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Research Article

Consolidation Effect of Prefabricated Vertical Drains with Different Lengths for Soft Subsoil under Vacuum Preloading

Chenhui Lou,[1] Junfeng Ni,[2] Jingchun Chai,[2] Hongtao Fu ,[1,2] Xiuqing Hu,[1,3,4] Donghai Xu,[5] Youchang Lyu,[6] Zhi Guan,[5] Zhengde Xia,[7] and Qiang Ye[1]

[1]*College of Architecture and Civil Engineering, Wenzhou University, Chashan University Town, Wenzhou 325035, China*
[2]*Department of Civil Engineering and Architecture, Saga University, Saga, Japan*
[3]*Key Laboratory of Engineering and Technology for Soft Soil Foundation and Tideland Reclamation of Zhejiang Province, Wenzhou, China*
[4]*Innovation Centre of Tideland Reclamation and Ecological Protection, Wenzhou University, Wenzhou, Zhejiang 325035, China*
[5]*Wenzhou Longda Reclamation Development and Construction Co., Ltd., Wenzhou, Zhejiang 325035, China*
[6]*Wenzhou Oufei Development and Construction Investment Group Co., Ltd., Wenzhou, Zhejiang 325035, China*
[7]*CCCC Shanghai Dredging Co., Ltd., Huangpu District, Shanghai, China*

Correspondence should be addressed to Hongtao Fu; fuhongtao2012@163.com

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The application of vacuum preloading to prefabricated vertical drains (PVDs) with different lengths is widely used in practical engineering to investigate their consolidation at the same depths of even and multilayer subsoils from the seabed. In a laboratory, model experiment was conducted using even subsoil and embedded PVDs with lengths of 0.6 and 1.2 m. The obtained results showed that in the even subsoil, the 1.2 m PVDs maintained a higher vacuum pressure in the shallow layer and demonstrated better consolidation behavior as compared to those of the 0.6 m PVDs. In the upper subsoil layer, the average vane shear strengths of these two systems increased to 18.2 and 22.6 kPa, respectively. The degree of consolidation of the upper subsoil layers in the two model experiments calculated from the pore water pressures under boundary drainage conditions were 51% and 68%, respectively. For practical verification purposes, similar experiments were conducted for multilayer subsoil by inserting PVDs with lengths of 6 and 15 m into different test sites. As a result, the vane shear strengths of the upper 6 m subsoil layers increased to 26.3 and 33 kPa, while the degree of consolidation were 72.1% and 80.9%, respectively, although some irregularities were observed at different depths.

1. Introduction

The use of vacuum preloading with prefabricated vertical drains (PVDs) to improve the subsoil strength is becoming increasingly popular due to their ability to promote the formation of soft clay deposits by accelerating the consolidation process and has been widely utilized in highway and airport construction [1–4]. By reducing the pore water pressure while maintaining a constant total pore pressure during vacuum preloading, the effective pressure increases. The installation of PVDs improves the vacuum pressure distribution in deep subsoil layers [5–15]. In addition, there is an issue that accelerating the consolidation process at different depths of soft soil may take many years. In practical engineering applications, the booster PVDs have been applied and easily inserted into the deep marine clay without special equipment and efforts. Part of the booster PVDs could provide an inflow channel for the compressed air when the booster pump is activated; otherwise, it plays as ordinary PVDs providing the outflow channel for the air and water, so this new approach of vacuum preloading with booster PVDs was presented by Cai et al. [9] and verified as an effective and attractive method for soil improving, even up to 20 m depth. In addition, the designed PVD lengths vary due to the different consolidation requirements for the subsoil layer. Theoretically, different PVD lengths lead to different drainage boundary conditions (including the one-way and two-way drainage ones). They also produce different consolidation effects on the same layer of subsoil because embedding longer PVDs that fully penetrate the subsoil causes vacuum pressure leakage through the bottom drainage boundary. Chai et al. [16, 17] examined the equivalent vertical hydraulic conductivity of PVD-containing subsoil and determined its relation to the square of the PVD length. Some researchers investigated the improvement of the subsoil layer at different PVD lengths, but not at the same layer depth. Furthermore, the mechanism of the effect caused by vacuum preloading has not been sufficiently clarified yet.

The objective of this study was to conduct a model experiment, in which PVDs with lengths of 0.6 and 1.2 m were embedded in even subsoil and compare the resulting vacuum pressures, pore water pressures, settlements, and other key parameters measured under vacuum preloading. In addition, water contents, vane shear strengths, and degrees of consolidation were determined after stopping the vacuum pump, and the differences between the results of these two model experiments obtained for the upper and lower soil layers were compared. Similar tests were performed for practical engineering applications by embedding 6 m and 15 m PVDs into multilayer subsoil to determine the similarities and differences between the consolidation parameters of the even and multilayer subsoils.

2. Laboratory Model Experiment

2.1. Subsoil. The subsoil tested in the laboratory model experiment was picked up from the new district of the Oujiang Estuary using a large container and mixed with an electrically operated mechanical mixer to ensure the uniformity of the soil properties. Table 1 lists some typical soil characteristics indicating that the utilized subsoil was extremely soft, had relatively large water content and liquid limit, and possessed considerably low shear strength.

Table 1: Summary of the subsoil properties.

Water content (%)	118
Liquid limit (%)	53.22
Plastic limit (%)	27.11
Void ratio	3.16
Vane shear strength (kPa)	$\cong 0$
Specific gravity	2.68
Wet density (g/cm^3)	1.40

2.2. Testing Apparatus. Figure 1 schematically shows the experimental apparatus used for laboratory testing, which consists of two poly(methylmethacrylate) cylinders with inner diameters of 0.6 m and heights of 1.2 m [18, 19]. PVDs with lengths 0.6 m and 1.2 m were inserted into the centers of the test cylinders and fixed using customized cylindrical iron shelves placed on their bottoms. Piezometers were attached to the shelves to monitor changes in the pore water pressure at depths of 0.3, 0.6, 0.9, and 1.2 m. To measure the vacuum pressures inside the PVDs, syringe needles were inserted into their cores, whose other ends were connected to vacuum gauges via vacuum tubes. Additionally, when measuring the vacuum pressure in subsoil, the syringe needles were inserted into small PVD blocks as pressure media instead of the subsoil directly to avoid blocking, and the vacuum suction levels at depths of 0.3, 0.6, 0.9, and 1.2 m were monitored. One geotextile layer and two layers of polyvinyl chloride geomembrane were used to seal the cylinders on the top. After the cylinders were sealed, airtight caps were utilized to connect the central PVDs to the water-air separation bottles directly attached to a vacuum pump. Under the action of vacuum suction, the water and air in the subsoil reach the PVDs and get discharged into the water-air separation bottles. In this setup, the cylinder with the 0.6 m PVD was named $T1$, and the cylinder with the 1.2 m PVD was labeled $T2$.

2.3. Testing Procedure. Testing was performed as follows:

(1) The PVD was first fixed on the customized cylindrical iron shelf, then the piezometers used for measuring the pore water pressure and PVD blocks used for vacuum pressure in the subsoil were attached at depths of 0.3, 0.6, 0.9, and 1.2 m and radius of 0.15 m from the central PVD. The syringe needles were inserted into the central PVD at a length of 0.6 m and depths of 0.3 and 0.6 m for measuring their internal vacuum pressure. Similarly, the PVDs with a length of 1.2 m were inserted at depths of 0.3, 0.6, 0.9, and 1.2 m. The iron shelves were placed on the bottom centers of the cylinders.

(2) The well-mixed soil was poured into test cylinder until the specified height (1.2 m) was achieved.

(3) The geotextile and geomembrane pieces were placed on the top of the subsoil; the airtight caps were attached to the central PVDs and vacuum tubes; and the tubes were connected with the water-air separation bottles attached to the vacuum pump, which collected the discharged water and air to be weighted by an electronic balance.

(4) Surface settlement plates were placed at a radius of 0.15 m from the central PVDs.

(5) The geomembrane was sealed to ensure excellent air tightness of the entire vacuum system. The pressure provided by the vacuum pump was maintained at about 90 kPa. During the vacuum consolidation process, the vacuum pressure in the subsoil and PVDs, pore water pressure, surface settlement, and volume of the discharged water were monitored. When no significant increase in the water discharge was observed for both cylinders, the vacuum pump was stopped, and the subsoil test was performed.

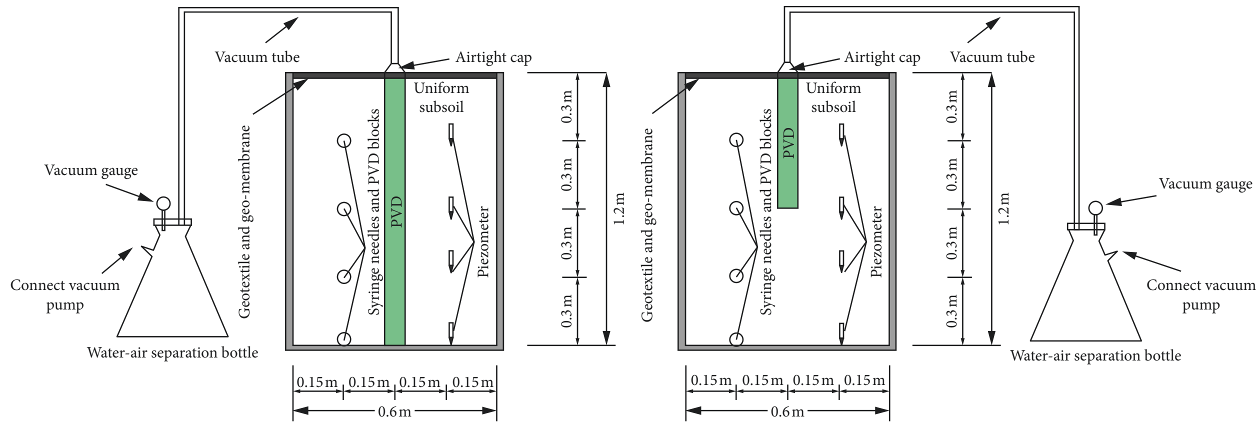

Figure 1: Model experiment conducted for improving the subsoil by embedding the PVDs with different lengths.

(6) During the test, the water content and vane shear strength were measured at a radius of 0.15 m from the central PVDs and depths of 0, 0.2, 0.4, 0.6, 0.8, and 1 m.

3. Test Results and Data Analysis

3.1. Distributions of Vacuum Pressure in the PVDs and Subsoil. Figure 2 displays the vacuum pressures in the PVDs measured at different depths during vacuum preloading. It shows that both the 0.6 m and 1.2 m PVDs maintained vacuum pressures of over 80 kPa at depths of 0.3 and 0.6 m. Further, the vacuum pressure did not significantly differ between *T*1 and *T*2 at the same depth during the consolidation process. A slight attenuation of the vacuum pressure occurred because soil particles moved and accumulated around the polyester filter membrane during consolidation, which caused PVD clogging [10, 20, 21]. As a result, the average vacuum pressure in the 1.2 m PVD at depths of 0.9 and 1.2 m was below 80 kPa. The vacuum pressure in the subsoil was much lower than that in the PVDs (Figure 3). In particular, at depths of 0.3 and 0.6 m, the vacuum pressures were about 36 and 30 kPa in *T*1 and 40 and 35 kPa in *T*2, respectively. With the depth increase, the vacuum pressure decreased, its losses observed for the depth from 0 to 0.6 m in both *T*1 and *T*2 amounted to approximately 20 kPa/m, which was consistent with the results obtained by Cai et al. [22]. The depth in *T*1 spanning from 0.6 to 1.2 m exhibited even greater attenuation, indicating that it was impossible to achieve uniformly distributed vacuum pressure along the vertical direction in the improved soil under vacuum preloading [23, 24]. The significant differences between *T*1 and *T*2 included the times required to reach measurable vacuum pressure levels within the subsoil and those passed until steady pressures value were attained. At a depth of 0.3 m, the first time required to reach measurable vacuum pressure levels was equal to 192 h in for *T*1 and 106 h for *T*2, and the second one 600 and 400 h, respectively. At a depth of 0.6 m, the measurement time was 372 h for *T*1 and 246 h for *T*2, and the corresponding times required to reach stable pressure

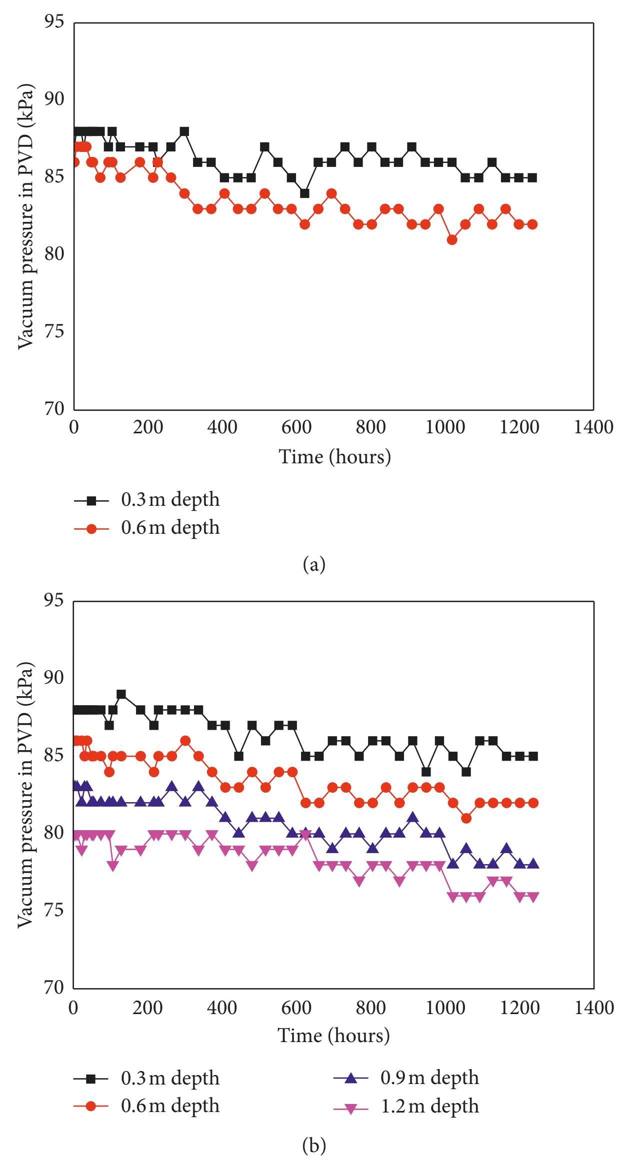

Figure 2: Vacuum pressures in the PVDs of cylinders (a) *T*1 and (b) *T*2 plotted as functions of time at various depths.

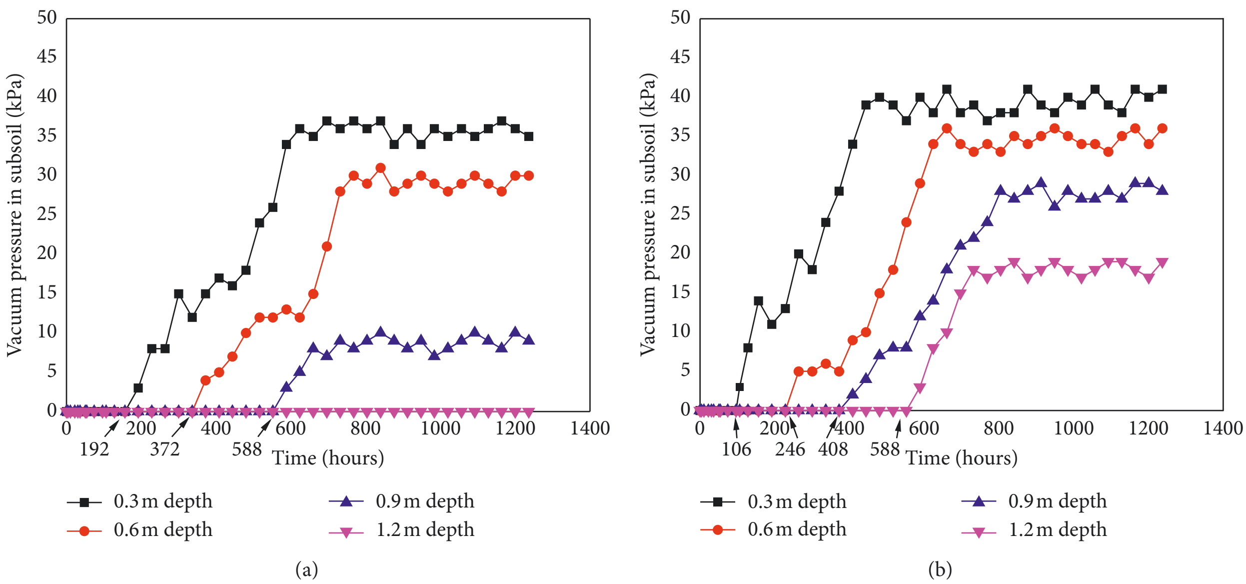

Figure 3: Vacuum pressures in the subsoils of cylinders (a) $T1$ and (b) $T2$.

values were about 700 and 600 h, respectively, as different vacuum levels within the soil were achieved within the same period at various depths [25]. The obtained measurement times indicate that the soil was in an unsaturated state and that the existence of the unsaturated zone during preloading accelerated the increase in the subsoil vacuum pressure and raised the maximum pressure limit [26]. Hence, it can be concluded that, at the same depth of the improved soil, the longer PVDs can induce an earlier appearance of the unsaturated zone followed by the achievement of a steady vacuum pressure (as compared with the effects produced by the shorter PVDs).

3.2. Variations of the Pore Water Pressure. Figure 4 shows the variations of the pore water pressures in $T1$ and $T2$ during vacuum preloading. At a depth of 0.3 m, the two cylinders reached steady pore water pressure values after approximately 600 and 500 h, which were equal to −43.2 and −55.4 kPa, respectively. A similar situation was observed at a depth of 0.6 m (the corresponding steady values obtained after 800 and 700 h were −30.6 and −43.2 kPa, respectively). Because no PVD was inserted in $T1$ at depths from 0.6 to 1.2 m, the large vacuum pressure gradient induced almost no dissipation of the pore water pressure, whereas stronger dissipation was observed in $T2$ at the same depth and greater vacuum pressures. These observations verified by the consistency between the vacuum pressure in the subsoil and pore water pressure suggest that the higher vacuum pressure increases the drain rate and accelerates the dissipation of the pore water pressure [27]. Meanwhile, the pore water pressure dissipation caused by the longer PVD in the improved zone is greater than that produced by the shorter PVD.

3.3. Surface Settlement. The average ground surface settlement over time is plotted for the two cylinders in Figure 5. It shows that, during the first 200 h, rapid increments in the surface settlement were observed for both $T1$ and $T2$, after which their magnitudes began to decrease. After 800 and 1000 h, the settlements remained almost unchanged. Although achieving a steady surface settlement by $T2$ required a longer time as compared to that of $T1$, the former possessed a larger improved zone and produced a stronger consolidation effect, as indicated by its larger final settlement value.

3.4. Water Discharge. The water discharged from the subsoil was collected in the water-air separation bottles. Figure 6 displays the variations in the volume of extracted water over time plotted for cylinders $T1$ and $T2$. It shows that the volumes of the water extracted during the first 600 h exceeded 80% of the total values equal to 50.95 and 71.84 kg for $T1$ and $T2$, respectively. Thus, due to the longer PVDs, the final discharged water volume of $T1$ was much greater than that of $T2$ and thus exhibited better consolidation behavior (see the surface settlement data).

3.5. Water Content and Vane Shear Strength. In this study, soil samples were collected at different depths to measure the water contents in $T1$ and $T2$ after vacuum consolidation. Figure 7 shows the variations in the water content with the soil depth plotted for cylinders $T1$ and $T2$. Their average values were 70.8% and 61.4%, respectively, which corresponded to a difference of 9.4% for the entire subsoil. For the upper 0.6 m subsoil layer, the average water contents were 65.7% and 57%, respectively, which indicated that the 1.2 m PVD was more effective in extracting water from the improved subsoil at depths above 0.6 m than the 0.6 m PVD. A similar increase in the water content with increasing depth was observed for both $T1$ and $T2$ because the vacuum pressures in the shallow soil layers were higher than those in the deeper layers [28, 29]. This phenomenon further demonstrates that the vacuum pressure in the subsoil decreases as the drainage depth increases, as described above.

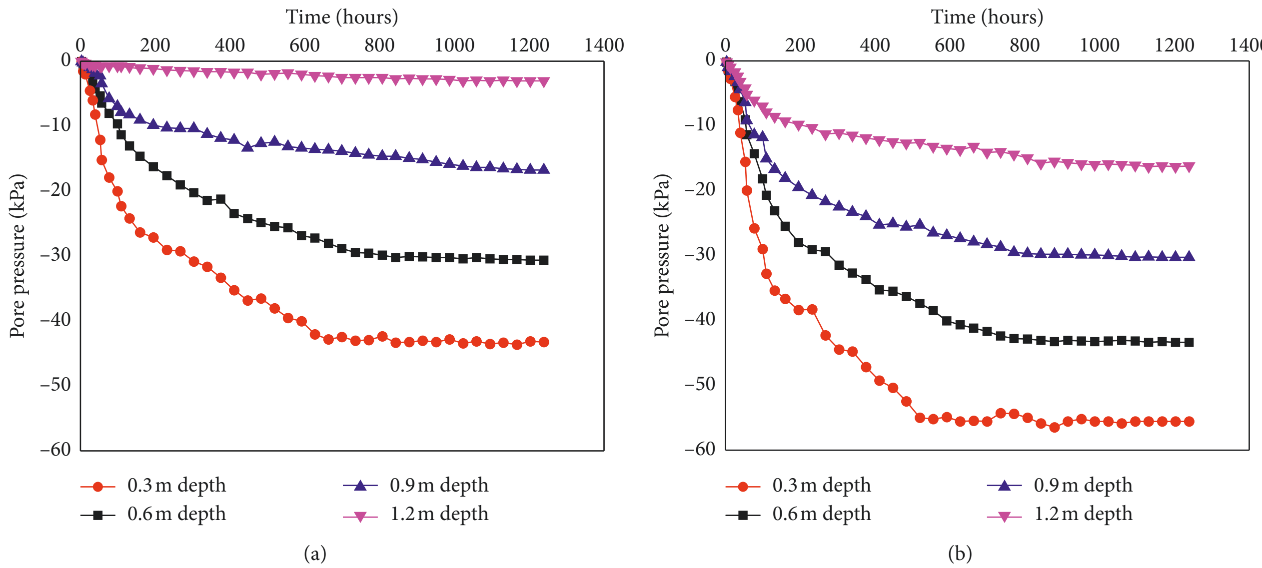

Figure 4: Variations of the pore water pressures in cylinders (a) *T*1 and (b) *T*2.

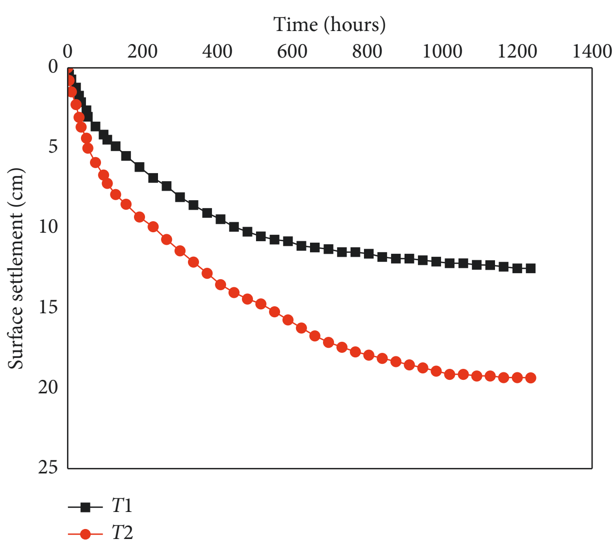

Figure 5: Surface settlements plotted as functions of time for cylinders *T*1 and *T*2.

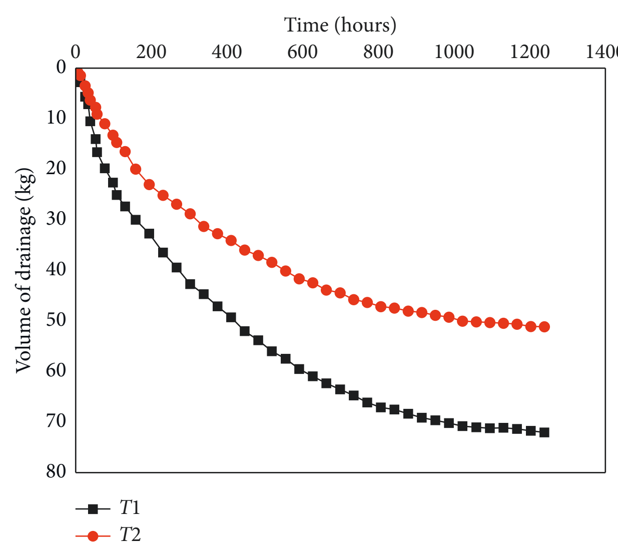

Figure 6: Volumes of extracted water plotted as functions of time for cylinders *T*1 and *T*2.

Figure 8 shows the variations in the vane shear strength with the soil depth. After vacuum consolidation, the average strength increased from zero to 13.5 and 19.5 kPa for *T*1 and *T*2, respectively. The main trends obtained for the vane shear strengths of both cylinders were similar to those observed for the reduction in the water content, indicating that better consolidation was achieved in the shallow soil layers, as the average strengths measured in the upper 0.6 m subsoil layers were 18 and 23.9 kPa due to the lower water contents. These observations were attributed to the higher vacuum pressure in the subsoil of the system with a longer drainage path.

3.6. Degree of Consolidation. The degree of consolidation at a given depth can be determined from a corresponding pore water pressure distribution profile. In this method, the average degree of consolidation is estimated as $((1-\Delta u_f)/90)\times 100\%$, where Δu_f is the excess pore water pressure at the end of vacuum preloading, which is measured as the difference between the final pore water pressure and that of the suction line [5]. The degrees of consolidation determined for the upper and lower subsoil layers in *T*1 were 51% and 24% and those of the subsoil in *T*2 were 68% and 35%, respectively.

Because the PVD in *T*1 was partially inserted into the subsoil, and the vacuum pressure was applied by an airtight sheet method [30], both the vertical and radial drainages in the surface layer must be considered using Carillo's formula [31]:

$$U_1 = 1-(1-U_v)(1-U_r), \quad (1)$$

where U_1 is the average degree of consolidation of the surface layer, U_v is the average degree of consolidation due

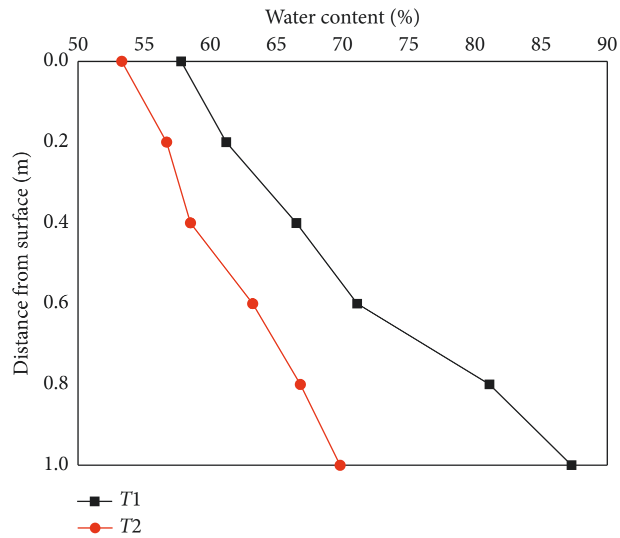

Figure 7: Variations in the water content with the soil depth plotted for cylinders $T1$ and $T2$.

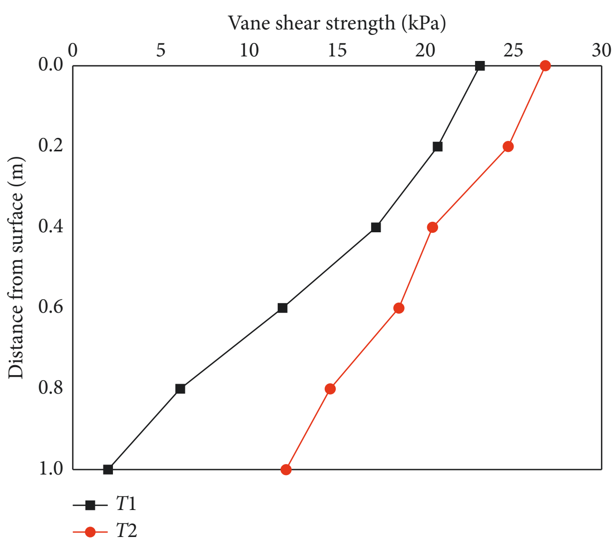

Figure 8: Variations in the vane shear strength with the soil depth plotted for cylinders $T1$ and $T2$.

to vertical drainage, and U_r is the average degree of consolidation due to radial drainage. The value of U_r is calculated by Hansbo's formula (1980), which was derived based on the equal vertical strain assumption and neglected the vertical drainage of natural subsoil:

$$U_r = 1 - \exp\left(-\frac{8}{\mu}T_h\right), \tag{2}$$

where T_h is the time factor equal to $C_h t/D_e^2$, in which C_h is the coefficient of consolidation in the horizontal direction, D_e is the diameter of the unit cell, and t is the time. The value of μ can be expressed as

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln(s) - \frac{3}{4} + \pi\frac{2l^2 k_h}{3q_w}, \tag{3}$$

where $n = D_e/d_w$ (d_w is the diameter of the drain); $s = d_s/d_w$ (d_s is the diameter of the smear zone); k_h and k_s are the horizontal hydraulic conductivities of the natural soil and smear zone, respectively; l is the drainage length; and q_w the discharge capacity of the PVD.

The average degree of vertical consolidation is defined as

$$U_v = 1 - \exp(-C_d T_v), \tag{4}$$

where T_v is the time factor for the vertical consolidation equal to $C_v t/H^2$, in which C_v is the coefficient of consolidation in the vertical direction, and H is the vertical drainage length; and C_d is the axial symmetry radial consolidation parameter. The parameters used in this study are listed in Table 2, and the average degree of consolidation of the upper subsoil layer in $T1$ obtained by this method was 71%.

To calculate the average degree of consolidation of the layer without PVDs, a special method was developed by Ong et al. [32]. When the bottom of the layer is an impermeable boundary, the one-way drainage conditions should be adopted; in this case, the average degree of consolidation of the studied layer can be expressed as

$$U_1 = \alpha_2 U_T, \tag{5}$$

where U_T is the degree of consolidation of the layer without PVDs calculated using Terzaghi's one-dimensional consolidation theory, and α_2 is determined by

$$\alpha_2 = \left(0.33U_p^2 + 0.20U_p + 0.1\right)\left(\frac{k_h/k_s}{2}\right)^{0.07}\left(\frac{D_0}{D_e}\right)^{0.3}, \tag{6}$$

where U_p is the average degree of consolidation of the layer with PVDs located above the bottom layer, D_0 is the constant (1.5 m), and D_e is the diameter of the unit cell. By applying this method, the value of α_2 equal to 0.57 was obtained, and the average degree of consolidation of the lower subsoil layer in $T1$ determined via Terzaghi's one-dimensional consolidation theory under the one-way drainage conditions was 40%. As indicated by the degrees of consolidation calculated for $T1$ by the two methods, their values obtained for the lower layers were different, which could be attributed to the following factors. (1) The pore

Table 2: Subsoil and drain parameters.

Subsoil					Drain				
k_h (10^{-8} m/s)	k_v (10^{-8} m/s)	e	a_v	C_d	d_w (m)	D_e (m)	d_s (m)	k_h/k_s	q_w (m^3/year)
0.92	0.5	2.72	0.12	4.2	0.05	0.6	0.1	5	100

water pressures were measured only at specific points and thus might not be representative of the average values for the entire layer. (2) The pore water pressures were likely maintained at higher levels, as was previously observed by other researchers, because of compression and the rearrangement of the soil structure [33–35]. In the following section, the results of a vacuum consolidation study conducted in Wenzhou, China, are described to illustrate the effect of the PVD penetration depth on the key parameters of the vacuum consolidation process.

4. Study of Soft Clay Deposits in Eastern China

4.1. Subsoil Conditions and Testing Site. Wenzhou Vocational Secondary School is located in the new district of the Oujiang Estuary. The ground elevation of the proposed construction site is 2.30–2.60 m, and the designed outdoor elevation is 5.2–5.5 m (the site is to be reclaimed). Owing to the adverse conditions at the field located in the reclamation area of an alluvial plain that contains soft clay deposits and thus cannot meet the construction requirements, it is necessary to reinforce the construction site by vacuum preloading for preliminary shallow layer treatment. The treated area covers 157,820 square meters and is divided into six sections due to different reinforcement requirements.

Before construction, the site conditions were investigated by a series of field exploration programs. The site consists of a dredger fill in the upper layer with an average depth of 3 m, which possesses high compressibility, liquid-plastic state, and poor engineering characteristics. Below this layer lies a highly sensitive mud deposit (mud-1) with a thickness of approximately 6.8 m. The next layer contains muddy silt with a thickness of approximately 6.4 m. Beneath the muddy silt, a silty clay layer is underlain by the layer of mud deposit (mud-2) with a thickness of approximately 20 m. The first three layers were mainly used for PVD improvement studies. The soil profile and properties of the soft clay deposits at the test site are shown in Figure 9.

Figure 10 shows the plan views of the test site. The elevation of the used equipment was above the 1.5 m depth, and its various parts were arranged in intervals of 3 m. The monitored elevations of sections 1 and 2 were 10.5 and 15 m, respectively. The PVDs in the subsoil of section 1 were installed at a depth of 6 m, and those in section 2 at a depth of 15 m. All PVDs were arranged in the square pattern with a spacing of 0.8 m. Vacuum pressure was applied using the air-sealing sheet method [10]. A polyvinyl chloride membrane was placed above the two layers of geotextile spread, and the edges of the sealing sheet were embedded in a 1.5 m deep trench. During the vacuum preloading consolidation process, the vacuum pressure under the sealing sheet was maintained at a level of about 80 kPa. After 120 d of the experiment, the vacuum pump was stopped, and a subsoil test was conducted.

4.2. On-Site Measurement Results and Analysis

4.2.1. Pore Water Pressure. The pore water pressures measured at different elevations of the subsoils in sections 1 and 2 are plotted as functions of time in Figure 11. At an elevation of 1.5 m, the pore water pressure in section 2 exhibits a steeper downtrend as compared to that of section 1; similar trends were observed at other elevations. After 120 d of the vacuum consolidation process, the pore water pressure in each monitored subsoil layer demonstrated a steady trend for both sections. At the same elevation, section 2 exhibited greater pore water pressure dissipation as compared to that of section 1 (consistent results were obtained for the even and multilayer subsoils). In the even subsoil, the pore water pressure exhibited a nearly uniform decline, while in the multilayer subsoil, the observed change was more complex because the vertical hydraulic conductivity in mud-1 and muddy slit were greater than that in the dredger fill, although the shallow layer with a depth below 4.5 m showed a little difference in the dissipation of the final pore water pressure.

4.2.2. Layered Settlement. Subsoil settlements were measured at different elevations by the multilevel settlement gauges. The multilevel settlements in sections 1 and 2 are plotted as functions of time in Figure 12, which demonstrates that the PVD influence range is deeper than its embedded depth. Generally, the settlements in section 2 decreased faster than those in each subsoil layer of section 1. At the end of vacuum preloading, all settlement curves started converging, and the settlements in section 2 measured for each subsoil layer were greater than those in section 1. The final average ground surface settlements in sections 1 and 2 were 0.98 and 1.20 m, respectively.

4.2.3. Lateral Displacement. The lateral displacements measured by inclinometers in sections 1 and 2 at different depths and durations are plotted in Figure 13. It shows that the highest lateral displacement was detected at the ground level and decreased sharply with a depth increase [36]. The observed trends were relatively smooth except for the points at the boundary of the subsoil layer, which was likely due to a change in the parameters of the soil between different layers [37]. After each 15 d interval, the

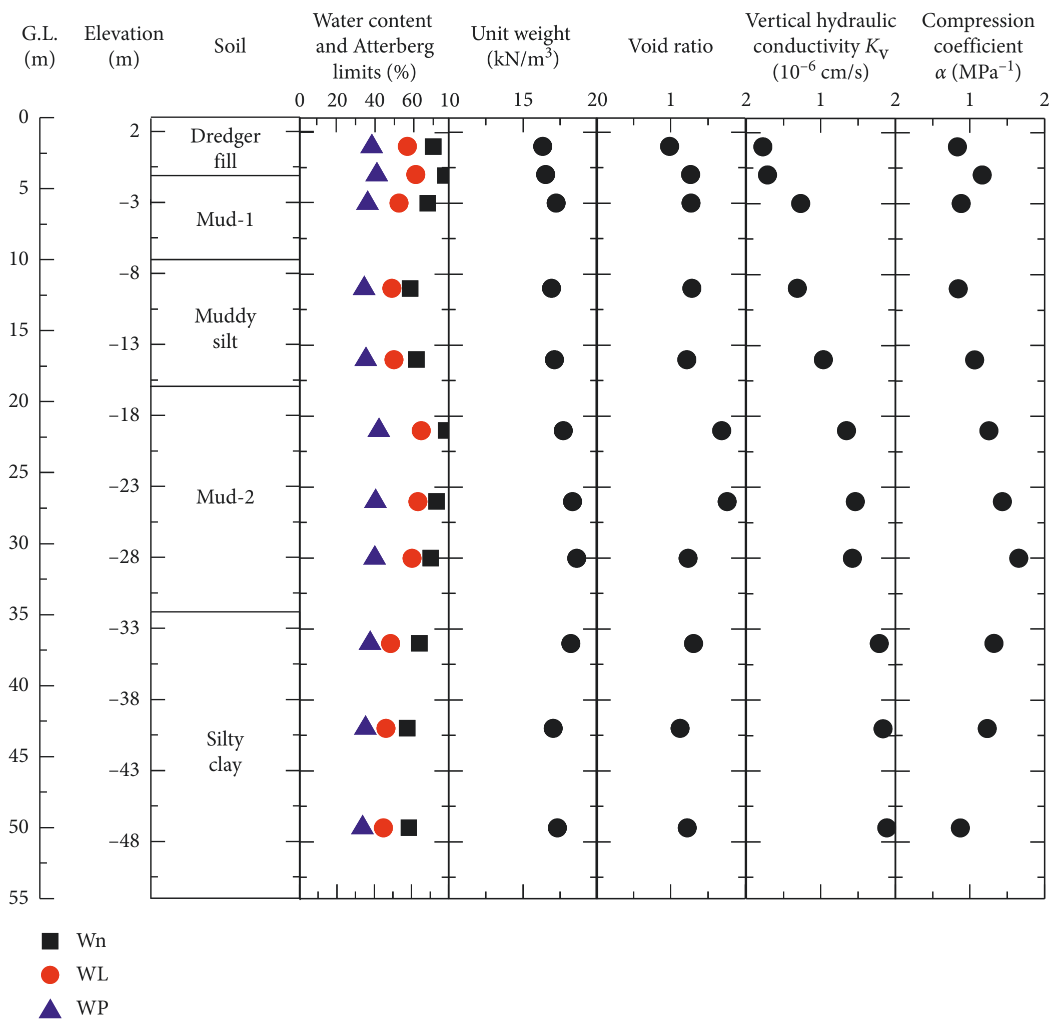

FIGURE 9: Soil profile and physical properties of the test site.

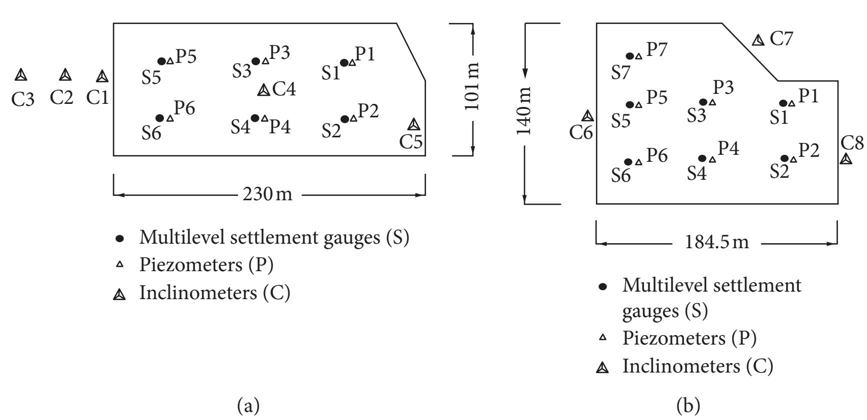

FIGURE 10: Plan views of the test equipment locations. (a) Section 1. (b) Section 2.

lateral displacements became greater, while their increase rate decreased. At the same depth and time, section 2 showed a greater displacement as compared to that in section 1, and by increasing the PVD length, a broader influence range that was slightly larger than the length of the embedded PVDs was observed.

4.2.4. Vane Shear Strength. Field measurements of the vane shear strengths of sections 1 and 2 were conducted after 120 d of vacuum preloading, and the resulting strength profiles are plotted in Figure 14 (here, the depths of the test points were calculated from the distances to the ground surface after vacuum preloading). It shows that

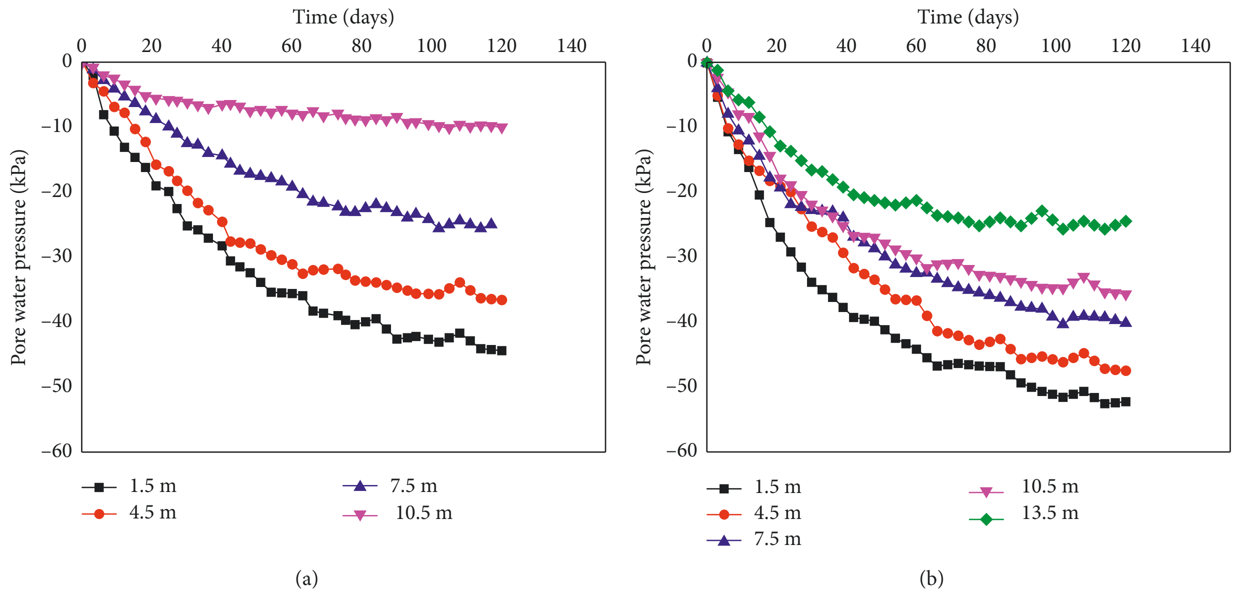

Figure 11: Pore water pressures plotted as functions of time for sections (a) 1 and (b) 2.

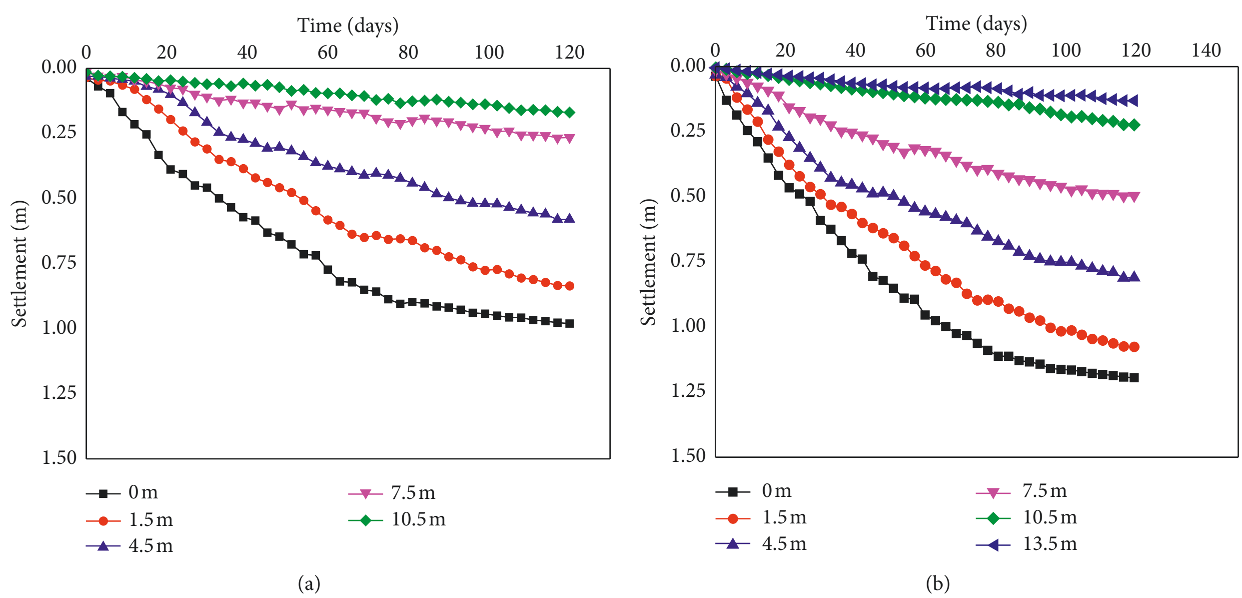

Figure 12: Multilevel settlements plotted as functions of time for sections (a) 1 and (b) 2.

after 120 d of vacuum preloading, considerable improvement in the vane shear strength was observed throughout the entire improved zone. The average vane shear strength of the top subsoil layer with a depth of 6.5 m increased from approximately 11 kPa to 37 and 43 kPa for sections 1 and 2, respectively. Because the PVDs in section 1 were embedded at a depth of 6 m, the vane shear strength of the subsoil below this level decreased more rapidly than that of the soil in section 2, in which the PVDs were inserted at a depth of 15 m.

4.2.5. Water Content. The changes in the subsoil water content observed before and after vacuum preloading are plotted in Figure 15. A substantial reduction in the water content was detected in the layers with depths up to 6.5 m, which corresponded to decreases from approximately 71% to 58% and 51% for sections 1 and 2, respectively. It was found that, in the shallow layer, the change in the water content was proportional to the increase in the vane shear strength; however, in section 2, the change in the water content at depths greater than 10 m significantly decreased despite the PVD embedment and considerable increase in the vane shear strength. This phenomenon can be explained by the higher stiffness of the subsoil layers deeper than 10 m, as indicated by their smaller void ratios and higher vane strengths [36]. For this reason, the change in the water content is not a good indicator of the

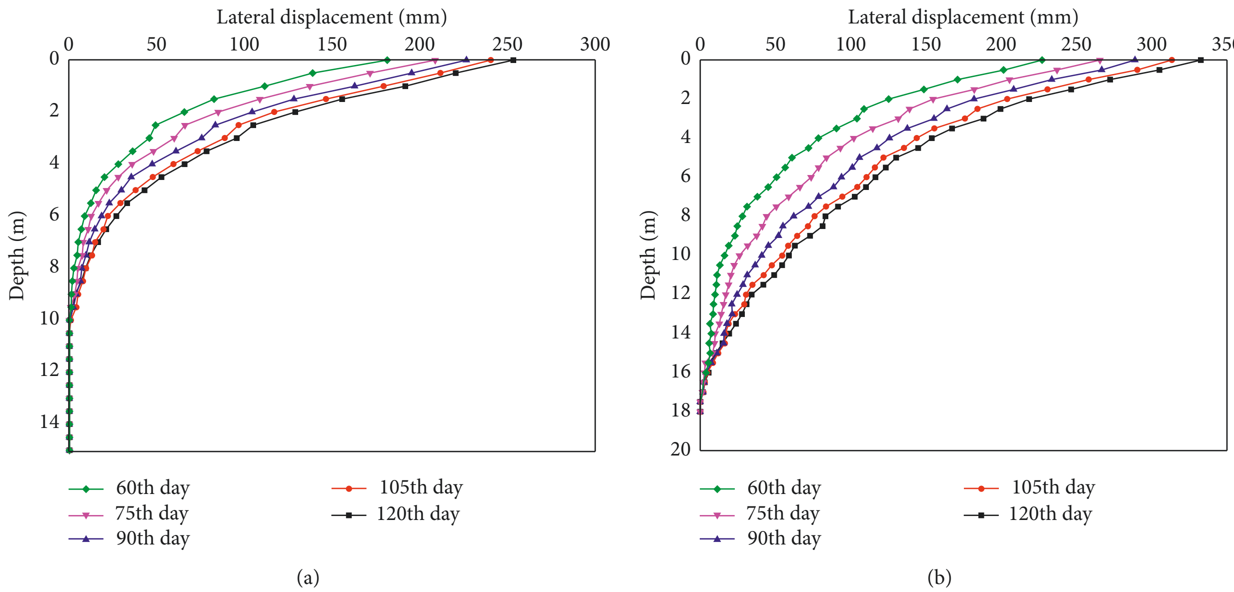

FIGURE 13: Lateral displacements plotted as functions of time for sections (a) 1 and (b) 2.

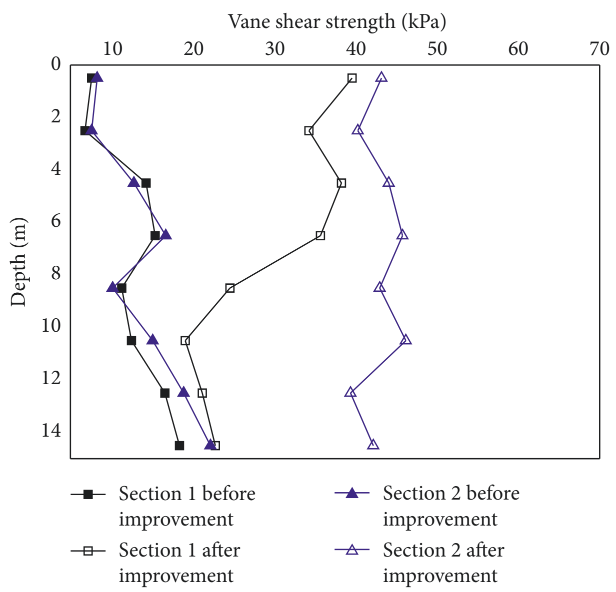

FIGURE 14: Vane shear strengths plotted as functions of depth for sections 1 and 2.

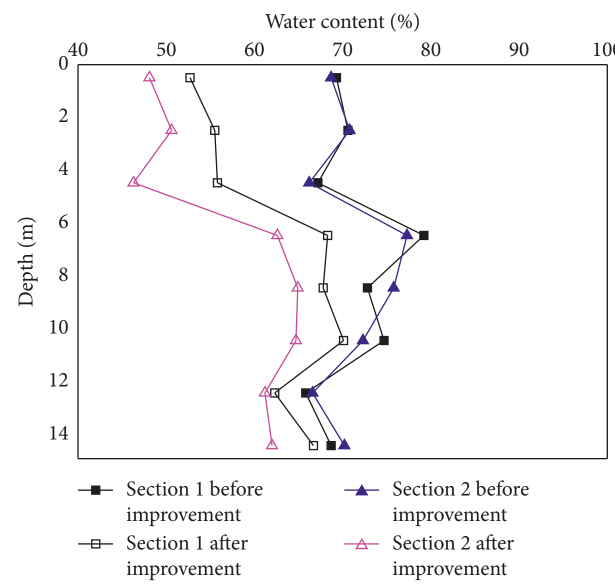

FIGURE 15: Water contents plotted as functions of depth for sections 1 and 2.

improvement of the vane shear strength of multilayer subsoil.

4.2.6. Degree of Consolidation. The average degree of consolidation of multilayer subsoil can be calculated using the following pore water pressure distribution profile [38]:

$$U_{\text{avg}} = 1 - \frac{\int u_t(z) - u_s(z)}{\int u_0(z) - u_s(z)} dz, \qquad (7)$$

where $u_0(z)$ is the initial pore water pressure at depth z, $u_t(z)$ is the pore water pressure at depth z and time t, and $u_s(z)$ is the pressure in the suction line. The integral in the numerator of the equation denotes the area between the curves $u_t(z)$ and $u_s(z)$ [4, 12, 20, 21], and the integral in the denominator corresponds to the area between the curves $u_0(z)$ and $u_s(z)$. By applying this method in Figure 16, the calculated average degrees of consolidation of the dredger fills in sections 1 and 2 were 72.1% and 80.9%, and those of mud-1 were 38.6% and 56.6%, respectively. Therefore, the degrees of consolidations of all subsoil layers in section 2 were systematically higher than those in section 1.

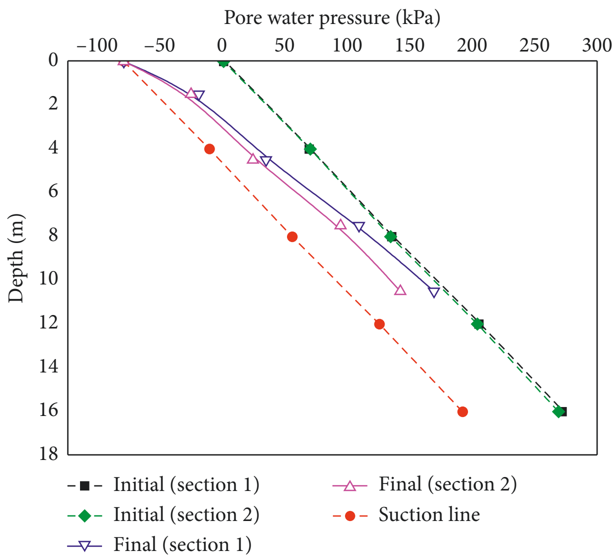

Figure 16: Pore water pressure profiles obtained for sections 1 and 2.

5. Conclusion

Laboratory model experiments and field testing involving the application of vacuum preloading combined with the embedment of PVDs into subsoil were performed in this study. From the obtained results, the following conclusions can be drawn:

(1) The PVDs with longer lengths maintained a higher vacuum pressure in the shallow soil layer as compared to that achieved using the shorter PVDs. Greater pore water dissipation and better soil consolidation were achieved in the improved zone at the same elevation. In the model experiments, the degrees of consolidation obtained for the upper subsoil layers in the two cylinders were 51% and 68%, and the corresponding vane shear strengths increased to 18.2 and 22.6 kPa, respectively. At the practical engineering test site, the resulting degrees of consolidation at depths below 6 m were 72.1% and 80.9%, and the vane shear strengths increased to 26 and 32 kPa, respectively.

(2) In both the improved and unimproved zones, the measured parameters of the even subsoil changed almost linearly with the depth, while in the multilayer subsoil, the observed changes were more complex due to its nonuniform physical properties.

(3) Unlike the multilayer subsoil, the change in the vane shear strength of the even subsoil was proportional to that of the water content, which could be explained by the differences between the physical parameters of these two soil types.

Data Availability

These data are available. In their cooperation agreements, any type of date, including testing and recording, belongs to the unit and is therefore confidential to anyone else. The author thanks the readers for their understanding of the cooperation agreement.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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