



# A Novel Reinforcement Method for Soft Soil Foundation: Numerical and Experimental Investigations

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**Abstract.** The utilization of soft soil in civil engineering projects is fraught with challenges, primarily due to its inherent weaknesses including high water content, high void ratio, high compressibility, low permeability, and low bearing capacity. This study proposes a novel three-dimensional sandy drainage system that integrates vertical sand columns and horizontal diffusing sand piers or slender sand belts formed high-pressure rotary jetting. The proposed method addresses the limitations of conventional techniques, including prolonged construction periods, environmental concerns associated with plastic drainage boards, and insufficient deep-layer treatment, by leveraging natural sand to establish an eco-friendly and efficient underground drainage network. To evaluate the performance of the novel reinforcement method, numerical simulations and large-scale consolidation tests were conducted. The numerical simulation results demonstrated that the placement of a horizontal drainage body at the mid-depth of a vertical sand column optimizes consolidation efficiency, reducing the time reaching the degree of consolidation of 90% by 44% (from 25.06 days to 13.99 days) and decreasing settlement by 8% compared to a system with only vertical drainage. Experimental tests further validated the superiority of the three-dimensional sandy drainage system over plastic drainage board and vertical sandy drainage, showing 55% higher vane shear strength at 20 cm depth. The horizontal sandy drainage body enhanced radial drainage capacity and introduced an "anchor effect" improving deep soil stability and bearing capacity. These findings highlight the proposed three-dimensional sandy drainage system as a sustainable and efficient solution for soft soil foundation reinforcement, offering significant advancements over existing techniques in both engineering performance and environmental compatibility.

**Keywords:** Soft soil foundation; Three-dimensional drainage; Drainage consolidation; Reinforcement effect.

## 1 Introduction

Soft soil exhibits poor engineering properties owing to its high water content, high void ratio, high compressibility, low permeability, and low bearing capacity. Infrastructure projects, such as highways and harbors, are particularly vulnerable to the detrimental effects of soft soil foundations when subjected to additional stress. This can result in excessive settlement, leading to the degradation of both the foundation and the construction. Currently, soft soil foundation reinforcement techniques are plagued by long construction periods, substantial resource consumption, and significant environmental impacts. Conventional methods struggle to uniformly address deep soil layers with increasing soft soil thickness, resulting in uncertainty regarding reinforcement effectiveness and durability. Consequently, the development of eco-friendly and efficient deep-soil foundation treatment technologies has emerged as a critical challenge.

As a fundamental technology of soft soil foundation treatment, the drainage consolidation method achieves soil consolidation by accelerating pore water discharge, and its theoretical and engineering applications continue to deepen<sup>[1-3]</sup>. In recent years, the vacuum preloading method and the surcharge preloading method have been widely used in the treatment of soft soil foundations for large-scale land reclamation. Engineering practice has shown that inhomogeneity occurs in the consolidation process of dredger fill<sup>[4]</sup>. Therefore, a plethora of improved technologies have been proposed sequentially. According to the different principles of improvement, these can be reflected in three aspects. Firstly, the mode of preloading can be altered. As demonstrated by Leong<sup>[5]</sup>, Wu<sup>[6]</sup>, and Feng<sup>[7]</sup>, the positive pressure generated by surcharge load combined with the negative pressure generated by vacuum pressure, can increase the consolidation pressure and reduce the duration of the treatment effectively. The promotion of drainage can be achieved through the additional radial consolidation pressure increments facilitated by the injection of pressurized gas<sup>[8-10]</sup>. To alleviate the clogging, the loading modes in the graded vacuum loading method<sup>[11,12]</sup> and the alternating vacuum preloading method<sup>[13]</sup> can be effective in slowing down soil column generation and improving consolidation efficiency. Secondly, the objective is to enhance the soil properties. Wang et al.<sup>[14]</sup> proposed the flocculation vacuum preloading method, where flocculants, such as lime slurry and polyacrylamide, are injected into the soft soil, which in turn promotes drainage efficiency. The electro-osmotic combined preloading method<sup>[15-17]</sup> involves the burial of electrodes in the soil, which alters the electrical potential to facilitate the water movement from the anode to the cathode. This enhances the effect of the plastic drainage board between the cathode and the anode. Finally, the enhancement of plastic drainage boards constitutes a significant approach. It principally comprises enhancements to the core plate<sup>[18]</sup>, modifications to the filter membrane<sup>[19]</sup>, and improvements to the connection between the filter membrane and the core plate<sup>[20]</sup>. Moreover, the arrangement of drainage plates in a horizontal position has emerged as a promising approach for enhancing soft ground foundation treatment<sup>[21,22]</sup>.

Moreover, green sustainability has become an essential part of engineering worldwide. Soft soil foundation reinforcement is mainly applied in new green materials. Hamza et al.<sup>[23]</sup> utilized green material Xanthan Gum biopolymer to treat expansive soil foundation, investigated the strength attenuation of different dosages of Xanthan Gum

at various aging ages, and explored the bridging effect between soil particles and Xanthan Gum through microstructural analyses. Onyelowe et al.<sup>[24]</sup> reduced carbon emissions by using quicklime-activated rice husk ash instead of cement in road foundation engineering. Yao et al.<sup>[25]</sup> demonstrate that geopolymer-stabilized soft soils exhibit enhanced mechanical strength through optimized microstructure formation while maintaining eco-friendly characteristics as a sustainable alternative to traditional soil stabilization methods. Especially, in the drainage consolidation method, sustainable technologies are mainly focused on vacuum loading systems, with high efficiency and low-consumption jet pumping equipment as well as cyclic loading techniques being proposed. In terms of drainage body, the plastic drainage board is now the primary choice for the drainage consolidation method due to its cost advantages. However, the plastic drainage board is not green and sustainable, especially for areas with sufficient sand. Sand is a more natural and eco-friendly drainage body, so it is necessary to conduct research on improved technology for the drainage body.

This paper introduces a novel method for reinforcing soft soil foundations, to improve the efficiency and effectiveness of reinforcement around vertical drainage systems. The study conducts numerical simulations to analyze the layout of drainage systems. Model experiments are performed to compare and analyze the new reinforcement method with the traditional drainage plate method, confirming the advantages of the new approach in reinforcing soft soil foundations.

## 2 New Soft Soil Foundation Reinforcement Method

The novel method proposed in this study combines the benefits of composite foundation and drainage consolidation methods. As shown in Figure 1, this approach involves creating vertical drainage bodies of sand underground and forming horizontal drainage bodies by implementing a high-pressure rotary spraying process to establish diffusing sand piers or slender sand belts at specific depths within the soil layer. The construction of this underground three-dimensional drainage system is followed by the application of a surcharge load or vacuum load. The excess pore water pressure generated by the foundation soil due to additional stress is then transmitted and dissipated through the underground drainage system, enhancing drainage efficiency and consolidation. Furthermore, once the underground drainage system of sand has been formed, it provides an effect similar to the flexible composite foundation, after the drainage and consolidation processes have been completed.

In comparison to the conventional drainage consolidation method utilizing plastic drainage boards, as well as modified methods like horizontal and radiation drainage boards, this technique employs natural sand as material, offering superior environmental benefits over plastic drainage boards. As natural materials, the sandy drainage body generates significantly lower carbon emissions during production by avoiding energy-intensive petrochemical processing and high-temperature manufacturing. Furthermore, the sandy drainage body aligns more closely with low-carbon policies and circular economy principles, particularly through localized material sourcing and grading

design. This makes them a more ecologically sustainable choice for soft soil foundation treatment. Through the utilization of high-pressure injection technology, a horizontal drainage channel is created, enabling 360° drainage capability in the horizontal plane, thereby reducing construction duration. This approach overcomes layout challenges and construction limitations while improving drainage efficiency and reinforcement effectiveness on a larger scale around vertical drainage bodies. Additionally, the use of sand as drainage channels can partially substitute in soft soil foundations, particularly in weak underground areas where horizontal sand piers are established. Following drainage consolidation, the bearing capacity of weak soil layers can be significantly enhanced.

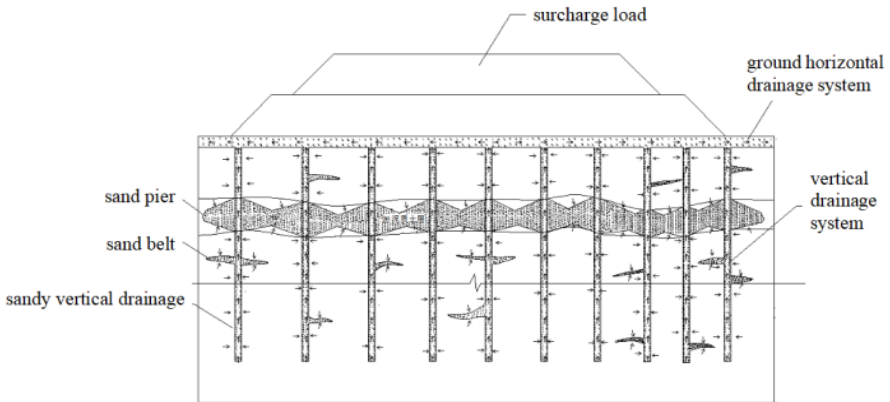
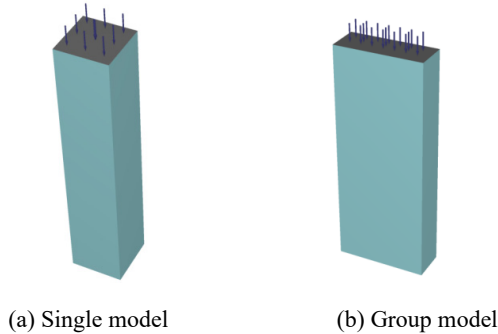


Fig. 1. Diagrammatic drawing of the new foundation reinforcement method.

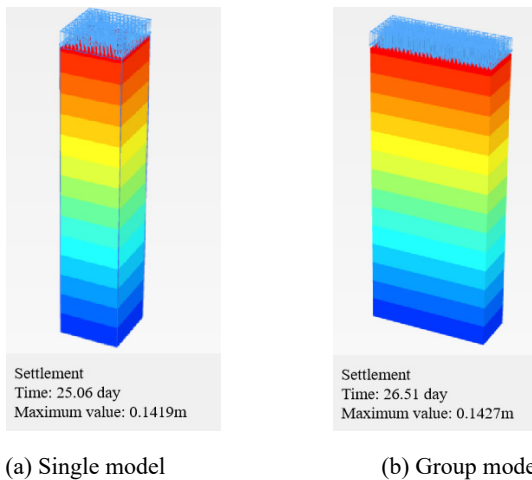
### 3 Analysis of Drainage Body Layout

To analyse the reinforcement technology of three-dimensional multi-directional drainage consolidation more efficiently and systematically, this paper carried out relevant numerical simulation analysis through PLAXID 3D. Initially, a comparative analysis is conducted between the single model and the group model (shown in Figure 2). The boundary conditions of the model are set to be completely fixed at the bottom and fixed normally to the sides. The drainage conditions were then established such that the clay was undrained, whilst the top boundary and the sandy soils were drained. The weight of sand is  $18\text{kN/m}^3$ , the friction angle is  $35^\circ$ , and the permeability coefficient is  $7.128\text{m/day}$ . The weight of clay is  $17\text{kN/m}^3$ , the friction angle is  $8^\circ$ , the cohesion is  $5\text{kPa}$ , and the permeability coefficient is  $4.752 \times 10^{-2}\text{m/day}$ .



**Fig. 2.** Numerical model of the novel foundation reinforcement.

The single model analyzes the situation where drainage is set at the center position within  $2\text{m} \times 2\text{m}$ . In contrast, the group model is the situation where drainage bodies are set at a distance of 1m. In both models, a uniform load of 50kPa was put on the top to simulate the common load in actual engineering and ensure the practicality and reliability of the research results. As shown in Figure 3, under the same calculation conditions, the results of the single model and the group model are not much different. Both reached a 90% consolidation state within about 26 days, and the displacement settlement was 0.1419m and 0.1427m respectively, which shows that the two models have high consistency in consolidation. However, the time required for single calculation models is only about 20% of the group model. This significant advantage makes the selection of single models for subsequent analysis an efficient and feasible choice. It not only greatly improves the computing efficiency, but also ensures the accuracy and scientificity of the research results, providing a solid foundation for subsequent research and practical engineering applications.



**Fig. 3.** Calculation results of single model and group model.

A detailed investigation was conducted on the layout of horizontal drainage bodies to examine their impact on the reinforcement effectiveness in the three-dimensional drainage consolidation technology. By increasing the diameter of the vertical drainage body to  $0.3d$ , where  $d$  represents the spacing between sandy drainage bodies with a value of 1m in this case. The desired effect of horizontal drainage called "sand piers" was achieved. Table 1 illustrates five distinct conditions considered in this study. Through comparative analysis across multiple conditions, the objective is to comprehensively elucidate the specific influence mechanism of horizontal drainage bodies on the reinforcement of the three-dimensional drainage consolidation technology at varying depths.

**Table 1.** The layout of horizontal drainage body.

Serial number	Layout
Condition I	No horizontal drainage body
Condition II	Horizontal drainage body is located on the upper part of the vertical drainage body (at 1/4 of the depth range)
Condition III	Horizontal drainage body located in the middle of the vertical drainage body (at 1/2 of the depth range)
Condition IV	Horizontal drainage body is located in the lower part of the vertical drainage body (at 3/4 of the depth range)
Condition V	Horizontal drainage body located at the bottom of the vertical drainage body (lower end of the depth range)

The calculation results are displayed in Table 2. As the control group, under the condition of no horizontal drainage, it took about 25 days to reach the degree of consolidation of 90%, and the maximum settlement value was 0.1419m. Compared with other conditions, after adding the horizontal drainage body, the time required for drainage consolidation to reach the degree of consolidation of 90% is significantly shortened, and the consolidation time decreases by between 20 and 44%. When the horizontal drainage channel is in the middle (Condition III), the shortest time is about 14 days. This is closely related to the influence range of the drainage system formed by vertical drainage bodies and horizontal drainage bodies. When the horizontal drainage channel is in the middle position, the range of influence of its horizontal drainage body is optimal compared to the reinforcement range of the vertical drainage body. Consequently, the water in the soil can be discharged more quickly. On the other hand, after the horizontal drainage channel is formed, the total settlement is reduced, with a decrease of 2% to 8%. This is mainly because the sandy drainage body formed similar pile structure effects, especially the formed convex horizontal drainage sand body, which produces a similar "anchor" effect in the soft soil foundation. This enhances the overall stability of the foundation and effectively controls the overall settlement.

**Table 2.** Numerical simulation results for different layout types.

Serial number	Settlement (m)	Time reaching the degree of consolidation of 90% (days)
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Condition I	0.1419	25.06
Condition II	0.1325	15.15
Condition III	0.1303	13.99
Condition IV	0.1385	19.71
Condition V	0.1391	20.39

### 4 Analysis of the Reinforcement Effect of New Soft Soil Foundation Reinforcement Method

The model test was used to evaluate the reinforcement effect of plastic drainage board (Type I), vertical sandy drainage body (Type II), and three-dimensional sandy drainage body (Type III) using a large consolidation device, as depicted in Figure 4. The filling height of soil in the column is 48 cm, and the soil particle grading is detailed in Figure 5, with a mean median particle size of  $5.8 \times 10^{-6}$  m and a plasticity index of 15.2.



Fig. 4. Testing device for three-dimensional drainage body consolidation test.

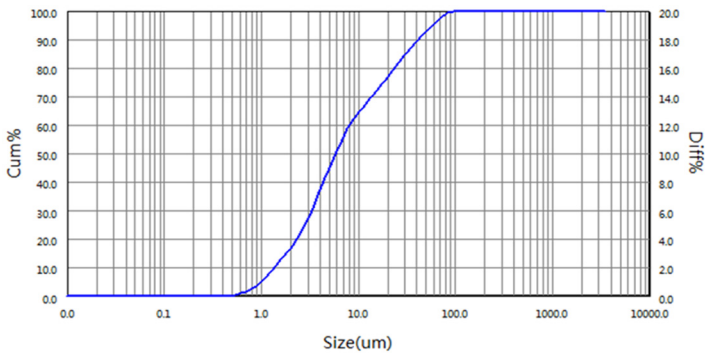
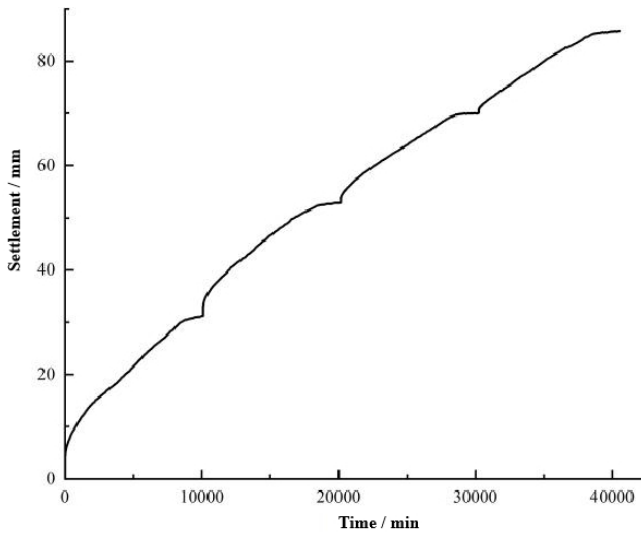
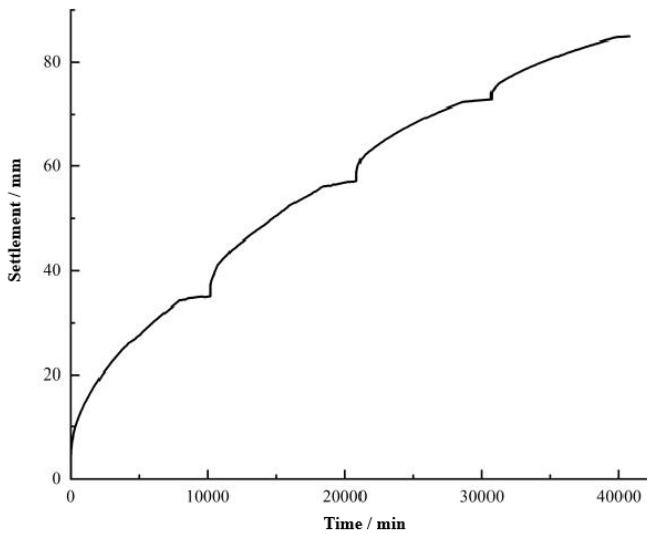


Fig. 5. Soil particle grading curve.

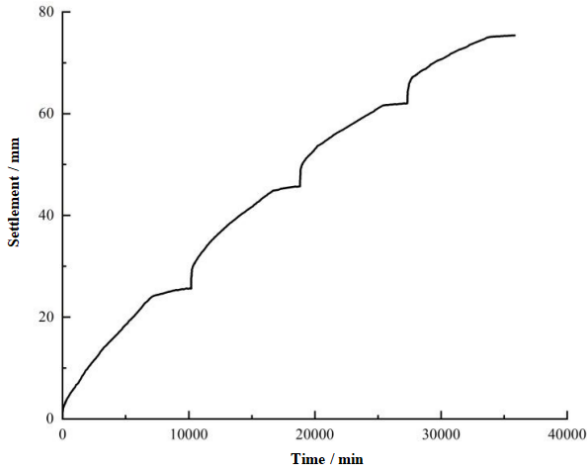
Figure 6 illustrates the settlement-time curves for three different conditions. The final settlement deformation values of Type I, Type II, and Type III were 85.76 mm, 84.81 mm, and 75.39 mm, respectively. It is evident that the final settlement amount of the three-dimensional sandy drainage body was the smallest, which was consistent with the results of the numerical simulation. Furthermore, the time required to reach steady state under each level of loading condition of the Type III was earlier compared to the other two types of drainage channels, approximately 15-20% ahead.



(a) Plastic drainage board



(b) Vertical sandy drainage body



(c) Three-dimensional sandy drainage body

**Fig. 6.** Settlement-time curve of model test.

Table 3 presented the alteration in moisture content before and after the test, and Table 4 listed the vane shear strength at different depths after the test. The results obtained from tests indicate that the reinforcement effects of the Type I and Type II are similar. However, in terms of the vane shear strength, the Type II is marginally higher than the Type I. The vertical sandy drainage body consists of a cylindrical sand pile. As the drainage consolidation progresses, a dense soil layer is formed in the vicinity of the vertical sandy drainage body. Compared with the plastic drainage board situation (Type I), its distribution range widened greatly, resulting in differences in the vane shear strength. Besides, Type III is obvious in terms of moisture content and vane shear strength. In comparison with the other two types of drainage body, especially near the depth of the horizontal drainage body, Type III has a significant effect on improving the reinforcement effect of deep soil. Specifically, at a depth of 20cm, the vane shear strength is increased by 55% and 36% compared with the Type I and Type II respectively.

**Table 3.** Sample water content.

Serial number	Before test (%)	Surface after test (%)	Depth of 15cm after test (%)
Type I	46.3	30.6	39.1
Type II	46.1	31.8	38.7
Type III	45.8	30.3	35.3

**Table 4.** Vane shear strength.

Serial number	Surface (kPa)	Depth of 10cm (kPa)	Depth of 20cm (kPa)	Depth of 30cm (kPa)
Type I	38.4	27.2	23.2	21.1

Type II	38.6	32	26.5	22.4
Type III	40.8	34.3	36	27.4

## 5 Conclusions

Through numerical simulation and model tests, this paper analyzes the layout and reinforcement effect of the three-dimensional drainage consolidation method, and obtains the following main conclusions:

(1) The three-dimensional sandy drainage body can significantly reduce the time reaching steady state under each level of loading condition. When the horizontal drainage body is arranged in the middle of the vertical drainage body, the reinforcement efficiency is the most pronounced.

(2) The three-dimensional sandy drainage body not only improves the efficiency of drainage consolidation but also improves the overall bearing capacity of the foundation. Furthermore, the settlement displacement variation is less than the conditions without the horizontal drainage body.

(3) Compared with plastic drainage boards, the three-dimensional sandy drainage body been shown to significantly enhance the efficacy of deep soil reinforcement, leading to substantial improvements in the strength of the reinforced soil at depths proximate to the horizontal drainage body.

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