A case study on the field performance of vacuum consolidation method using PVDs subjected to individual vacuum pressure

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ABSTRACT

The vacuum consolidation system has been revised to overcome the shortcomings of the conventional method using an airtight sheet and a cut-off wall. This system consists of a collection tank embedded in the ground, and a vacuum drain pipe connecting the collection tank and PVDs (prefabricated vertical drains). All these components are under the vacuum pressure throughout the whole consolidation process. Air and water extracted from the ground is separately drained through the vacuum drain pipe and thus the loss of vacuum pressure can be minimized. The efficiency of this revised vacuum consolidation system has been evaluated based on field measurements, in-situ tests, and laboratory tests on soil samples.

Keywords: vacuum consolidation, vacuum pressure, collection tank, vacuum drain pipe, prefabricated vertical drains

1 INTRODUCTION

A vacuum consolidation technique, originally proposed by Kjellman (1952), has been successfully employed to improve a soft soil. The conventional vacuum consolidation system consists of an airtight membrane and a cut-off wall to maintain a vacuum pressure of 80kPa or greater for a period of treatment. It has been reported that the airtight membrane or the cut-off wall can be damaged during construction. Thus, the vacuum pressure is decreased and the consolidation process is delayed (Cognon et al., 1994).

The vacuum consolidation system has been revised to overcome the shortcomings of using the airtight membrane or the cut-off wall by Dong-Ah Geological Co. in South Korea in 2012. The revised vacuum consolidation system reported herein consists of prefabricated vertical drains (PVDs) with an airtight connecter at the top which is directly connected to the vacuum pump through a specially designed drain pipe and thus the vacuum pressure is individually applied to the PVD. The airtight sheet on the surface or the cut-off wall to maintain the vacuum pressure is not required in this system. The system has been successfully applied to several ground improvement projects in South Korea (Lee et al., 2012). Since then, a specially designed air-water separation vacuum pump system was added to maintain the vacuum pressure as stable throughout the whole process (Jung, et al., 2013; Shin et al., 2015). And also, a portable inspection device was developed to check an air leakage at the airtight connector or the drain pipe embedded in the fill. The inspection device is employed to check the airtightness of the connector or the drain pipe prior to the operation of the whole system and then enables the system to maintain the vacuum pressure as stable.

This study focuses on the field performance of the revised vacuum consolidation system to improve the soft ground. The applicability of the system is evaluated in terms of maintaining the vacuum pressure, achieving the target settlement within the scheduled construction period, and the improvement of engineering properties of soft soil.

2 PROJECT DESCRIPTION

2.1 Site descriptions

The vacuum consolidation method has been applied to reduce ground settlement and to minimize down-drag forces on piles which support a chemical plant. The project site is located in Yeosu national industrial complex, South Korea and the area to be treated is approximately 6,820 m2. The site was divided into three sub-sections (AD1~AD3) as shown in Figure 1.

Exploratory borings were performed at 4 locations shown in Figure 1 and a typical soil profile at the site is illustrated in Figure 2. A 14.8～19.4 m thick layer of saturated, normally consolidated silty clay overlies a permeable sandy gravel formation. The silty clay layer is underlain by a 2.4～2.6 m thick reclaimed fill. The reclaimed fill consists of sandy gravel. A series of laboratory tests were performed on undisturbed samples of silty clay obtained from exploratory borings and engineering properties of silty clay are given in Table 1. The silty clay in the site is classified as a highly compressible and plastic silty clay (CH) according to the unified soil classification system.

2.2 Construction sequences

Field instrumentations are first installed within the project area. The filed instrumentations employed in the project consist of inclinometer, settlement plates, magnetic extensometers, water level meters, piezometers, and pore water pressure meters. And then, collector wells and vacuum drain pipes (ϕ 16mm, ϕ50mm) are placed in the reclaimed fill. One collector cell was placed in the center of each sub-section and vacuum pipes are connected to the collector cell located in the center of each sub-section as shown in Figure 3.

Vacuum pressure meters for a pressure control are installed at specified locations prior to the installation of PVDs.

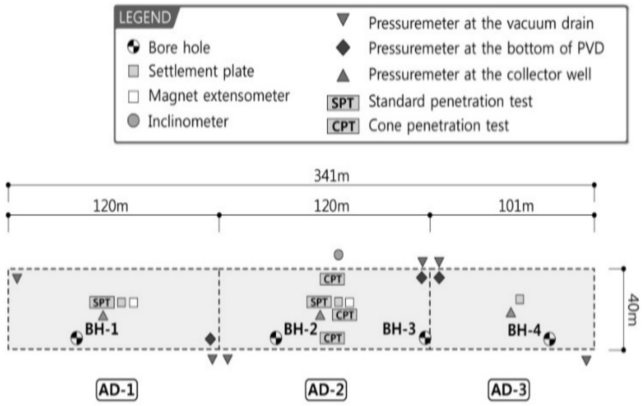


Figure 1. A plan view of project site with locations of exploratory borings and field instrumentations

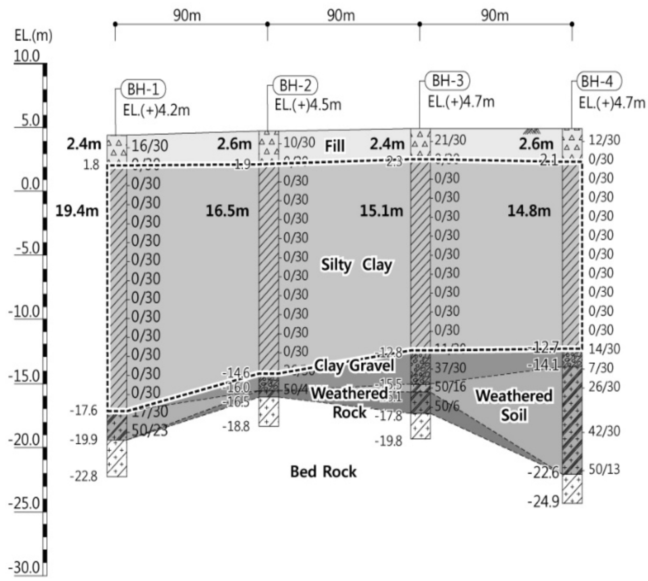


Figure 2. A typical soil profile of the site

Table 1. Engineering properties of silty clay

Property	Value
Natural water content, w_n	52.0~78.9 %
Initial void ratio, e_o	1.457~2.148
Liquid limit, LL	66.6~90.4 %
Plasticity index, PI	37.1~59.3
Compression index, C_c	0.38~1.20
Coefficient of consolidation, c_v	4.0 x 10^{-4} cm^2/sec

PVDs are installed in a triangular pattern at a center-to-center spacing of 0.9m to the predetermined depths. And then, PVDs are connected to the vacuum drain pipe using a specially designed airtight connector. Pressure meters are attached to both the top and bottom of selected PVDs to measure vacuum pressure. The airtightness of connectors and drain pipes are confirmed by using the inspection device. Finally, a 2.4~3.0m thick make-up fill is placed over each sub-section. After the placement of make-up fill, vacuum consolidation works have been carried out through monitoring observed settlement and vacuum pressure. Figure 4 shows a cross sectional view of vacuum consolidation system employed in the project together with field instrumentations and a plan view of field instrumentations is illustrated in Figure 1.

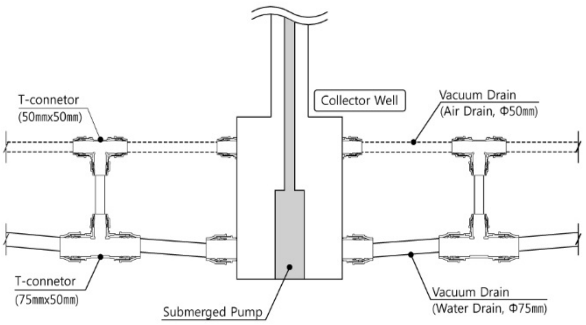


Figure 3. A connection of vacuum drain pipes to a collector well

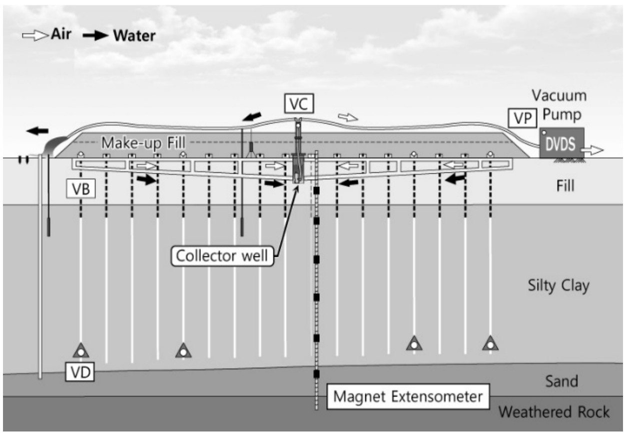


Figure 4. A typical cross sectional view of vacuum consolidation system employed in the project

3 PERFORMANCE ASSESMENT

3.1 Measurement of vacuum pressures

Vacuum pressures are measured at the vacuum pump, the collector well, the vacuum drain pipe, and the bottom of PVDs. The variation of vacuum pressures with time are illustrated in Figures 5 through 7. Significant loss of vacuum pressures were not indicated and the vacuum pressures measured at all locations were kept well above 80 kPa throughout the vacuum consolidation process.

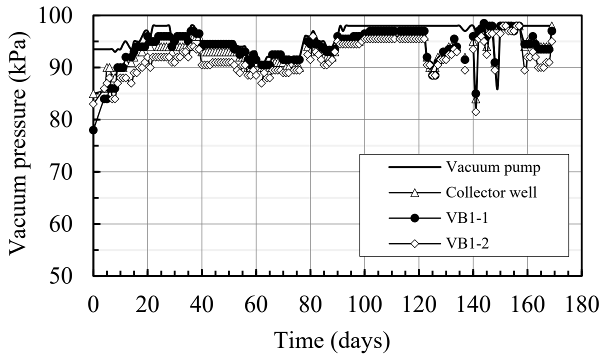


Figure 5. A variation of vacuum pressures with time at sub-section AD-1

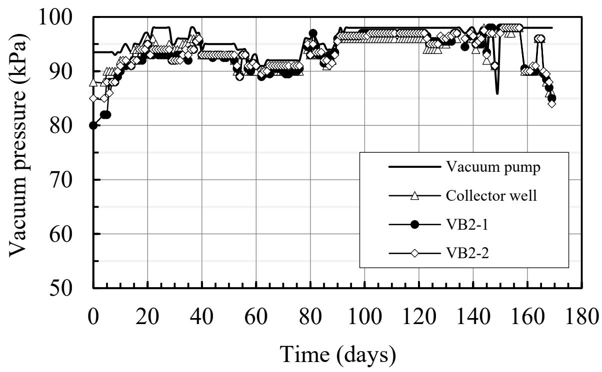


Figure 6. A variation of vacuum pressures with time at sub-section AD-2

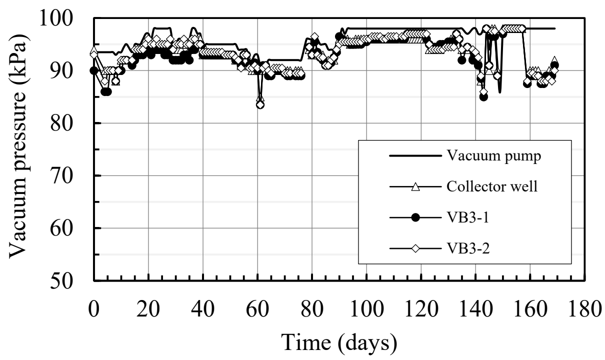


Figure 7. A variation of vacuum pressures with time at sub-section AD-3

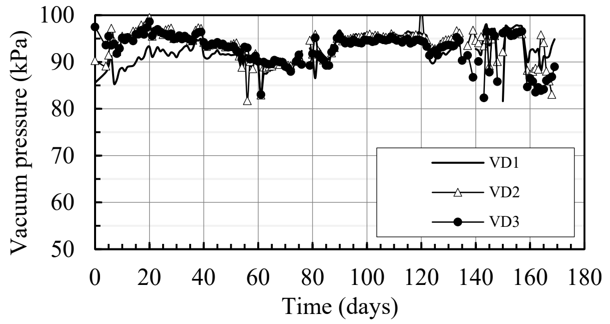


Figure 8. A variation of vacuum pressures with time at the bottom of PDVs

In addition, vacuum pressure meters (VD1 ~ VD3) were embedded into the silty clay layer to check vacuum pressures at the bottom of PVDs. Figure 8 shows a variation of vacuum pressures at the bottom of PVDs with time. The average values of vacuum pressures at all measuring locations are summarized in Table 2. The vacuum pressures measured at the bottom of PVDs were also kept well above 80 kPa and the losses of vacuum pressures were minimal. The average value of vacuum pressure at the bottom of PVDs was 92.6 kPa, which was equal to or slightly lower than the average vacuum pressures at the vacuum drain pipes.

Table 2. Average vacuum pressures at vacuum pumps, colle ctor wells, vacuum drains, and bottom of PVDs

Average vacuum pressure (kPa)	AD1	AD2	AD3
Vacuum pumps (VP)	96.0	96.0	96.0
Collector wells (VC)	93.0	98.0	93.0
Vacuum drains (VB-1)	94.0	93.0	93.0
Vacuum drains (VB-2)	91.0	94.0	93.0
Bottom of PVDs (VD)	92.0	93.3	92.5

3.2 Lateral displacement of ground

The lateral displacement of ground in the process of the vacuum consolidation is shown in Figure 9. The vacuum pressure induced inward lateral displacement of ground in early stages. Upon placing a make-up fill, the lower silty clay layer begins to displace outward whereas the upper fill layer displaces consistently inward. The outward displacement of silty clay layer may be attributed to a rapid loading of the make-up fill prior to the dissipation of excess pore water pressure. In addition, it can be assumed that the deformation of the inclinometer was badly affected by the tension crack developed close to the inclinometer.

3.3 Consolidation settlement

Consolidation settlements were measured to determine a completion time of treatment. In order to measure consolidation settlements, settlement plates (S-AD1, S-AD2, S-AD3) were installed on the surface of make-up fill and magnet extensometers (D-AD1, D-AD2) were embedded in the silty clay layer underlain by the fill layer. Variations of consolidation settlements measured from settlement plates and magnetic extensometers were compared in Figures 10 and 11. Figure 12 shows a variation of consolidation settlement measured from the settlement plate S-D3 only. The magnet extensometer was not installed in the sub-section AD-3. The final settlements measured from settlement plates and magnetic extensometers are summarized in Table 3. Final settlements measured from the settlement plates ranged from162.3 cm to 162.4 cm. Accumulated settlements from the magnetic extensometers ranged from 163.6 cm to 149.8 cm. The measured final settlements exceeded the target settlements of 140.2cm to 150.9 cm which were predicted in the design phase within the scheduled treatment period. The depth indicated in Figure 9 was measured from the ground surface.

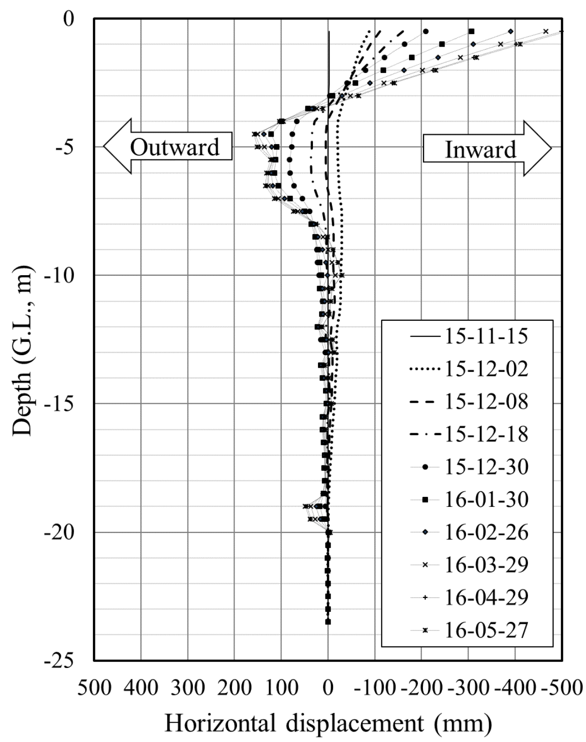


Figure 9. Lateral displacement of ground during the vacuum consolidation process

Final settlements measured from settlement plates and magnet extensometers are compared in Table 3. Final settlements measured from magnet extensometers were appeared to be slightly greater or smaller than those measured from settlement plates depending on locations.

3.4 Ground improvement effect

The efficiency of ground improvement with the vacuum consolidation method has been evaluated based on field tests and laboratory tests on silty clay samples.

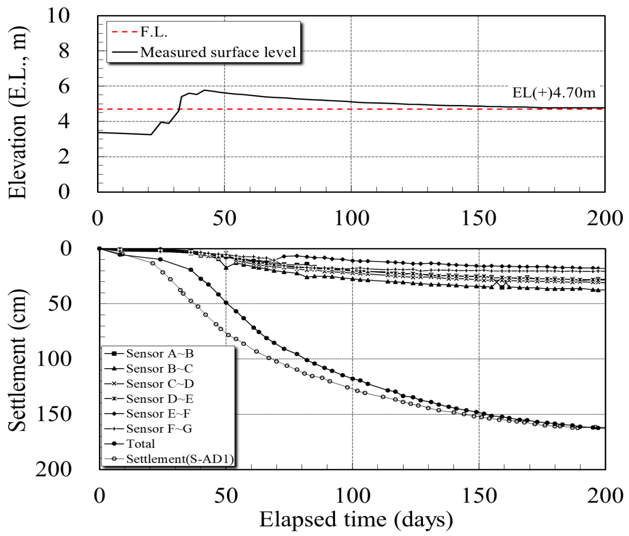


Figure 10. Comparison of settlement-time histories from the settlement plate S-AD1 and the magnet extensometer D-AD1

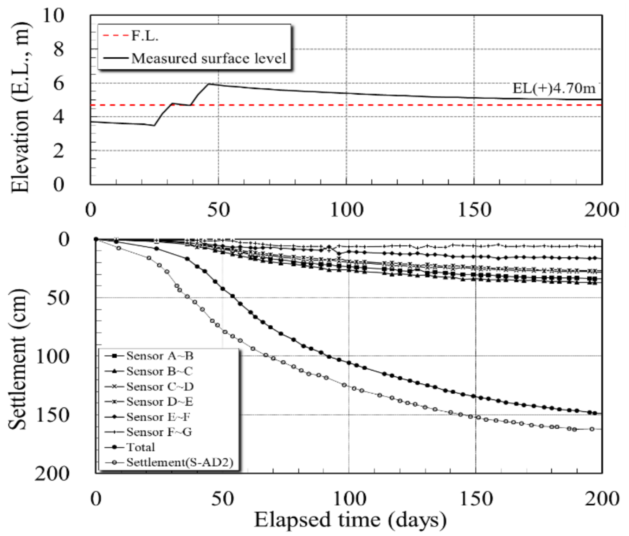


Figure 11. Comparison of settlement-time histories from the settlement plate S-AD2 and the magnet extensometer D-AD2

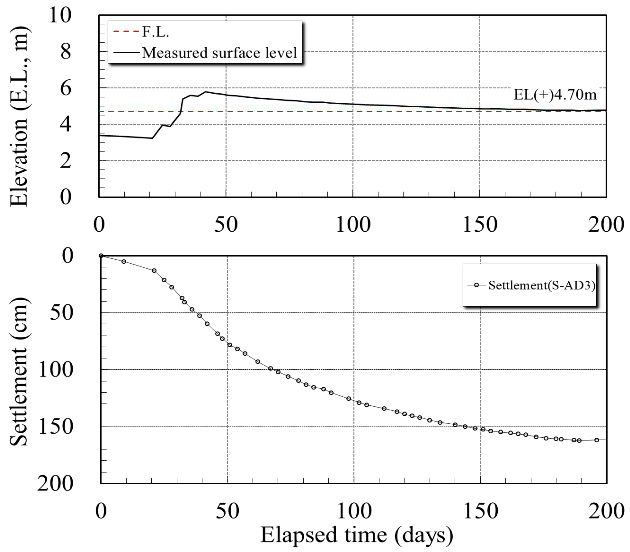


Figure 12. Time history of settlement from the settlement plate S-AD3

Table 3. Final settlements measured from settlement plates and magnet extensometers

Item	S-AD1	D-AD1	S-AD2	D-AD2	S-AD3
Settlement (cm)	161.8	162.8	162.4	149.5	159.6

Standard penetration tests and piezocone penetration tests were performed in the site. Laboratory tests were performed on soil samples obtained before and after the treatment. Standard penetration test results are compared in Figure 13 and a comparison of piezocone penetration test results is illustrated in terms of undrained shear strengths in Figure 14. Depths indicated in Figures 13 through 15 were measured from the top of silty clay layer.

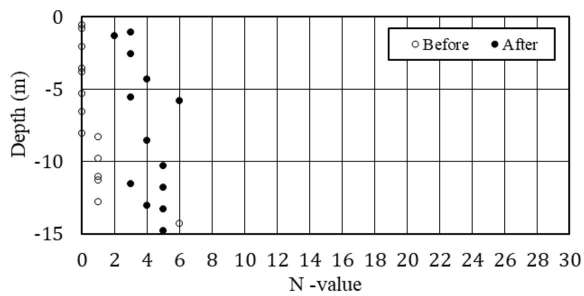
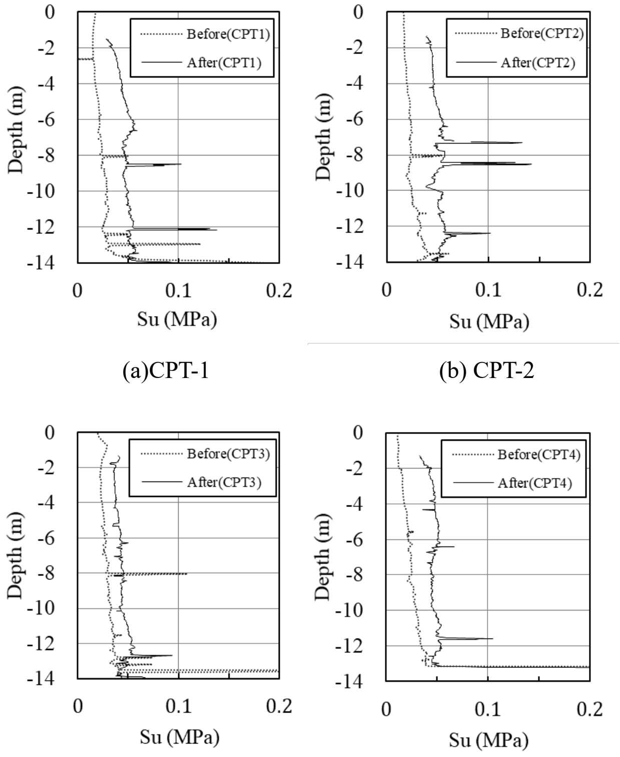


Figure 13. Comparison of standard penetration N-values before and after the treatment



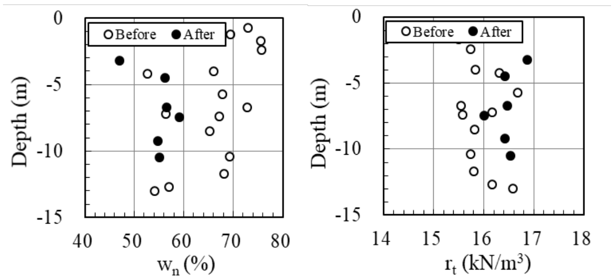
(a)CPT-1 (b) CPT-2

(c) CPT-3 (d) CPT-4

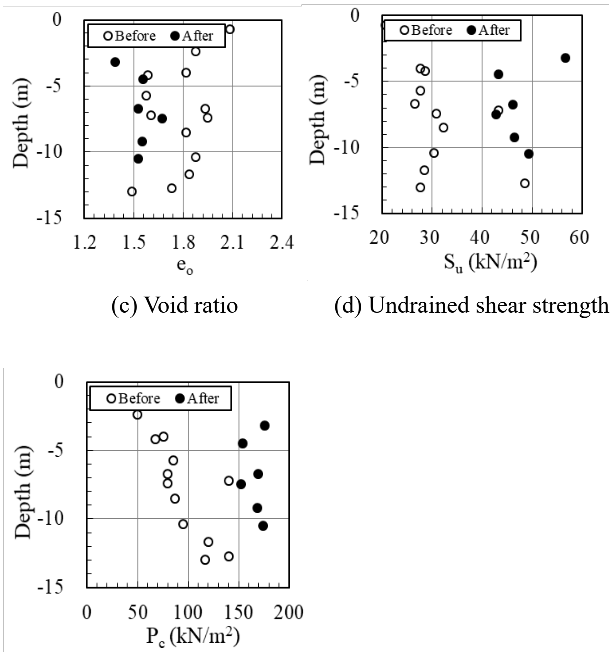
Figure 14. Comparison of undrained shear strengths before and after the treatment

It can be noticed that SPT N-values and undrained shear strengths of silty clay layer were significantly increased after the treatment.

Engineering properties of soft clay before and after the treatment are compared in Figure 15. It was appeared that the engineering properties of silty clay were significantly improved after treatment. Water contents and void ratios were decreased whereas unit weights, unconfined compressive strengths, and pre-consolidation pressures were significantly increased after the treatment.



(a) Natural water content (b) Wet unit weight



(c) Void ratio (d) Undrained shear strength

(e) Pre-consolidation pressure

Figure 15. Comparison of engineering properties of soft clay before and after treatment

4 CONCLUSION

Based on the assessment of field performance of the vacuum consolidation system employed in the project, the following conclusions can be obtained.

1. The vacuum consolidation system employed in the project can effectively maintain a vacuum pressure of above 80 kPa at the collector wells, the vacuum drain pipes, and the bottom of PVDs throughout the whole consolidation process.

2. The loss of vacuum pressure resulted from extracting air and water from the ground under the vacuum pressure was estimated to be less than 1kPa.

3. Uncontrolled rapid placement of a make-up fill can result in a detrimental ground deformation to adjacent underground facilities. A construction schedule should be carefully controlled where underground facilities exist close to the treatment site.

4. It was confirmed that engineering properties of soft clay can be significantly improved with the vacuum consolidation system reported here in.

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