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Research Article

Laboratory and Field Experimental Study on the Vacuum Preloading Method with Pumping and Discharging

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Negative vacuum pressure hardly reaches deep soils due to the drain board bending and serious blockage with the existing vacuum preloading methods (VPMs), thus resulting in poor reinforcement relative to practical engineering applications. To address this issue, this paper proposes a vacuum preloading method with pumping and discharging (a new dredger filling foundation processing technique based on vacuum preloading). This new VPM is developed through technological improvement and plastic drain board innovations in traditional VPMs. The new VPM uses a plastic vertical drainage board with double drainage channels, and the core board is in a "tic-tac-toe" shape with a hollow centre and square pipeline channels. It can execute air and water drainage. Vacuum transfer holes were set at two grooves, every 2-3 m from the central pipeline of the core board. Grooves at two sides of the core board and filter membrane were rolled together to improve drainage. In addition, the vacuum pipe, tube connector, and core board centre of the vertical plastic drainage board were connected directly and securely. A stereoscopic vacuum transmission system composed of a horizontal and vertical drainage system was built. In this vacuum transmission system, the transfer route was shortened, and the loss of vacuum along the route was decreased. The negative vacuum pressure was transferred to different soil depths through the central pipeline of the core board to accelerate the dissipation of pore pressure in soil mass and prevent vacuum pressure loss caused by drainage board bending, thus improving the reinforcement effect. Dredger filling silt foundation reinforcement by VPM and VPM with pumping and drainage were compared in laboratory simulations and field tests with different drainage boards. Test results show that the loss of vacuum pressure along the drainage path was relatively smaller in the new physical vapor deposition (PVD), and the pressure transfer efficiency was increased. Deep soil mass was reinforced effectively by using the new PVD. After reinforcement, the physical and mechanical properties of soil layers were improved. Moreover, soil strengths were remarkably improved, with sharp reductions in natural moisture content and porosity. Then, the transfer law of vacuum on different drainage boards and the reinforcement mechanism of VPM with pumping and drainage were analysed. Research conclusions show the superiority of VPM with pumping and drainage in terms of effectiveness and soft foundation reinforcement. This study provides a theoretical basis for the application and development of the new VPM.

1. Introduction

Sludge soils from seas, rivers, and lake beds are often used as dredger filling materials in reclamation projects in coastal and offshore areas in China. Vacuum preloading methods (VPMs) are extensively used to reinforce dredger filling silt foundation, which often has high moisture content, high compressibility, low strength, and low bearing capacity [1–3]. A plastic drainage board (Figure 1) is inserted into the soft foundation as a vertical drainage channel to transfer vacuum pressure to the soil; consequently, pore water is drained under the negative pressure difference between soil mass and vertical drainage channels [4]. Hence, the soil mass is solidified, and the soil strength is increased, thus reinforcing the foundation [5, 6].

However, VPM has low utilization of vacuum energy. Most vacuum energies are concentrated in the soil surface, and vacuum pressure in the drain board decreases significantly with the increase in depth [7–9]. Studies on the attenuation law of vacuum along the depth direction have been reported globally. The vacuum transfer is influenced by the coating, resistance, bending, and blockage of the drainage board. As a result, the transfer of vacuum pressure along the depth of the drainage board may be lost [10–12]. During the soft foundation reinforcement with the VPM, the formation and distribution of vacuum pressure are vital to the reinforcement effect and depth. They are significant in determining the effective reinforcement depth [13–15]. The vacuum pressure at deep positions of the drainage board decreases significantly due to vacuum pressure loss along the transfer path. Therefore, the reinforcement effect in lower soil mass is significantly weaker than that in superficial soil mass [10–15], resulting in the poor reinforcement of deep soil layers. Hence, the consolidation of deep foundation is not achieved [16].

To prevent the vacuum degree loss in common drainage boards in the VPM, a VPM with pumping and drainage (hereinafter referred to as the new VPM) was proposed [17] (Patent number: ZL201310328314.x; Figure 2) through technological improvements and drainage board innovation. The new VPM involves a plastic drainage board with double drainage channels [18] (Patent number: ZL201310328542.7; Figure 3) to replace the common plastic vacuum drainage (PVD). The performance of the common and new drain boards in terms of vacuum pressure transfer and reinforcement was compared with laboratory simulations and field tests. The research results proved the superiority of the new VPM [19–21].

2. Working Principle of the New VPM

The core board of the common PVD is a concave-convex structure covered with a filter film (Figure 1). In this study, a new PVD with double drainage channels was used (Figure 3), and the core board was combined in "tic-tac-toe" structures. A hollow square-shaped tube exists in the centre of the core board to transfer vacuum pressure. Grooves were located at the two sides of the core board, which were covered with a filter membrane. Vacuum transfer holes were constructed every 2-3 m in the grooves at the two sides of the core board. The core board is connected to a vacuum pipeline through tube connectors.

The VPM structure is shown in Figure 4. A geotextile was paved onto the soft foundation surface first, and the PVD was inserted vertically (Figure 1), followed by a pavement of sand cushion and permeable ripple tubes. The PVD and permeable ripple tubes were connected to a transverse drainage system, and the geotextile was then paved. Next, two layers of the plastic membrane were paved for sealing purposes. The water-collecting pipe was extended from a filter membrane, and the head was tied securely. Finally, the

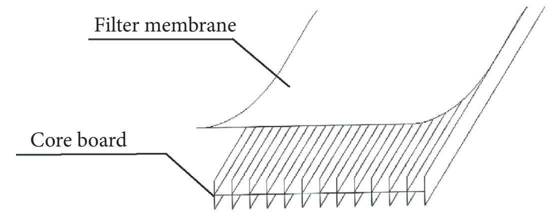


Figure 1: Common PVD.

water-collecting pipe in the transverse drainage system was connected to a vacuum pump.

The improvement of the new VPM (Figure 2) comparing to the traditional VPM was mainly reflected in the new PVD. The new vertical PVD (with double drainage channels) was connected tightly to the hole-free vacuum tube through tube connectors, forming vertically and horizontally closed stereoscopic drainage systems. The vacuum pressure was directly transferred along the pipeline in the centre of the PVD to different soil layer depths through vacuum transfer holes. In this manner, the vacuum transfer path was shortened, the vacuum degree loss was decreased, and pore pressure dissipation was accelerated. The PVD bending caused by excessive foundation settlement will not influence the transfer of vacuum pressure along the air channels in PVD. Moreover, the vacuum pressure can still be transferred to deep soil layers through the central channel of the PVD after the external grooves have been blocked, thus increasing the utilization of vacuum pressure.

3. Model Test

3.1. Soil Sample Preparation. Soil samples were collected from sludge, which were mainly sludge clay, in the Qinhuai River Bed in Nanjing City. The basic physical properties of soil samples are shown in Table 1.

3.2. Testing Apparatus and the Testing Process. The testing apparatus is shown in Figure 5. A laboratory simulation test was conducted on sludge samples with the same properties in two model cylinders. The testing apparatus mainly included model cylinders, a pressure control system, an air-water separation system, and a measurement system. The model cylinder size was ϕ 0.4 m $*$ 2.0 m, and it was divided into two sections, which were connected by an internal band. The measurement system mainly included a vacuum-monitoring detector, a settlement mark, and an air-water separator.

During sampling, the common PVD and new PVD were placed in the centre of the model cylinder. The vacuum measurement system was set still for 24 h after filling, and the air was drained completely. The common PVD and new PVD were 200 cm long and 5 cm wide. Inside the new PVD, the distance between the pressure transfer holes on the core board was 1.0 m. In addition, the vacuum tube was buried in a 5 cm thick sand cushion on top of the left model, whereas the new PVD on the right was connected to vacuum tubes directly. Finally, geotextiles and geomembranes were paved on top of the samples for sealing purposes.

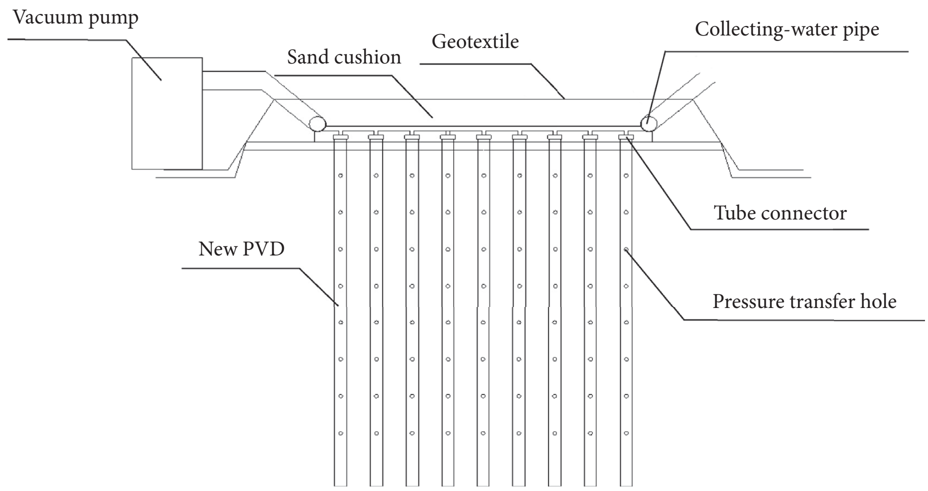


Figure 2: Vacuum preloading method with pumping and discharging.

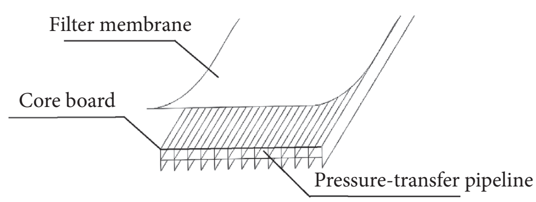


Figure 3: New PVD.

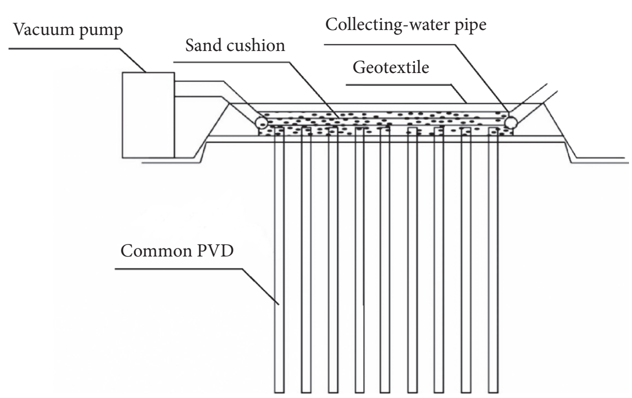


Figure 4: Vacuum preloading method.

Vacuum-monitoring detectors were buried in the model cylinder with an interval of 1.0 m. Vacuum pressures at sand cushion level (D1), 1 m (D2), and 2 m (D3) of the PVD were measured. Meanwhile, settlement marks were buried in the model with an interval of 0.65 m. Soil mass in the model was divided into upper (S1), middle (S2), and lower (S3) layers to monitor the settlement of different soil layers. The drained water in the air-water separator in different models was weighed by an electronic balance.

3.3. Test Content. In the present study, VPM tests of different drainage boards (common and new PVD) were performed using a laboratory simulation model. The effectiveness of the drainage boards on different soil layer settlements in the VPM-reinforced dredge filling silt foundation was discussed in accordance with the test results. The reinforcement effect of the common and new PVD was compared.

4. Test Results

4.1. Transfer Laws of Vacuum Pressure. Vacuum pressures at different depths of sand cushion and PVD were measured in two tests. The relationship between the vacuum pressure and time is shown in Figures 6(a) and 6(b). The negative vacuum pressure in the sand cushion and PVD increased quickly. The vacuum pressure in the common PVD stabilized after 50 h, but in the new PVD, it stabilized after 10 h, which indicates that the loss of vacuum pressure along the drainage

Table 1: Basic physical and mechanical properties of soil samples.

Soil samples	Moisture content (%)	Density (g/cm^3)	Gs	Liquid limit (%)	Plastic limit (%)	Plasticity index	e_0
Sludge	56.9	1.67	2.74	46.4	28.6	17.8	1.57

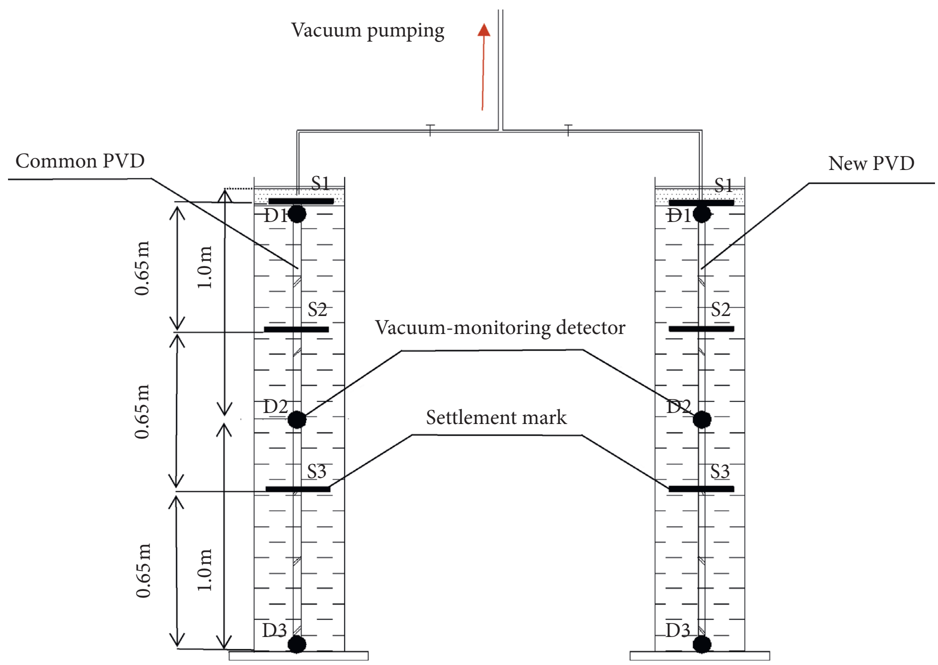


Figure 5: The model-testing device (applying the common PVD on the left and new PVD on the right).

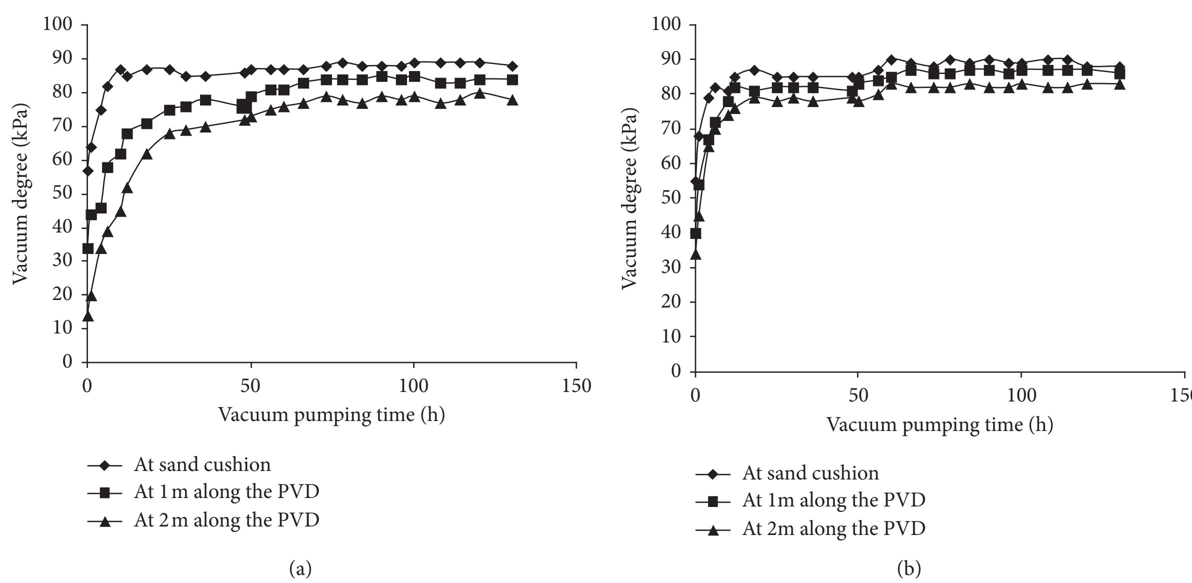
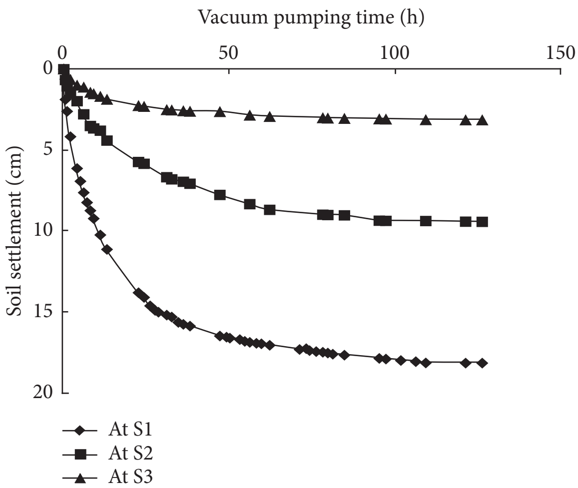


Figure 6: Vacuum degree at different depths: (a) common PVD; (b) new PVD.

path was relatively smaller in the new PVD, and the pressure transfer efficiency was increased.

In Figure 6(a), the attenuation of vacuum negative pressure along the conventional drain plate is about 5 kPa/m. In Figure 6(b), the attenuation of vacuum negative pressure along the new drain plate is slight (only approximately 2 kPa/m). The results show that the attenuation of vacuum degree along the new drain plate is slight, and the transfer efficiency is obviously increased. The main reason is that the central drainage channel on the new PVD can compensate vacuum pressure loss so that the vacuum pressure was kept high at the end.



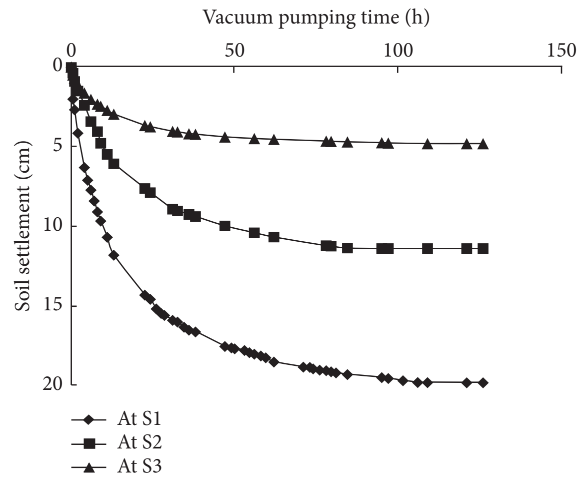


Figure 7: Variation curve of layered settlements with time: (a) common PVD; (b) new PVD.

Table 2: Comparison of layered settlement in different models.

Working conditions	Total accumulated settlement (cm)	Settlement (cm)		
		Upper layer	Middle layer	Lower layer
Common PVD	18.1	8.7	6.3	3.1
New PVD	19.8	8.4	6.6	4.8

4.2. Layered Settlements. After the self-weight settlement was stable at 24 h, soil samples were continuously vacuumed for 126 h at 90 kPa, until the settlement was stabilized. Subsidence displacements of the upper (S1), middle (S2), and lower (S3) settlement markers were recorded during the test. The settlement vs. time curves of the two models at two locations are shown in Figures 7(a) and 7(b). Given the high upper settlement of soil mass, layered settlements of soil layers decreased with the increase in depth. Test soils in the common and new PVD models developed uneven vertical settlements.

Soil mass in models was divided into three layers in accordance with the settlement marker. Cumulative settlements of different layers are listed in Table 2. The total settlement of soil mass in the new PVD was 10% higher than that in the common PVD. The settlement of the upper layer was basically consistent after the new PVD was applied to the model, whereas the settlement of the lower layer increased significantly by 53.2%, and the settlement of the middle layer increased by only 4.8%.

On the basis of the contrast analysis of settlements in different layers, the total settlement after the use of the new PVD was mainly attributed to the compression of the lower soil mass. Moreover, settlements of different layers were more uniform than that of the common PVD. According to the proportion of different layers in the total settlement, the super layer is the main reinforcement layer, and the degree of compaction accounts for most of the upper settlement. After the new PVD was used, the settlement of the lower layer increased. Consequently, deep soils were reinforced, and the effective reinforcement depth of VPM increased, proving that the new VPM claimed a small settlement. Moreover, the new VPM is more practical than the common VPM.

5. Field Test

To verify the reinforcement effect of the new VPM further, a field test in the Tianjin Marine Manufacturing Site (10,000 m^2) was performed. A soft dredger filling silt foundation was identified in the study area. The dredger filling height was 5 m, and this project was finished in 120 days. In this site, a 100 m^2 area was selected for the field test, and a new PVD was used. The common PVD was inserted 5 m deep in rest areas with an interval of 0.8 m $*$ 0.8 m. The water-collecting tube was located perpendicular to the horizontal PVD, and they were connected to diameter-variable connectors. The outcrop of the vertical common PVD was connected to the nearest horizontal PVD. In accordance with standards and design requirements, a cross-plate test was performed before and after foundation reinforcement. The physical and mechanical properties of soils before and after reinforcement were tested.

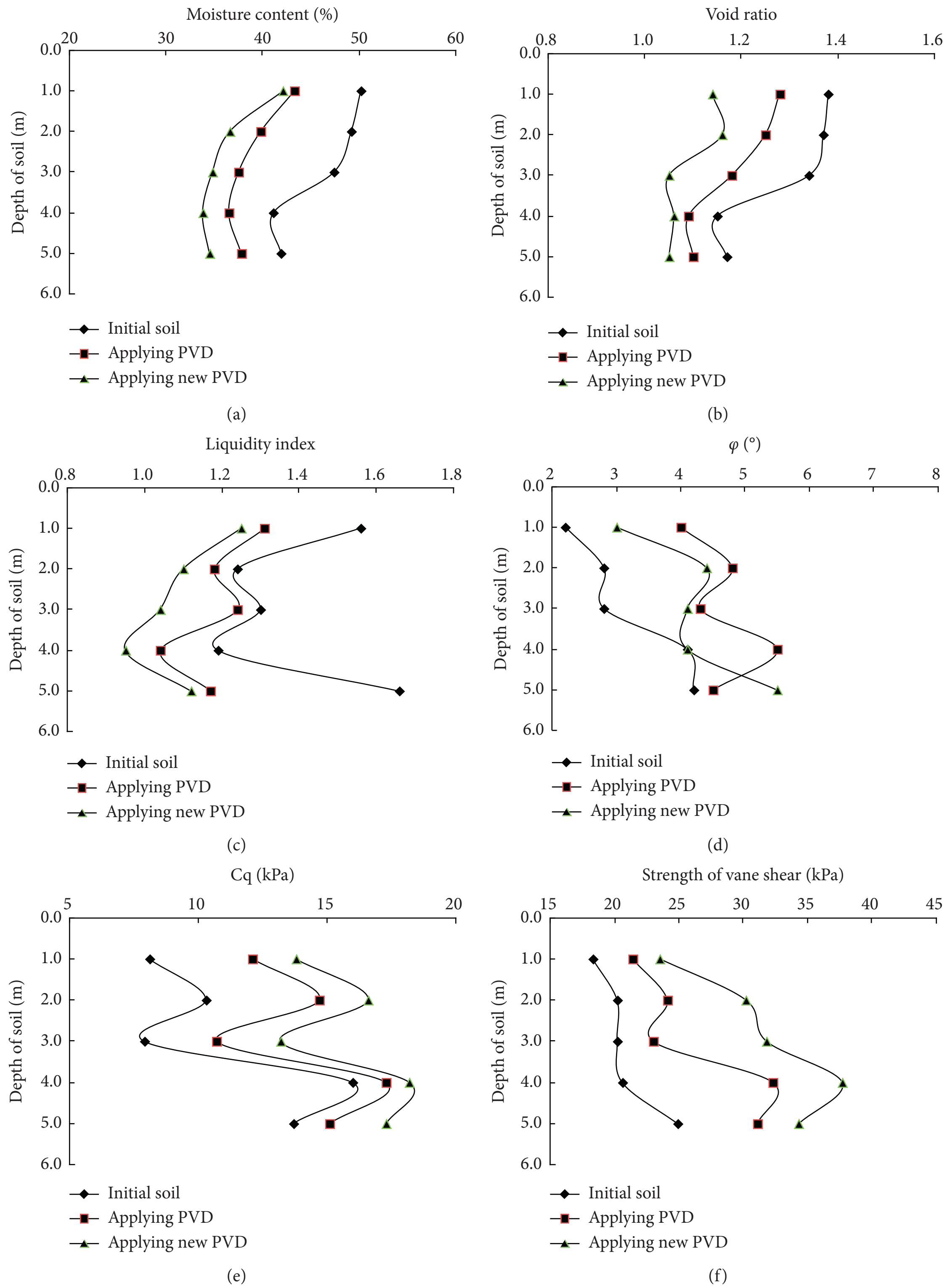


Figure 8: Basic physical and mechanical properties with depth: (a) soil moisture content with depth; (b) soil void ratio with depth; (c) soil liquidity index with depth; (d) φ with depth; (e) Cq with depth; (f) strength of vane shear with depth (before and after reinforcement with common and new PVD).

Undisturbed soils were collected before and after reinforcement for a laboratory in the field cross-plate test to evaluate the reinforcement effect of the foundation. Changes in soil intensity and soil properties before and after reinforcement were disclosed. The results are shown in Figure 8.

After vacuum preloading treatment, the moisture content of different soil layers relatively declined, the void ratio of soil correspondingly reduced, and the shear strength of soil mass increased significantly. The physical and mechanical properties of soils in the entire reinforcement area have greatly improved. Moreover, such improvement is more evident in the upper layers compared to the lower layers. The natural moisture content of each layer of soil has a relative range of reduction, the degree of reduction of natural moisture content of surface soil is greater than that of the lower layer, and the porosity also decreases.

Figure 8 shows that the physical and mechanical properties of soils improved after reinforcement. The natural moisture content and porosity dropped sharply. The natural moisture content of the soil after reinforcement was 10% lower than that before, and the natural moisture content in the new PVD was 20% lower than that in the common PVD, and the pore ratio of soil decreased by about 15%. The shear strength increased by 30% after reinforcement, and it increased by 50% to the maximum extent in the new PVD. The main reasons are that the transfer vacuum efficiency of the new drainage board is improved, the drainage efficiency of pore water is improved, the natural moisture content and porosity dropped, and the shear strength of the soil is increased. The new PVD was evidently superior to the common PVD in terms of reinforcement effect, especially in the lower layers. The effectiveness of the new VPM in soft foundation reinforcement was confirmed in the test.

6. Analysis and Discussion

With the basic principle of VPM and its combination with the field test results, the superiority of the new VPM was mainly analysed and discussed preliminarily from the vacuum transfer and effective sphere of influence of the single pile.

6.1. Transfer of Vacuum Pressure. PVD in the VPM accelerated vertical drainage and vacuum pressure transfer significantly. Pore water may infiltrate PVD due to the pressure difference between soil mass and PVD, whereas pore water in PVD may infiltrate the sand cushion as a response to the pressure difference and can then be drained by the water-collecting pipe. Vacuum pressure can easily be lost during transferring in the common PVD due to the pile resistance. Therefore, vacuum pressure attenuates gradually during the downward transfer [21–23]. The vertical transfer of vacuum pressure in PVD and the radial distribution in the surrounding soil mass are shown in Figure 9(a).

In the new VPM, the PVC pipe was connected with the vacuum pump, which was subsequently connected to the central channel of the new PVD's core board. Vacuum pressure was transferred to the stereoscopic vacuum pressure transfer system, which is composed of the vacuum pump, PVC pipeline, and new PVD (Figure 10). Vacuum pressure was shifted to the vacuum pressure transfer hole at different depths along the central channel of the new PVD until it finally reached different depths of the PVD. Then, vacuum pressure was transferred to the soil mass surrounding the new PVD. During this process, the pile resistance against the transfer of vacuum pressure was weakened, and the utilization of vacuum pressure was improved. Therefore, the vacuum pressure at the end of the new PVD (or deep soil layers) remained high. The vertical transfer of vacuum pressure in the new PVD and the radial distribution of vacuum pressure in the surrounding soil mass are shown in Figure 9(b). The attenuation of vacuum pressure was reduced by the increasing pressure transfer efficiency; thus, the negative pressure difference between the PVD and the surrounding soil increased. This increase can accelerate the drainage of pore water and thus accelerate the solidification of surrounding soil masses.

The new PVD has some advantages. Firstly, the core board has double channels for air and water drainage. And the vacuum pressure transfers along the central channel of the core board can decrease the loss caused by pile resistance and clay blockage in the external grooves. Secondly, a hard surface layer which has high settlement is formed after VPM reinforcement. The PVD may be bent due to excessive settlement, thus influencing the transfer of vacuum pressure along the PVD. The air channel in the new PVD can overcome shortages of traditional PVD and maintains good air pressure transfer even when it is bent. The pressure transfer holes on the new PVD can compensate the attenuation of vacuum pressure during the downward transfer.

The field test was performed in a project field, which covers an area of 100 m^2. Limited by the size of the test area, the new PVD was not applied at a large scale. Instead, only physical and mechanical properties of soil mass before and after the VPM reinforcement were compared to analyse reinforcement effect and validity. The field monitoring data of the vacuum pressure transfer is sensitive to the transfer near the test field; thus, field monitoring vacuum pressure data were not studied thoroughly in the present study. The attenuation law of vacuum pressure along the new PVD still requires a special field test. The interval of pressure transfer holes on the new PVD and the effective reinforcement depth of the new VPM must be further explored.

6.2. Effective Sphere of Influence of Single Pile. The distance from the "0" vacuum pressure point to PVD is different due to the attenuation of vacuum pressure along the PVD and the horizontal direction of sludge. When the radius of "0" vacuum pressure point is the sphere of influence of a single pile [24–26], PVD only influences soil mass within this radius. It is assumed that the radius of the "0" vacuum degree point is the influence range of a single well, and the drainage plate only affects the soil within the radius. The sphere of influence of a single pile with consideration to the attenuation of vacuum pressure along PVD is shown in Figure 11.

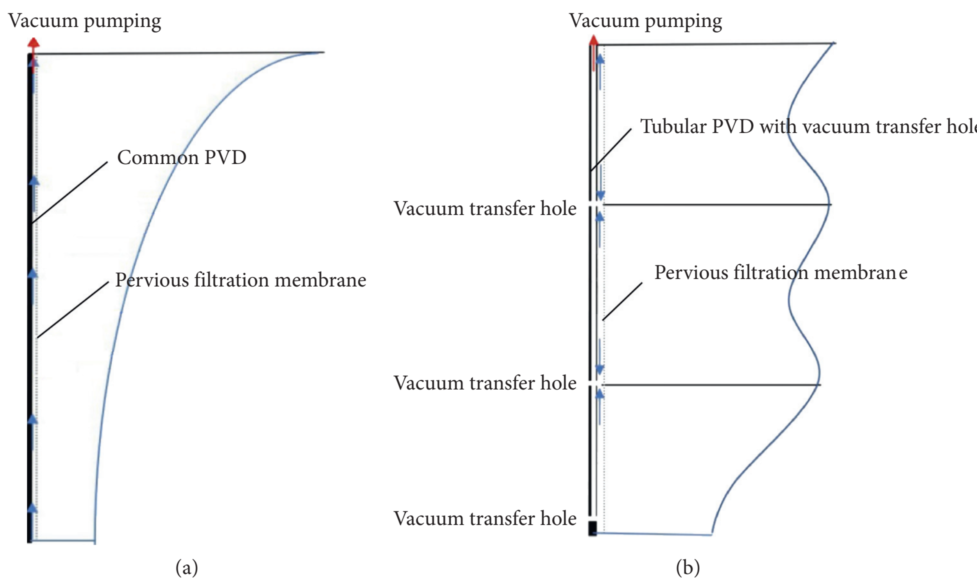


Figure 9: Distribution of the vacuum pressure along PVD: (a) common PVD; (b) new PVD.

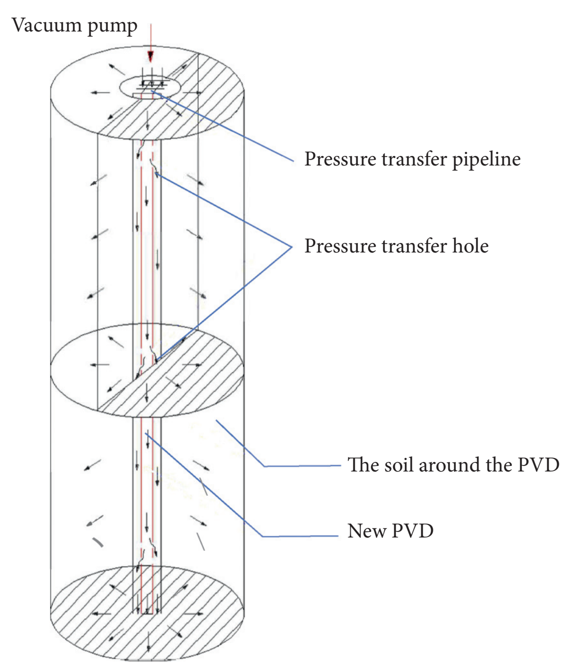


Figure 10: Transfer of vacuum pressure along the new PVD.

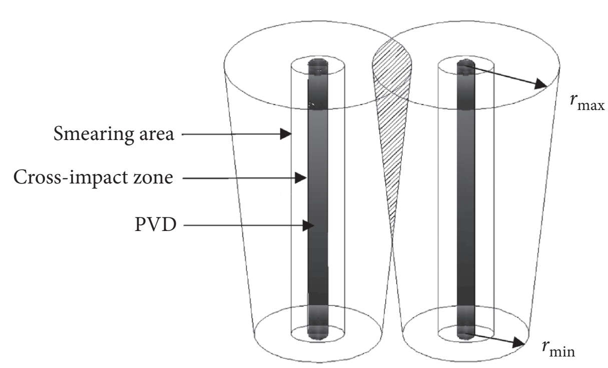


Figure 11: Sphere of influence of a single pile.

The sphere radius of influence of the single pile decreases gradually after the use of the common PVD due to the attenuation of negative vacuum pressure. The crossing reinforcement area of adjacent PVDs is narrowed accordingly. As a result, the upper layer is reinforced, and however, a weak reinforcement region exists in the lower layer, causing different solidification speeds between the upper and lower layers as well as uneven reinforcement effect. A "hard layer" is formed as a consequence of the growth rate differences in soil strength between the upper and lower layers.

After using the new PVD, the vacuum degree in the three-dimensional transmission channel composed of vacuum pump, PVC pipe, and new drainage board pipe has high conduction efficiency. The vacuum degree around the drainage plate is always kept at a high level from the top to the bottom. The sphere radius of influence of the single pile maintains a large range from the top to the bottom. A large area of the crossing reinforcement area exists along adjacent PVDs, which decreases differences in solidification speed between the upper and lower layers and brings relatively uniform reinforcement.

The new VPM achieves better reinforcement by using the new PVD. Pressure transfer holes on the PVD are designed to compensate loss of vacuum degree along the transfer path. Therefore, reinforcement effects (e.g., soil strength, compactness, difference of solidification speed between upper and lower layers, and uniformity of reinforcement effect) of the new VPM are related to the intervals of pressure transfer holes on the new PVD. However, it still requires a field test to determine the interval of pressure transfer holes.

7. Conclusion

(1) The laboratory simulation test reveals that the transfer loss of vacuum pressure along the new PVD is relatively small, and the transfer efficiency increases significantly, thus increasing the vacuum pressure in deep soil layers and achieving effective reinforcement to deep soil layers.

(2) In accordance with the field test, the physical and mechanical properties of the soil shear strength layer are improved after VPM reinforcement. Moisture content in the new VPM model is decreased by 20% at most. The shear strength is increased by 30% after common VPM reinforcement, and it is even increased by 50% after the reinforcement with the new VPM. In short, the new PVD is able to better reinforce the soil layers than that with the common PVD, especially in the deep soil layers.

(3) In the new VPM, vacuum degree is transferred to a stereoscopic system composed of a vacuum pump, a PVC pipeline, and the new PVD. Vacuum is transferred to different depths of soil layers through pressure transfer holes on the new PVD, so as to reduce the conductive resistance of well resistance to vacuum degree. By improving the vacuum conduction efficiency and reducing the attenuation, the drainage body and the surrounding area can be increased; the negative pressure difference between the surrounding soils accelerates the drainage of pore water and the consolidation of soil around the drainage body.

(4) The vacuum pressure surrounding the new PVD is maintained at a high level, the sphere radius of influence in a single pile maintains a large range from the top to the bottom layer, and the cross-reinforcement area of adjacent drainage boards is relatively large, which makes the difference of consolidation speed between the surface layer and the deep layer smaller and the reinforcement effect is relatively uniform.

The effectiveness and superiority of the new VPM are confirmed in the present study, which provides a theoretical reference for its application and development in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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