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Measured Performance and Analysis of the Residual Settlement of a PVD-Improved Marine Soft Ground

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Abstract Prefabricated vertical drains (PVDs) are commonly used to shorten the drainage path for consolidation as part of the improvement of marine soft ground. Many studies that focus on the primary consolidation settlement of PVD-improved soft ground have been conducted; however, residual settlement has been scarcely investigated. Residual settlement is the net effect of secondary compression and the remaining primary consolidation and generally occurs while the facilities are operating. In this study, residual settlement was investigated using the measured field settlement data obtained from the surface settlement plate and multilayer settlement gauges. This study determined that PVD still has some effect on residual settlement and can reduce the settlement times. Residual settlement is only related to the PVD-improved soil layer and only occurs significantly in the middle zone of that layer over a few months. The middle zone may be related to the time delay of excess pore water pressure dissipation. This study concluded that the remaining primary consolidation in the PVD-improved soil layer is the primary cause of residual settlement, whereas secondary compression in the PVD-improved soil layer is only a minor cause.

Key words residual settlement; prefabricated vertical drain (PVD); operating facilities; primary consolidation; secondary compression; marine soft ground

1 Introduction

Prefabricated vertical drains (PVDs) are commonly used to improve the soft ground in many large-scale projects, such as the Tianjin Port, Changi East Reclamation, Kansai Airport, Haneda Airport, Chek Lap Kok Airport, North Jakarta Waterfront Reclamation, and Incheon Airport. The PVD accelerates the consolidation of soft clay deposits (Hansbo, 1979; Chu *et al*., 2006). Numerous studies related to the PVD have included experimental and theoretical investigations of the smear zone, well resistance, installation pattern, discharge capacity, material properties, and permeability (Chai and Miura, 1999; Kiyama *et al*., 2000; Bo, 2004; Basu and Prezzi, 2007; Tripathi and Nagesha, 2010). The application efficiency, design, and various installation methods of the PVD have also been investigated (Abuel-Naga *et al*., 2006; Liu *et al*., 2008; Abuel-Naga and Bouazza, 2009; Geng *et al*., 2011; Howell *et al*., 2012).

Although previous research has explained the performance of PVDs, the factors affecting their function, and their effect on ground improvement, few studies have investigated the residual settlement of PVD-improved soft ground (Mesri, 2001; Long, 2005). Most studies have focused on settlement due to primary consolidation during the ground improvement period in an attempt to estimate the change in the strength of soft soil and the amount of time required to remove the surcharge (Hansbo, 1981; Zeng and Xie, 1989; Byun *et al*., 2009). Through the use of the vertical drain (VD) method, residual settlement of the improved soft ground can be determined on the basis of the following components in the consolidation process: 1) the remaining primary consolidation settlement under a service load of VD-improved soil layers ($\mathrm{RS_I}$), 2) the secondary compression of VD-improved soil layers ($\mathrm{RS_{II}}$), and 3) the remaining primary consolidation under a service load of underlying soil layers without VD improvement ($\mathrm{RS_{III}}$) (Long *et al*., 2013). Because of the removal of the surcharge (followed by the application of operational stresses), these components can aid in the determination of residual settlement. Only the first and third components should be affected by the PVD, as they are related to the dissipation of pore water pressures. These three components of residual settlement are difficult to differentiate. Therefore, engineers follow the rule that the maximum value of residual settlement should be smaller than the value specified in the design criteria of the project.

From the perspective of facility maintenance and management, residual settlement (also known as post-construction settlement), which occurs after the construction is

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complete, is no less important than primary consolidation because it is known to cause several problems and tends to occur continuously while the facility is operating. Design parameters and current design criteria often fail to consider residual settlement (Long, 2005). In some cases, significant differences between field performance and design expectations exist, particularly regarding residual settlement after construction (Long *et al*., 2013). Many researchers have conducted analytical and numerical studies (Yin and Graham, 1994; Balasubramaniam *et al*., 2010; Indraratna *et al*., 2011; Tashiro *et al*., 2011; Ghandeharioon *et al*., 2012) of residual settlement, as well as extensive laboratory and field (small-scale and large-scale) tests (Leroueil *et al*., 1985; Mersri and Castro, 1987; Mesri, 2001; Mesri and Vardhanabhuti, 2005). However, few studies of residual settlement behavior have been conducted during facility operation at a real project site because of the lack of complete instrumentation and the challenges of implementing the available instrumentation (Simons, 1957; Bjerrum, 1967; Salem and El-Sherbiny, 2014).

Therefore, in this study, the residual settlement behavior of soft ground improved by PVDs was investigated using the settlement data collected at a container yard site (1.92 km^2). The field settlement data were monitored throughout the entire soft ground improvement process, that is, from PVD installation to facility operation (approximately 4 years). In particular, the residual settlement data obtained from the multilayer settlement gauges after removing the surcharge load, followed by the application of the operating load, were investigated in detail to determine the effect of PVD on residual settlement, the variation of residual settlement with depth, and the soil layer that is primarily related to residual settlement.

2 Site Description, Clay Properties, and Ground Improvement Using PVDs

The site, which is located west of Busan City, was opened in 2006. This area corresponds to the lower delta plain of the Nakdong River Delta, which is covered by a thick deposit consisting of thick soft clay, sand, and gravel on the bedrock. In some areas, the thick soft clay layer is thicker than 70 m. The average depth of clay ranges from DL.(−)30 m to DL.(−)50 m (Fig.1).

In terms of physical and mechanical properties, the overconsolidation ratio (OCR) values of clay at depths greater than 30 m are greater than unity, whereas those of clay at depths less than 30 m are less than unity. Clay has a unit weight of approximately 15 to 18 kN m^{-3}, void ratio of 1.5 ± 0.5, and water content of approximately 20% to 75%. The compression index (C_c) ranges from 0.3 to 1.2 (Fig.2). The specific gravity is approximately 2.7. Clay is located between the A-line and the U-line on the plasticity chart and can be categorized as CL or CH on the basis of the Unified Soil Classification System. The activity of clay is approximately $A = 1.0$ and can be inferred to include mostly illite ($A = 0.5 - 1.0$) (Fig.3). On the basis of the results of the field vane shear test (FVST), unconfined compression (q_u), and unconsolidated undrained triaxial compression tests (C_{uu}), the undrained shear strength (S_u) is increased. The *N* values of the standard penetration tests of clay range between 0 and 2 in DL.(−)0 to 10 m and between 2 and 8 in DL.(−)20 to 40 m (Fig.4). The *N* value is the total number of blows required to drive the sampler to a depth of 30 cm (Lee *et al*., 2006; Byun *et al*., 2009). This soft soil is expected to have a large degree of settlement when it is subjected to loading.

To improve the soft ground, PVDs were installed at this site. The improved depth of soft clay was determined using the *N* value. Soil with an *N* value less than 8 was improved, and its depth approximately corresponded to DL.(−)30 to 40 m (Fig.1(c)). The time it took the ground to improve was 12 − 21 months, and the applied surcharge load was 15.38 − 28.56 t m^{-2}. In general, ground improvement with PVDs occurs through the following steps: sand mat formation, PVD installation, surcharge preloading, and surcharge removal (Fig.5(a)). The PVD was installed on the sand mat formed to DL.(+)3.0 m. After leveling the sand mat, the PVD installation positions were marked, the PVD installation equipment was assembled, and the PVD was installed. The PVD began to penetrate the ground, and the mandrel was kept vertical. When the PVD reached the required depth, the mandrel was pulled out, and the remaining 30 cm of PVD was cut. Before starting the surcharge, the top of the PVD was bent and the head was arranged (Fig.5(b)). The management of PVD installation is important because it directly influences the improvement of the ground. The installation position of PVD penetration must be accurate within 10 cm from its plan position. The installation depth of the PVD is approximately 30–40 m. If the length of the remaining drain is shorter than the installation depth, then the remaining drain should be disposed of. Three different spacings (pitches) of 1.0, 1.2, and 1.5 m were used with the square arrangement. The total length of PVDs installed at this site was approximately 32088326 m.

Compressible soil becomes consolidated as the pore water is expelled from the soil matrix. The time required for consolidation depends on the square of the distance the water must travel to exit the soil. PVDs provide short drainage paths for the water to exit the soil. Consolidating soft cohesive soils using PVDs with preloading can reduce the settlement times from years to months. Thus, settlement mostly occurs during construction, which keeps post-construction settlement to a minimum.

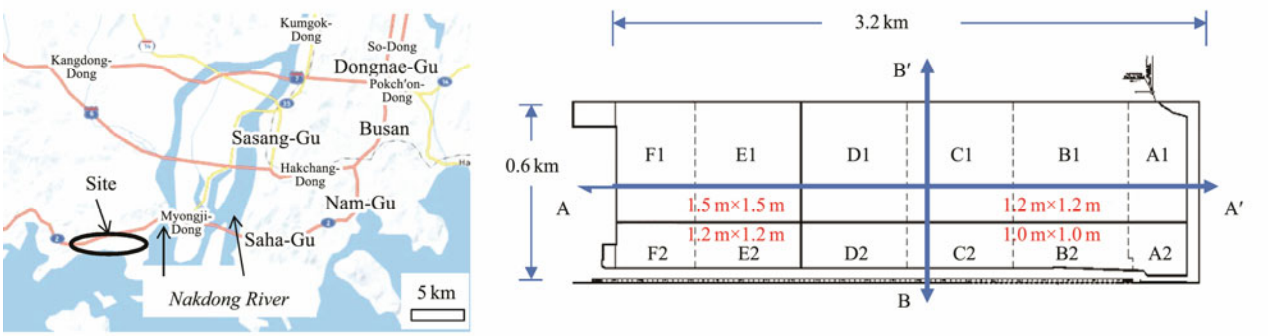
The PVD used (product name VD 849) at this site was a separate-form pocket drain. In this type of PVD, the drain core and filter are separate and made from a 100% virgin polypropylene core and a nonwoven filter jacket marked as a PVD filter material. Table 1 shows the required PVD quality criteria and properties of VD 849. The most important property for PVD quality control is the drainage capacity, which should be greater than 25 cm^3 s^{-1}.

3 Instruments and Monitoring

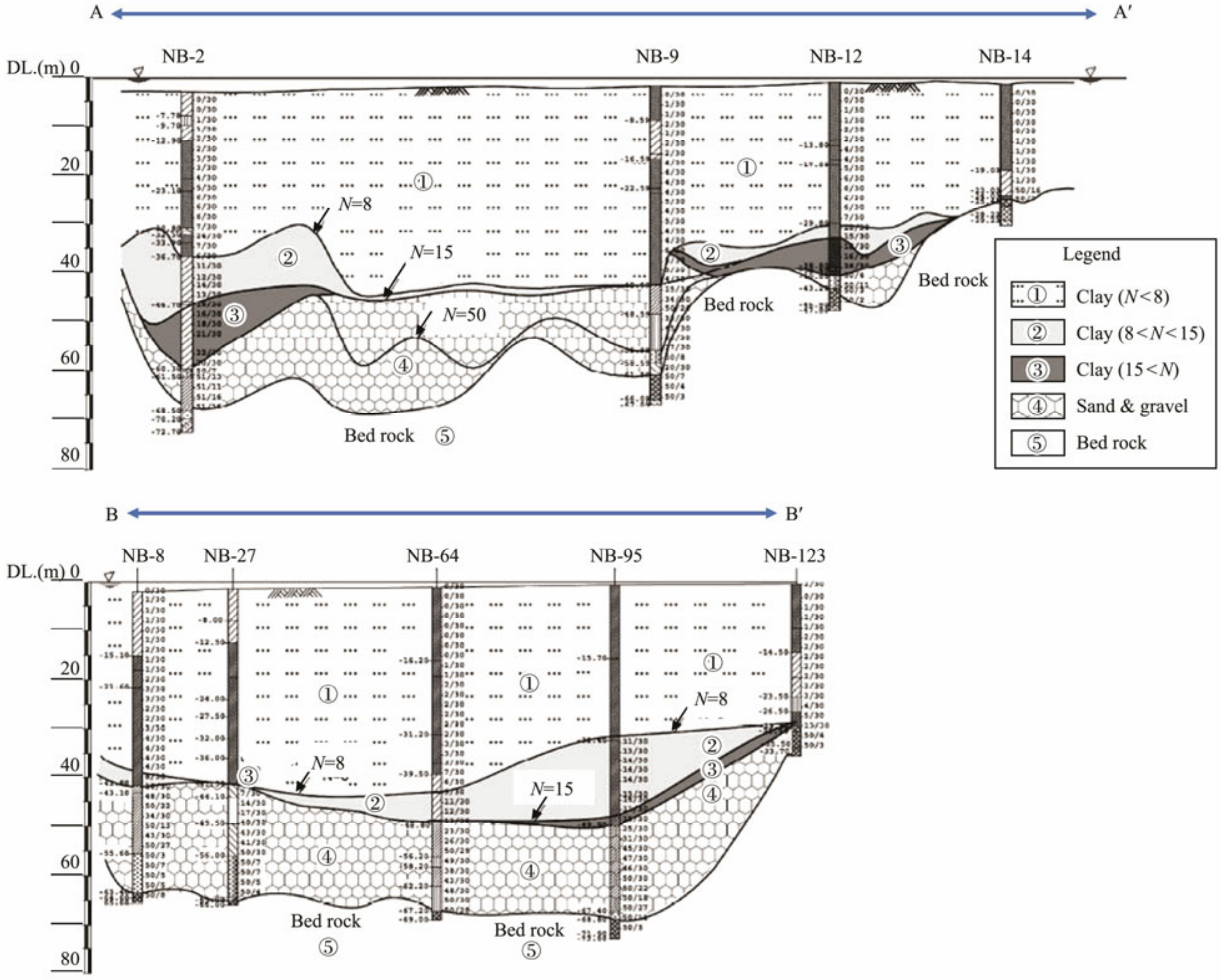
To verify the performance and control the construction

Table 1 Required prefabricated vertical drain (PVD) quality criteria and properties of VD 849

Part	Required criteria (test method)	VD 849
Filter	Over 70 kg of tensile strength (KS K 0520) Under 80 μm of AOS (KS F 2166) Over 1×10^{-3} of permeability (KS F 2128)	Over 70 kg 50–90 μm Over 1×10^{-3} cm s^{-1}
Drain (filter + core)	Over 200 kg (width) of tensile strength (KS F 2124) Over 25 cm^3 s^{-1} of drainage capacity (Delft method) Over 97 mm of width (KS K 0505) Over 3.5 mm of thickness (KS F 2122)	Over 400 kg Over 25 cm^3 s^{-1} 100 4.0



(a) Site location (b) Plan view of PVD improved area and its installation pattern



(c) Soil profile

Fig.1 Site description.

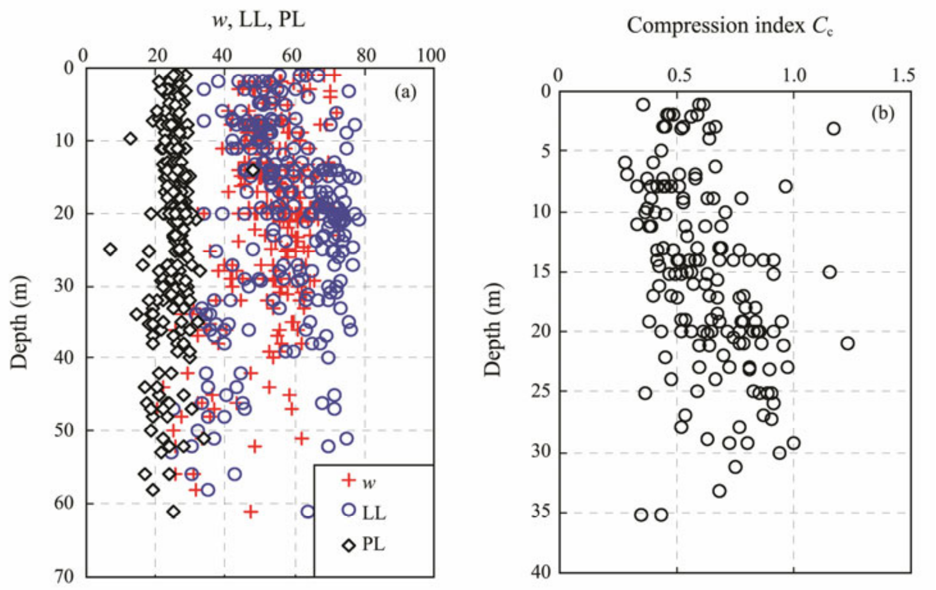


Fig.2 (a) Water content (*w*) with liquid limits (LL) and plastic limits (PL) and (b) Compression index (C_c).

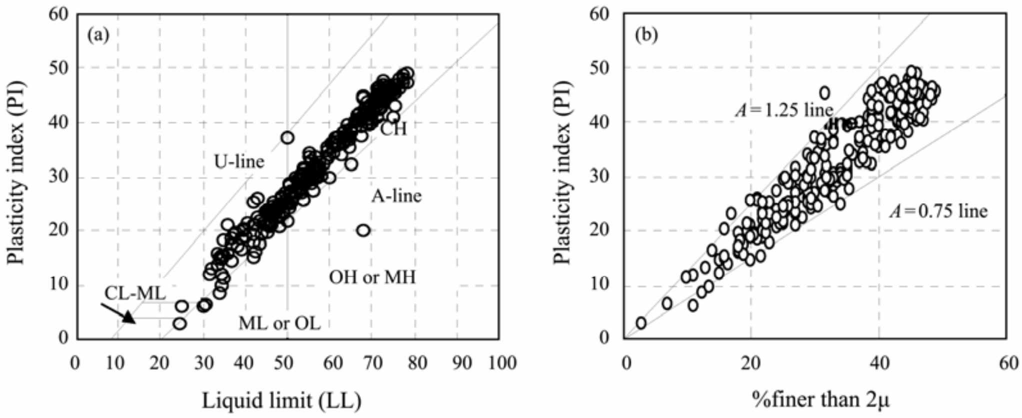


Fig.3 (a) Plasticity chart and (b) activity.

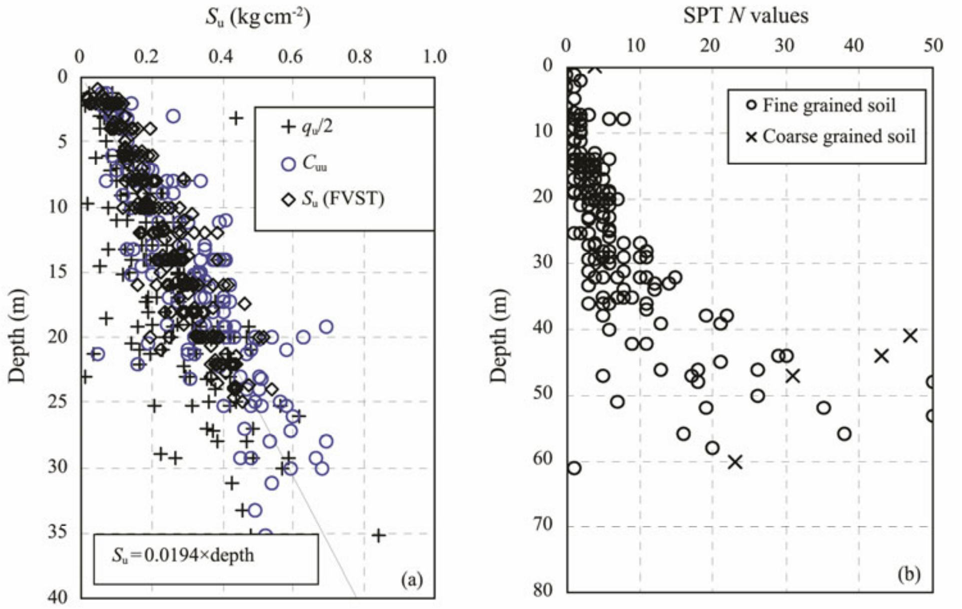


Fig.4 (a) Undrained shear strength (b) *N* value of standard penetration tests.

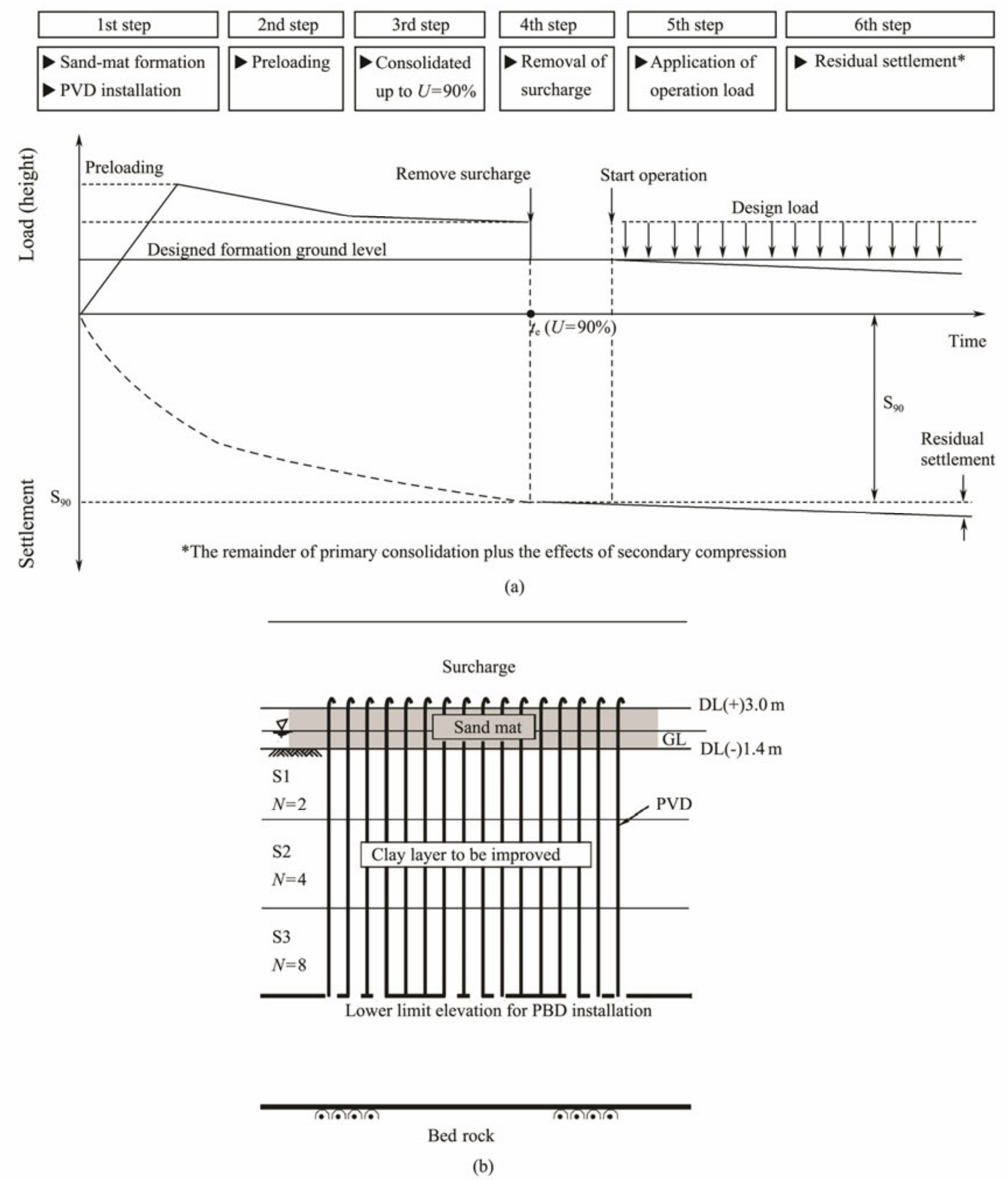


Fig.5 (a) Soft ground improvement process with PVD and preloading, and (b) Schematic profile of PVD installation.

work, several types of monitoring instruments, including 49 surface settlement plates, 92 multilayer settlement gauges, 10 inclinometers, 29 pore pressure transducers, and 8 groundwater level gauges, were installed after sand mat formation (Fig.6). The ground surface settlement plates were installed to monitor the vertical settlement of the original ground. The multilayer settlement gauges with a full-scale accuracy of ±0.5% were installed to quantify the compression between the soil layers. Measurements were taken from July 2002 to July 2009.

The settlement data were only used to assess the ground improvement and determine the degree of consolidation during the loading period at this site; these are the most important monitoring readings. The use of a pore water gauge to estimate the degree of consolidation was not recommended at this site.

Theoretically, the dissipation of excess pore water pressure can induce ground settlement, and pore water pressure gauges can estimate the degree of consolidation. However, these estimations may differ from the actual induced settlement. Pore water pressure gauges do not show consistent results because of the inhomogeneity of the ground, sensor corrections for depth due to settlement, and groundwater level variations; therefore, the degree of consolidation with the depth based on these gauges may not be reliable (Chu and Yan, 2005). Thus, the degree of consolidation predicted by the pore water pressure gauges at this site was not used. For this reason, this study used Eq. (1) to calculate the degree of consolidation on the basis of the amount of settlement, as follows:

$$U_{av} = S_t / S_c . \tag{1}$$

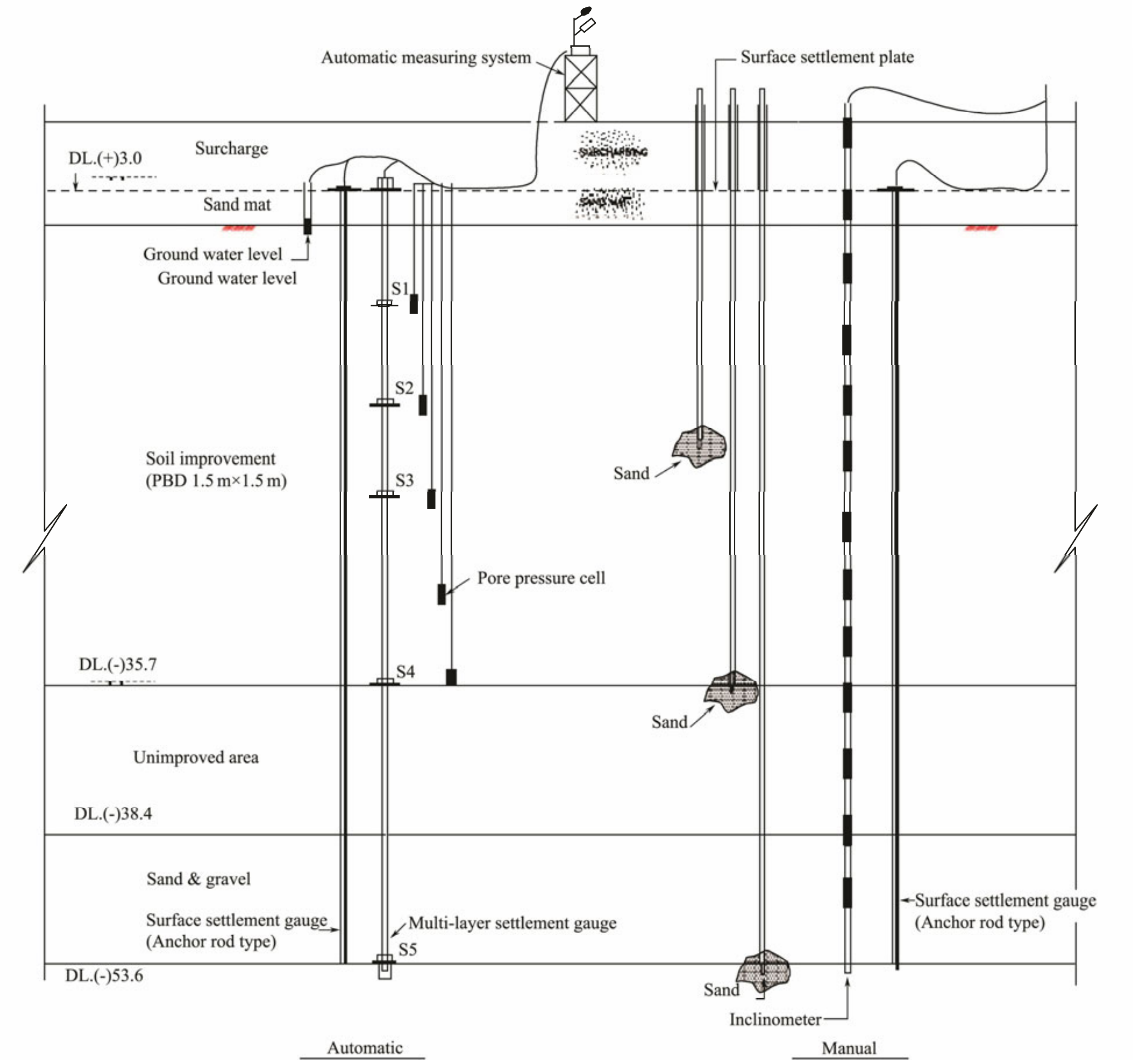


Fig.6 Layout of instrument installation and measurement system.

4 Ground Settlement

4.1 Primary Consolidation Settlement

Primary consolidation settlement is a type of settlement that occurs mainly during the ground improvement period. As discussed in the 'Instruments and monitoring' section, settlement was measured by gauges that were installed after PVD installation. However, the soft ground had already begun settling when the sand mat was placed on it. The initial settlement caused by sand mat formation, which was in the range of 4–5 m at this site, was estimated by groundwater level measurements and cone penetration tests. The results of both methods showed that the average initial settlement occurred at 0.6 m between sand mat formation and PVD installation. The sand mat layer itself did not compress. The initial settlement was incorporated in the total settlement because it affects the total settlement and the time required for surcharge removal. The surcharge load was removed when the ground reached the required degree of consolidation or settlement.

Fig.7 shows the measured settlement (denoted by an open square) until the time of surcharge removal at Blocks D2 and F2. The upper part of the figure shows the fill history. As illustrated in the figure, as the fill height increased, so did the settlement because of the consolidation of soft clay. The total settlement at the time of surcharge removal was approximately 4.85 and 5.53 m in Blocks D2 and F2, respectively. On the basis of the measured data, back analysis was also conducted to predict settlement. The TCON program (TAGA Engineering Software, 2013), a finite difference method, was used. TCON calculates the consolidation and rate of settlement, considering both radial and vertical drainage and providing the capability to simulate sand or wick drains. To conduct back analysis, first, the input data, such as the unit weight, water content, compression index, consolidation velocity, and coefficient of consolidation, were determined for each location where measurement gauges were placed. Table 2 shows the input parameters of each subsoil layer in the PVD-improved layer for TCON analysis. The depth of each soil layer is different for each block; thus, the ranges of the soil parameters are listed. Then, the soil properties were estimated by trial and error and by comparison with the measured data, with particular focus on the coefficient of consolidation. During the design phase, the coefficient of horizontal consolidation was assumed to be two times that of the coefficient of vertical consolidation, that is, $C_h=2C_v$. In back analysis, the predicted settlement was similar to the measured settlement if the coefficient of horizontal consolidation was assumed to be 2.3–3.5 times that of the coefficient of vertical consolidation. The settlement predicted by TCON is also shown in Fig.7 (denoted by a dotted line).

Table 3 shows the back analysis results predicted by TCON. The estimated settlement indicated that the time required for surcharge removal corresponded to a degree of consolidation of over 90%. For all blocks at this site, at the time the surcharge load was removed, the degree of consolidation had exceeded 94%. This degree of consolidation satisfied the target design criterion at this site (*i.e.*, a degree of consolidation of over 90%).

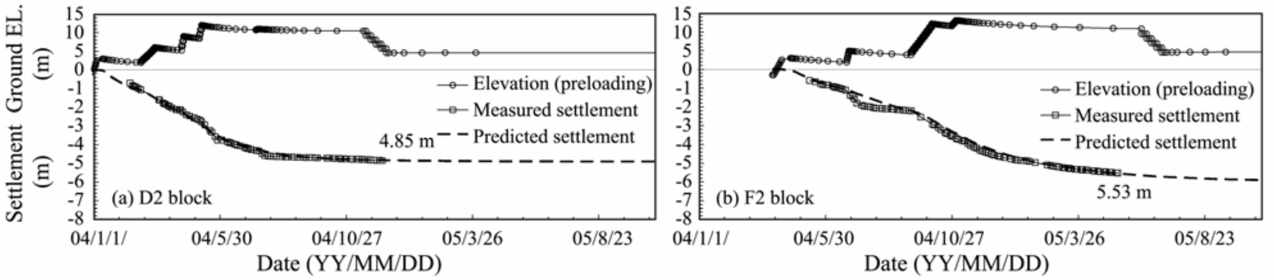


Fig.7 Fill and settlement histories during soil improvement period until the removal of the surcharge load.

Table 2 Input parameters for TCON analysis

Soil layer improved by PVDs	Unit weight (γ_t, γ_{sat}) (kN m^{-3})	Water content (w)	Compression index (C_c)	Coefficient of consolidation (C_v)
Top (S1)	16.5–17.0	55.4%–62.1%	0.56–0.61	0.099–0.106
Middle (S2)	16.3–17.0	56.2%–64.9%	0.50–0.96	0.093–0.105
Bottom (S3)	16.1–17.1	55.9%–68.7%	0.60–0.105	0.089–0.103

Notes: Specific gravity (G_s)=2.72, C_h=(2.3–3.5)C_v.

Table 3 Back analysis results based on the elimination of surcharge for each block

Block	PVD installation space (m)	Results of back analysis			Degree of consolidation (%)
		Removal of surcharge	Final	Residual	
A1	1.2	4.185	4.263	0.08	98.2
A2	1.0	2.922	2.967	0.04	98.5
B1	1.2	4.280	4.460	0.18	95.8
B2	1.0	3.973	4.092	0.12	97.1
C1	1.2	4.350	4.560	0.21	95.4
C2	1.0	3.968	4.114	0.15	96.5
D1	1.2	4.620	4.785	0.17	96.6
D2	1.0	4.812	4.910	0.10	98.0
E1	1.5	5.393	5.734	0.34	94.1
E2	1.2	5.792	6.150	0.36	94.2
F1	1.5	5.031	5.437	0.41	92.5
F2	1.2	5.650	6.113	0.46	92.4

4.2 Residual Settlement During Facility Operation

In this study, residual settlement was defined as the settlement that occurs from the time the surcharge is removed during facility operation. Therefore, residual settlement may include some remaining primary consolidation settlement under an operating load of PVD-improved soil layers, secondary compression of PVD-improved soil layers, and remaining primary consolidation under an operating load of underlying soil layers without PVD improvement.

After removing the surcharge load, super facilities, such as roadways and railroads, were constructed and operated on the improved area. Such super facilities influence the operating (or service) load by inducing residual ground settlement. During this period, settlement was monitored continually by the surface settlement plates and multilayer settlement gauges to observe the ground's behavior. The monitored settlement data were used to analyze the behavior of soft soil while the facility was operating.

4.2.1 Residual settlement on the ground's surface

Fig.8 shows the ground's surface settlement histories of

Blocks C2, D2, E2, and F2 after operating the facilities. Preloading was removed between February 2004 and August 2005 for Blocks C2 and D2 (Fig.8(a)) and between August 2005 and June 2006 for Blocks E2 and F2 (Fig. 8(b)). Generally, settlement rapidly occurred at first and gradually evened out over time. The settlement of Blocks C2, D2, E2, and F2 reached approximately 7, 10, 10, and 18 cm, respectively. The settlement of Block F2 was somewhat higher than that of other blocks because the temporarily overburdened load was removed from Block E2.

Fig.9 shows the final residual settlement contour of the ground's surface plotted in December 2008. Block A consisted of buildings that did not have residual settlement data because the transducers were damaged after removing the surcharge load and beginning the construction of these buildings. Blocks B, C, and D exhibited more settlement than the other blocks because of differences in the amount of time that the facilities operated. These blocks experienced one more year of operating time than the other blocks.

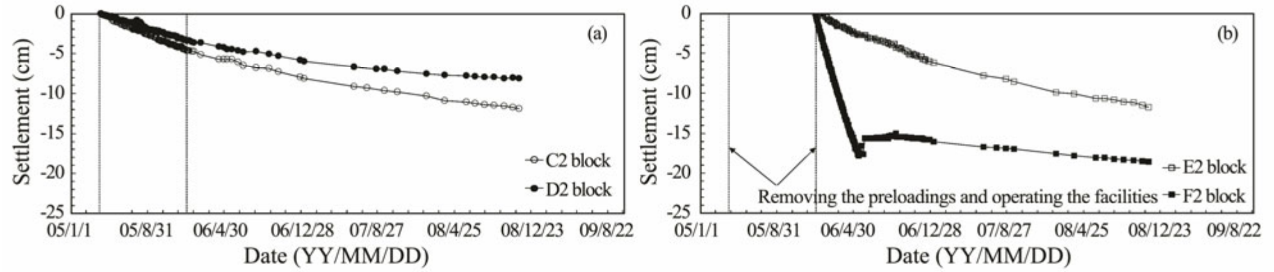


Fig.8 Residual settlement histories after operating the facilities at the ground surface: (a), Blocks C2 and D2; (b), Blocks E2 and F2.

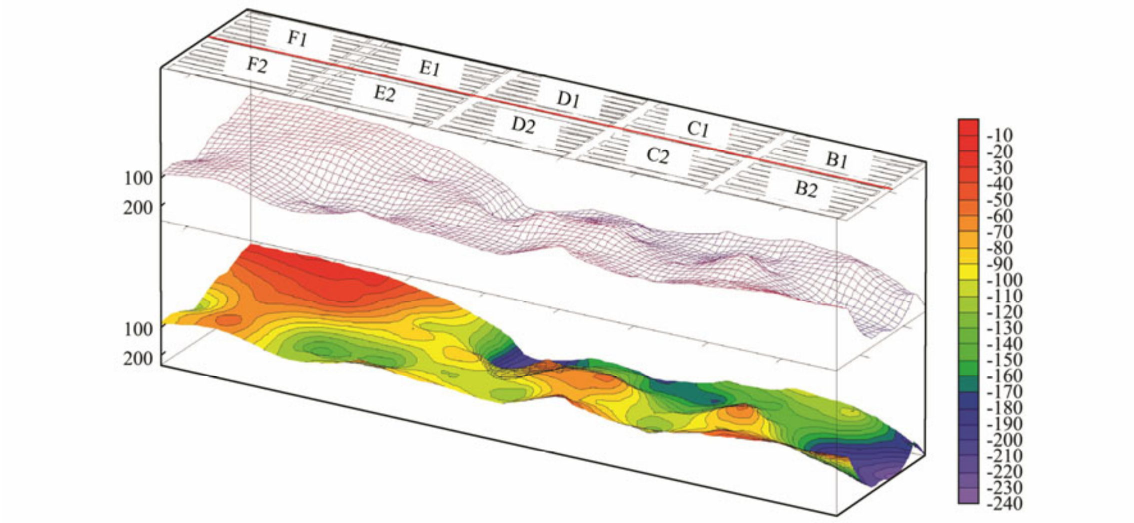


Fig.9 Contour map of final residual settlement at ground surface after operating the facilities (unit: mm).

As expected, the measured settlements were similar to the predicted settlements because the settlements were predicted using the recalculated coefficient of consolidation (C_v) and compression index (C_c) on the basis of the measured field settlement data at the time of surcharge removal (Fig.10). The residual settlement was less than the value specified in the project's design criteria. The measured residual settlements were similar to the residual settlements predicted by back analysis using TCON. However, the differences between them were significant for Blocks E and F, which can be attributed to the smaller operating load, particularly to the design load, which is approximately 4 and 5 tons in Blocks E and F, respectively. If the correct operating load is applied, then the settlement may increase. The measurement period may also negatively influence the comparison between measured and predicted settlements. Although the prediction period is 50 years, the measurement period is only approximately 3 years, which is insufficient. Thus, the predicted settlement is larger than the measured settlement, as shown in Fig.10. Notably, the secondary compression effect is not incorporated in the TCON program, theoretically. The discussion of the comparison between prediction and measured data may not be appropriate. However, from a practical point of view, this can be ignored because Terzaghi's theory was developed on the basis of the laboratory test. In the laboratory test, it is difficult to imagine that no secondary effects occurred during primary consolidation when secondary effects occurred under the previous load and after the primary load, thus indicating that it is a continuous phenomenon. Furthermore, even if the secondary effects follow primary consolidation, the primary effects should disappear near the drainage boundaries almost at once. Thus, the secondary effects should start in some parts of the soil sample before the primary effects have been completed everywhere in the sample.

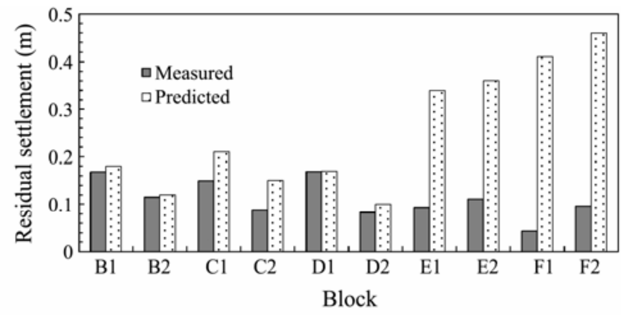


Fig.10 Comparison of measured and predicted residual ground settlement (Time period of prediction is 50 years and time period of measurement is about 3 years).

4.2.2 Residual settlement of each soil layer

Figs.11 and 12 show the residual settlement histories obtained from the multilayer settlement gauges in Blocks D2 and F2. As shown in Fig.6, five multilayer settlement gauges, that is, three in the middle of the PVD-improved soft ground (S1, S2, and S3), one on top of the soil layer having an *N* value between 8 and 15 (S4), and one at the bottom of the sand and gravel layer (S5), were installed. The layers in which Gauges S4 and S5 were installed were relatively firm, unimproved ground with *N* values greater than 8, as shown in Fig.1. These multilayer settlement gauges can measure the relative displacement between each layer.

In Fig.11, which depicts the results of Block D2, Gauges S1, S2, and S3 showed residual settlements of approximately 2, 7, and 0 cm, respectively. Gauges S4 and S5 did not obtain any settlement data because they were damaged. Fig.12 shows the residual settlement history obtained from the multilayer settlement gauges in Block F2. Block F2 had a residual settlement pattern similar to that of Block D2, as shown in Fig.11. The top settlement gauge (*i.e.*, Gauge S1) did not show much settlement during facility operation. Meanwhile, Gauges S2 and S3 measured approximately 10 cm of residual settlement. Gauges S4 and S5 recorded no settlement because the layers in which they were installed consisted of relatively firm, unimproved ground with *N* values greater than 8 (Fig.6).

Fig.13 shows a plot of residual settlement with depth, as measured by gauges in Blocks D2 and F2. Although residual settlement in the boundaries (*i.e.*, the top and bottom of the PVD-improved soil layer) barely occurred, the residual settlement measured in the middle zone of the PVD-improved soil layer was significant. The middle zone is related to the time delay of excess pore water pressure dissipation. Two important conclusions can be drawn from this figure.

First, the residual settlement that occurred during facility operation was related only to the soil layer that had been improved by PVDs, which had an *N* value less than 8. Meanwhile, no settlement occurred in the unimproved layer, which had an *N* value greater than 8. At this site, the residual settlement may be only a part of the remaining primary consolidation settlement and secondary compression under an operating load of improved soil layers. In general, the contribution of the residual compression of the unimproved soil layer when compared with the total residual settlement depends on the compressibility of the

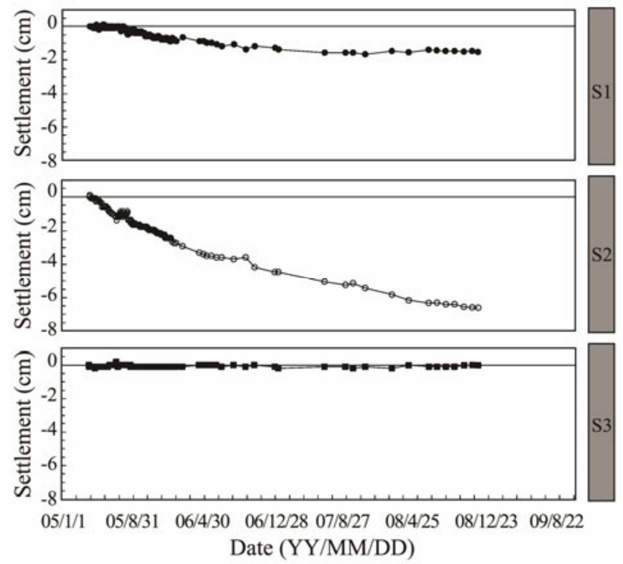


Fig.11 Residual settlement at each soil layer in block D2.

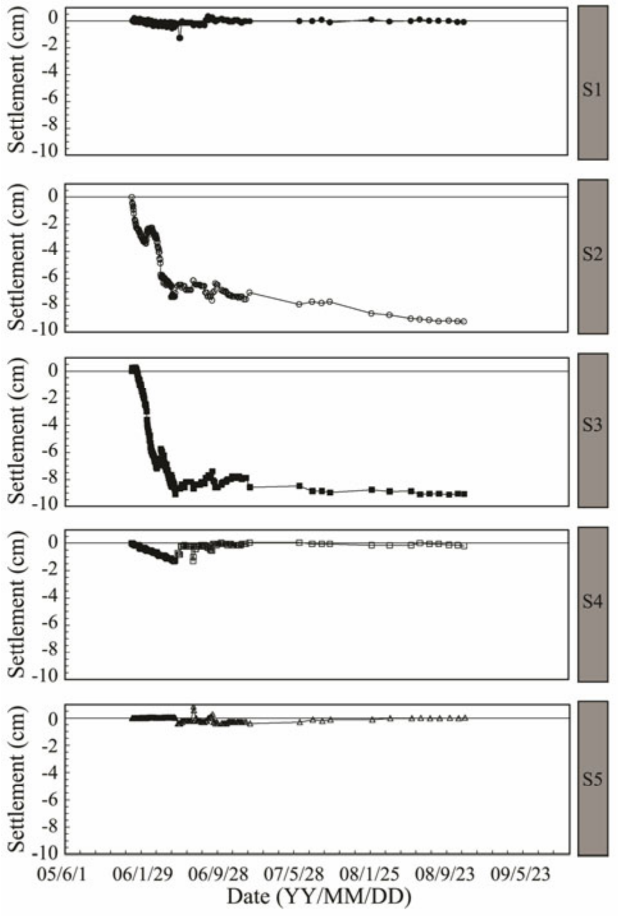


Fig.12 Residual settlement at each soil layer in block F2.

soil layer, as well as the time and magnitude of unloading. However, the residual settlement of the unimproved soil layer was not detected at this site. Second, residual settlement mainly occurred in the middle of the improved layer, which may be related to the time delay of excess pore water pressure dissipation in the midsection of the layer. That is, the remaining primary consolidation in the PVD-improved soil layer was the primary cause of residual settlement, whereas secondary compression was only a minor cause.

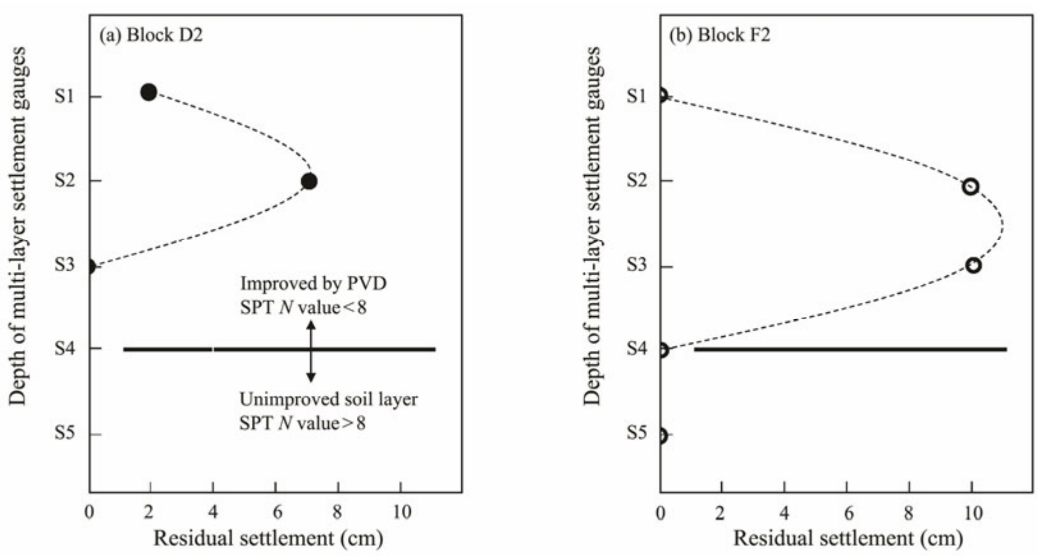


Fig.13 Variation of residual settlement with depth: (a) Blocks D2 and (b) Block F2.

4.2.3 Effect of PVD on residual settlement

PVD mainly accelerates primary consolidation because significant water movement is associated with it. However, with the consolidation of soil, the drain will buckle or deform inside the soil. Moreover, when the pores of the filter are too large, the fine-grained soils may ingress and clog the drain. The discharge capacity of the buckled and clogged drain will normally be smaller than that of a straight and unclogged drain. Thus, residual settlement (induced by the remaining primary consolidation settlement and secondary compression under a service load of PVD-improved soil layers) is not sped up by the drain. Hence, the effect of PVD on residual settlement may not be significant. That is, from the residual settlement point of view, the behavior of soil with PVD may not differ significantly from that of soils without VD. Residual settlement in soils without drains occurs for a long time, which is generally acceptable. In some clay (*e.g.*, Norwegian marine clay), residual settlement continues for thousands of years (Bjerrum, 1967).

However, at this site, the measured residual settlement is slightly different. As shown in Figs.11 and 12, although residual settlement in the boundaries (*i.e.*, the top and bottom of PVD-improved soil layer) barely occurred, the residual settlement measured in the middle zone of the PVD-improved soil layer was significant in just a few months. This finding indicates that PVD still has some effect on residual settlement and can reduce the time of residual settlement. The middle zone may be related to the time delay of excess pore water pressure dissipation. After removing the surcharge load, followed by the application of the operating load, the primary effects almost disappear near the drainage boundaries. However, in some parts of the soil layer (particularly in the middle part), primary consolidation has not been completed. If the soil is not improved with PVD, then it may take more time than was measured. Notably, this conclusion is only based on the settlement data obtained from the multilayer settlement gauges. In this study, the amount of residual settlement induced by PVD cannot be separated from the measured settlement because of the lack of data regarding the degree of consolidation for each subsoil layer. However, the key fact that can prove the effects of PVD on residual settlement is the significant residual settlement measured in the PVD-improved soil layer in just a short period, as shown in Fig.10.

5 Conclusions

This study investigated the residual settlement behavior of thick soft ground improved by PVDs. To this end, the settlement data obtained from the surface settlement plates and multilayer settlement gauges after removing the surcharge load, followed by the application of the operating load (approximately 4 years), were analyzed. Residual settlement can be determined on the basis of the following components: 1) some remaining primary consolidation settlement under an operating load of PVD-improved soil layers (RS_I), 2) secondary compression of PVD-improved soil layers (RS_{II}), and 3) the remaining primary consolidation under a service load of underlying soil layers without PVD improvement (RS_{III}). In this study, we obtained three key findings:

1) The residual settlement that occurred at this site was smaller than the value specified in the design criteria of

the project. Thus, it met the design criteria.

2) Three components of residual settlement (*i.e.*, RS_I, RS_{II}, and RS_{III}) were differentiated. This study is the first attempt to use the settlement data measured long-term in soil improved with PVD. Residual settlement only occurred in PVD-improved soil layers. This finding indicates that residual settlement is a problem that only occurs in PVD-improved soil layers (RS_I and RS_{II}), not in unimproved soil layers (RS_{III}).

3) For residual settlement at a depth within the PVD-improved soil layer, although residual settlement in the boundaries (*i.e.*, top and bottom of PVD-improved soil layer) barely occurred, the residual settlement measured in the middle zone of the PVD-improved soil layer was significant in just a few months. The middle zone may be related to the time delay of excess pore water pressure dissipation because, after removing the surcharge load, followed by the application of the operating load, primary consolidation in the middle part of the improved soil layer has not been completed. The remaining primary consolidation in the PVD-improved soil layer was the primary cause of residual settlement.

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