1999; Korean Geotechnical Society, 2004; Lee et al., 2006).

PBD installation was started in August 2002 in this site. The installation depth is about 30~50m, and three different spacing (pitch) of 1.0m, 1.2m, and 1.5m were used. The square arrangement was applied. A total of 8~12 PBDs installation equipments were used. The PBD installation depth and the amount of installed PBDs are summarized in Table 1.

Table 1 Summary of installed PBDs at container yard construction site

Pitch	Depth (m)	Installed amount(m)	Total amount (m)
1.5×1.5m	41-45	5,131,833	32,088,326
1.2×1.2m	26~48	18,353,390	
1.0×1.0m	25~41	8,603,103	

3. Management of PBD Allation

Figure 1 shows the layout of PBD installation in container yard construction site. In Areas F1 and E1, PBDs are installed with 1.5 m pitch with square arrangement. In Areas D2, C2, B2, and A2, PBDs are installed with 1.0 m pitch with same arrangement. For the rest of areas, 1.2m pitch with square arrangement is applied.

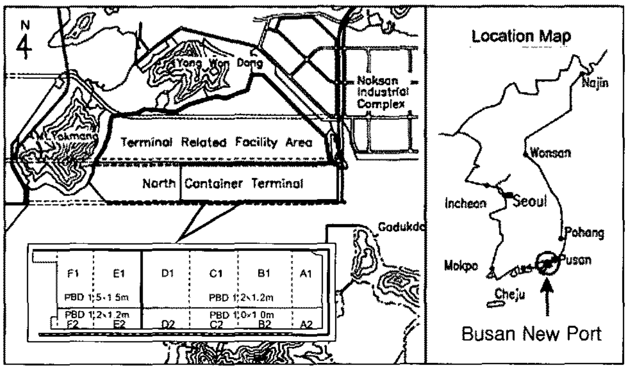


Fig. 1 Layout of PBDs installation at container yard construction site

The PBD used in this site is VD 849. The drain core and filter of this PBD are separated-form pocket drain. The selection criteria of PBD quality control include tensile strength of filter, apparent opening size (AOS) of filter, tensile strength of drainer, and drainage capacity of drainer. In details, the tensile strength for the filter should be more than 70kg and for the drainer it should be over 200 kg/m. The criterion of AOS is less than 80 μm, and the drainage capacity should be over than 25 cm^3/sec. Since the most important matter for PBD quality control criteria is the capacity of drainage, the drainage capacity of drainer is strictly obeyed.

The management of PBD installation is very important because it directly influences the ground improvement quality. Therefore, the following guidelines were strictly obeyed during PBD construction: The PBD penetration position was with accuracy under 10 cm, the length of each drain board roll was over 300 m. If the length of remaining board was shorter than penetration depth, the board would be joined and be disposed. In addition, a mandrel remained vertically when it started to penetrate and after pulling out the mandrel, and PBD cuts with remaining over 30 cm.

4. Estimation of Ground Improvement

4.1 Settlement Analysis

1) Initial Settlement

Before conducting settlement analysis, in this section, the initial settlement due to reclamation of sand mat is estimated. In general, the ground improvement is undertaken by following procedures; reclamation of sand mat, PBD installation, preloading surcharge, removal of surcharge (Fig. 2). During this procedure, estimation of initial settlement is very important because it is a critical factor, which affects the time of removal surcharge. The surcharge was removed when the ground reached over 90% of degree of consolidation or 10 cm of residual settlement.

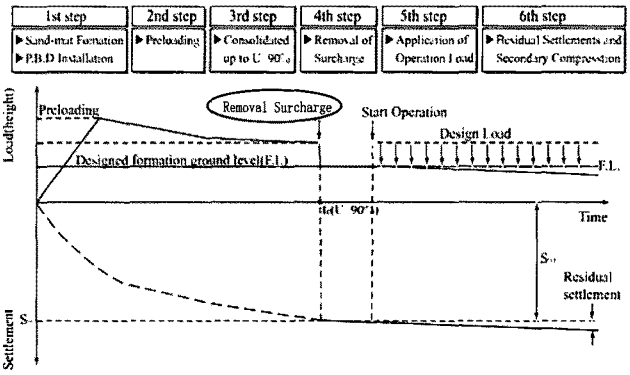


Fig. 2 Flow of ground improvement with PBDs

To estimate an initial settlement, typically, the settlement and pore water pressure gauges were used. However, due to installation of PBDs, these instruments were destroyed frequently. Therefore, before and after PBDs installation, it was very difficult to estimate the initial ground settlement. If the initial settlement is not considered, preloading surcharge may be overloaded or the time of removal surcharge may be wrong predicted.

The following two methods are applied to estimate an initial settlement: 1) ground level measurement and 2) cone penetration tests. The ground level was measured after reclamation of sand mat and PBD installation at the same locations installed the measurement gauges. In Fig. 3, the initial settlement occurs in range of 0.4 m ~ 1.0 m during between the reclamation of sand mat and the PBD installation. The average settlement is about 0.6 m and it is almost constant without the elapsed time between sand mat formation and PBD installation. In addition, the initial settlement is linearly increased with depth of reclamation of sand mat (Fig. 4). It is directly related to the pore water pressure occurred in soft ground due to loading pressure of sand mat.

An initial settlement was also estimated by cone penetration tests. The border between reclamation of sand mat and soft ground was clearly detected when CPTs were conducted, because the resistance of ground was very different between sand mat and soft ground. Figure 5 shows an initial settlement obtained from cone resistance, q_t (Eq. 1, Rodertson and Campanella, 1983), from CPT, before and after PBD installation.

$$q_t = q_c + (1-a)u_{bt} \tag{1}$$

where q_t = Corrected cone resistance

q_c = Cone resistance

a = net area ratio

u_{bt} = pore water pressure

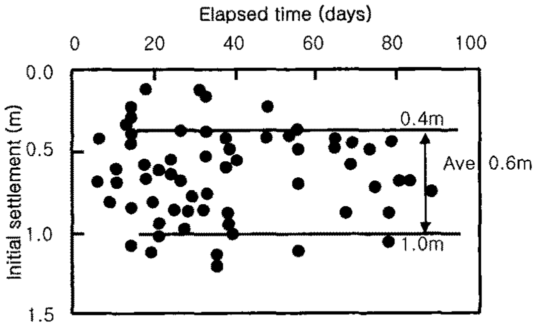


Fig. 3 Results of the measured ground level during the time between reclamation of sand mat and PBD installation

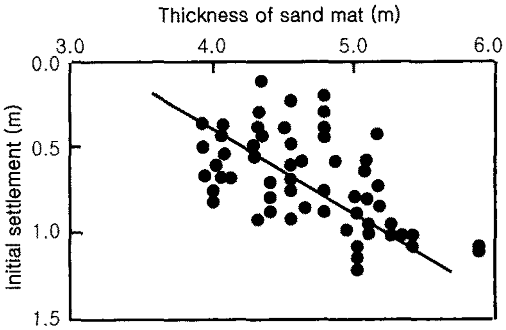


Fig. 4 Relationship between the initial settlement and the thickness of reclamation of sand mat

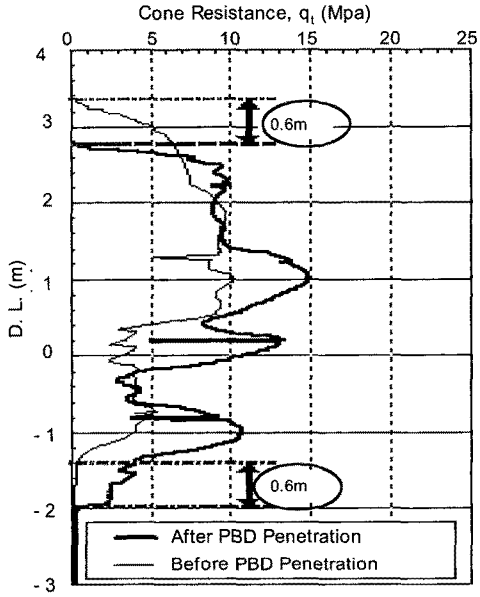


Fig. 5 CPT results before and after PBD installation on the soft ground with reclaimed sand mat

In Fig. 5, the variation of ground height is the same as that the height of soft ground underneath sand mat. It is evident that the ground settlement when the sand mat was formed is the settlement due to consolidation of original soft ground. Thus, it is considered in case of the analysis of removal surcharge loading. In addition, based on this CPT result, the compression of reclaimed sand layer itself was not occurred because in this site the reclaimed layer which was formed by pumping with a hopper ship was automatically compacted by water binding.

Figure 6 clearly shows the effect of initial settlement on settlement behavior of the soft ground improved by PBDs. Comparison between settlements included or not the initial settlement, there is always a difference with amount of the initial settlement by the end of consolidation. Therefore, if the initial settlement is not considered, surcharge is overloaded with an extra load to induce the settlement, and thus it makes difficult evaluating proper soil properties, which need to predict settlement behavior. Consequently, the prediction of settlement which requires to management of construction procedure may be wrong.

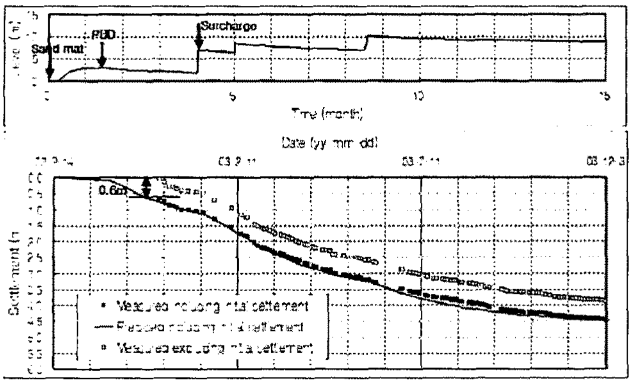


Fig. 6 Measured and predicted settlements of the soft ground improved by PBDs with considering initial settlement due to reclaimed sand mat in D 1 block area

2) Settlement Analysis Including Initial settlement

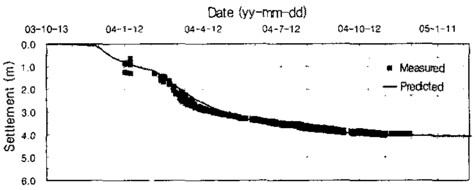
Theoretically, the dissipation of excess pore water pressure can induce settlement of ground and the same degree of consolidation could be estimated from pore water pressure and settlement gauges. However, the degree of consolidation obtained by pore water pressure and settlement gauges may be different compared to the induced real settlement. Since the pore water pressure gauge did not show consistent results due to nonhomogeneity of ground, sensor correction for depth due to settlement, variation of ground water level, the degree of consolidation along depth based on the pore water pressure gauges may not be correct. Therefore, the estimation of degree of consolidation using pore water pressure gauge is not recommended, and it is reasonable to use the degree of consolidation predicted by the pore water pressure gauge just for reference.

The degree of consolidation or the time of surcharge removal is estimates using the ground settlement. Table 2 shows the back analysis results predicted by TCON program (TAGA Engineering Ltd.) considering construction background history. TCON program (a Finite Difference Method) was developed based on Terzaghi one dimensional theory. This program can calculates consolidation settlements and rates of settlement. It allows radial as well as vertical drainage providing the capability to simulate sand or wick drains. To do back analysis, first, input data such as unit weight, water content, compression index, consolidation velocity, and coefficient of consolidation were prepared for each location placed measurement gauges. Then, estimated of soil properties especially coefficient of consolidation by trial and error method by comparison with the measured data. The time of surcharge removal in corresponding 10 cm of residual settlement for operating load (or over 90% of degrees of consolidation) was estimated.

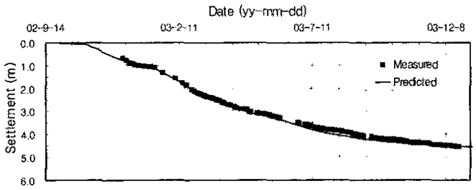
In Table 2, the time when the surcharge load was removed is the degree of consolidation that reached over 92% for all block areas. This degree of consolidation satisfied the design criterion. In design, the coefficient of horizontal consolidation is assumed as two times of the coefficient of vertical consolidation, $c_h = 2c_v$. In back analysis, the predicted settlement is closed to the measured one if the coefficient of horizontal consolidation is assumed as 2.3~3.5 times of the coefficient of vertical consolidation. The measured and predicted relationship between time and settlement at sites (A~F block areas) improved by PBDs with 1.0, 1.2, and 1.5m pitches are shown in Fig. 7. These results are included the initial settlement mention in Fig. 6. The improved depths of PBDs for each block are about 32 m, 40 m, and 40 m, respectively. The predicted results well matched measured results. Based on these settlement analyses, therefore, the PBDs used for this site are well working on improving the soft ground.

Table 2 Back analysis results predicted by TCON program

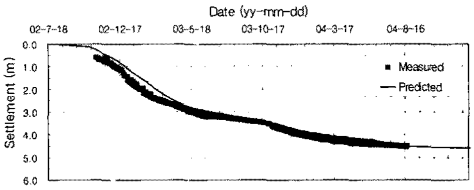
Block	Pitch of PBD (m)	Back Analysis Result from TCON (Settlement, m)			Degree of Consolidation (%)	c_h/c_v
		Removal of surcharge (Measured)	Final (Predicted)	Operating Load (Predicted)		
A-1	1.2×1.2	4.185	4.263	4.106	98.2	3.3
A-2	1.0×1.0	2.922	2.967	2.856	98.5	3.0~3.5
B-1	1.2×1.2	4.280	4.460	4.200	95.8	2.5
B-2	1.0×1.0	3.973	4.092	3.932	97.1	3.6
C-1	1.2×1.2	4.350	4.560	4.280	95.4	2.8~3.0
C-2	1.0×1.0	3.968	4.114	3.903	96.5	3.2
D-1	1.2×1.2	4.620	4.785	4.556	96.6	2.3~3.4
D-2	1.0×1.0	4.812	4.910	4.693	98.0	3.3~3.5
E-1	1.5×1.5	5.393	5.734	5.339	94.1	3.1
E-2	1.2×1.2	5.792	6.150	5.710	94.2	3.0
F-1	1.5×1.5	5.031	5.437	4.919	92.5	3.1~3.2
F-2	1.2×1.2	5.650	6.113	5.566	92.4	2.5~2.8



(a) C-2 Block



(b) D-1 Block

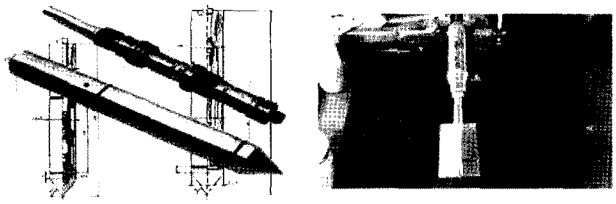


(c) E-1 Block

Fig. 7 Measured and predicted relationship between settlement and time in sites of C-2 (pitch 1.0 m), D-1(pitch 1.2 m), and E-1 (pitch 1.5 m) blocks included initial settlement

4.2 Laboratory and In-situ Tests Analysis

To find out the ground improvement in this site applied PBDs, additional laboratory and in-situ tests including cone penetration tests and field vane tests were conducted. Cone penetration test used in this site was manufactured from Geomil Corporation, Netherlands (Fig. 8). The pushing force of this device is up to 20 ton and the driving depth can be up to 100 m. This device is also equipped with the automatic data acquisition system and the wireless control system. Field van test device is an electrical field vane(3.5cm × 7.0cm, 5.0cm × 10.0cm), which is attached inside the cone penetration test device.



(a) Electric Cone (D=10㎠, 15㎠)

(b) Electric Field Vane

Fig. 8 In site test devices used for CPT and FVT

Figure 9 shows the results of CPTs obtained before and after PBDs installation. The corrected cone resistance q_t (Eq. 1) is employed. In Fig. 9, the cone resistance is increased after PBDs installation and the ground improvement is less dependent on the PBD's pitch.

Figure 10 shows the results of undrained shear strengths obtained from laboratory tests including triaxial compression tests (UU) and unconfined compression tests, and in-situ tests including field vane tests, and cone penetration tests. Most of in-situ tests were preformed on the improved ground by PBDs just before the surcharge removal. The laboratory tests were conducted on samples collected when the ground was before and after improved. Based on these results, all areas improved by PBDs shows an increase of 2 ~ 8 t/m^2 of undrained shear strength. In general, the undrained shear strength obtained from the laboratory tests was smaller due to disturbance of soil specimens during sampling, trimming and testing. Allowing for this fact, the results of Fig. 10 are another clear evident how much PBD well works for soft ground improvement in this site.

$$S_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \quad \text{for cone penetration test}$$

$$S_u = \frac{M_{\max}}{\pi D^2\left(\frac{H}{2}+\frac{D}{6}\right)} \quad \text{for field vane test} \tag{2}$$

where

q_t = Corrected cone resistance

N_{kt} = Undrained shear strength cone factor for clays 15

σ_{vo} = Overburden stress

D = Blade diameter

H = Blade height

M_{max} = Maximum moment

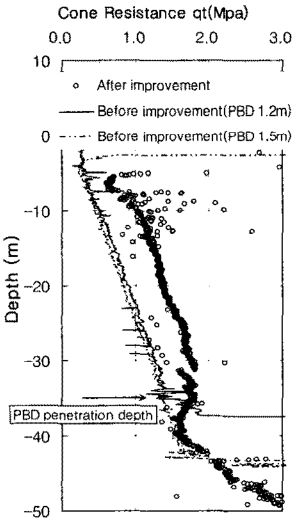
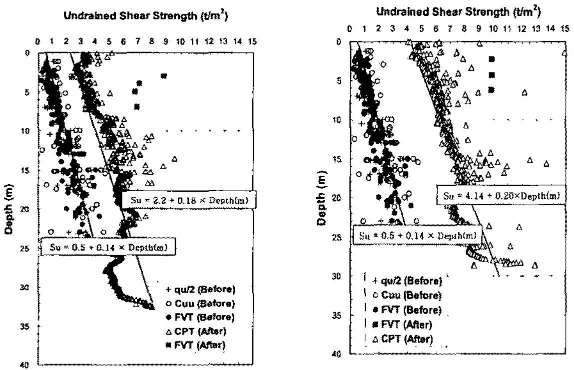


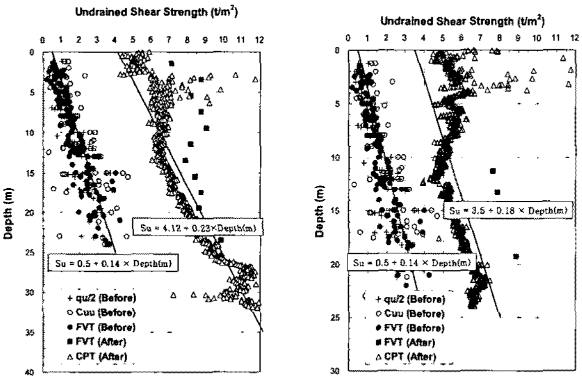
Fig. 9 Corrected cone resistance values before and after PBD installation in D-1 block area

4.3 Residual Water Head Analysis

After completion of surcharge removal, standpipe-type piezometers were installed, and then water pressure dissipation tests were performed to measure water level in soil. Figure 11 shows the results with relationship between static water head (denoted as solid line) and residual water head (Δh) after dissipation test. In this figure, the residual water head in soft ground is independent on the PBD pitches and is dependent on the depth of ground level. Another important fact from this figure is that the residual water head is about the same as the static water head. It means that the primary consolidation is almost completed and the effect of soil improvement with PBDs can be confirmed.



(a) A 1 Block (b) B 2 Block



(c) C 1 Block (d) D 1 Block

Fig. 10 Increase of undrained shear strength of the soft ground before and after PBDs improvement

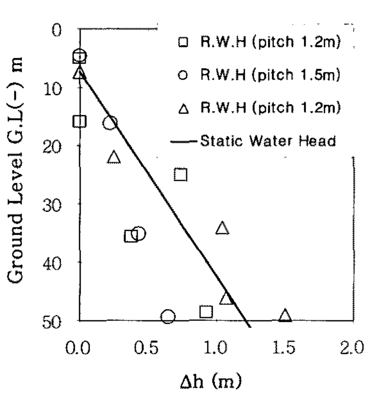


Fig. 11 Relationship between static water head and residual water head with depth

5. Conclusion

The soft marine clay improved by plastic board drains (PBDs) is analyzed on undrained shear strength, ground settlement, and residual water head to confirm the ground improvement. From this study, the following things are concluded.

1) Settlement included initial settlement induced by reclamation of sand mat indicates that the PBDs used for this site work well on improving the soft ground.

2) Undrained shear strength investigated by laboratory and in-situ tests including triaxial compression (UU) tests, unconfined compression tests, field vane tests, and cone penetration tests was significantly increased after PBD installation and also the increasing ratio of its strength is pronounced as increasing depth especially 10 ~ 15 m below the top surface of improved ground.

3) Residual water head obtained dissipation test in PBDs improved ground after surcharge removal was the same as the static water head, which means primary consolidation was completed and the effectiveness of soil improvement with PBDs can be confirmed.

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