

Effect of Vacuum Preloading with Inclined Drainage Boards on Soil Reinforcement [†]

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Abstract

This paper presents an innovative vacuum preloading method utilizing inclined prefabricated vertical drains (PVDs) and systematically evaluates its improvement effectiveness compared to conventional vertical PVDs. A theoretical consolidation model incorporating inclined boundary conditions is developed, leading to a governing equation that reveals the dependence of the equivalent consolidation coefficient on the drain inclination angle. Through numerical simulation validated against field monitoring data (showing a minimal error of -1.81%), the study demonstrates that the inclined PVD configuration achieves a significant settlement-based improvement exceeding 10%. Parametric analysis further indicates that settlement behavior relative to the inclination angle follows a pattern of initial increase, subsequent decrease, and eventual stabilization, with an identified optimal range of 3° to 5° for a drain spacing of 1.0 m. While smaller drain spacings consistently yield better improvement effects for inclined PVDs, the percentage increase in settlement compared to the traditional method becomes more pronounced as the spacing increases. The findings confirm the inclined PVD system as a superior alternative for ground improvement, providing theoretical guidance and practical design parameters for optimizing vacuum preloading techniques in challenging soft soil conditions.

Keywords: inclined drainage boards; vacuum preloading; improvement effect

1. Introduction

Construction activities in coastal and deltaic regions consistently face a persistent geotechnical challenge: managing consolidation in soft soil strata such as marine clays, silts, and dredged fills. These materials exhibit characteristically high natural water content, significant compressibility, low bearing capacity, and poor permeability, leading to pronounced and prolonged differential settlement under structural loads. Addressing these concerns while maintaining project timelines makes ground improvement techniques particularly crucial. Among available methods, vacuum preloading—especially when combined with vertical drainage systems—has emerged as one of the most widely adopted and effective approaches for stabilizing deep soft soil foundations [1].

The vacuum preloading technique was originally introduced by Kjellman [2] in the 1950s. Its fundamental operating principle relies on generating negative pore water pressure



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(i.e., vacuum pressure) within the soil mass. This induces an increase in effective stress without the need for surcharge embankments, thereby accelerating consolidation. The resulting effective stress increment ($\Delta\sigma'$) can be expressed as $\Delta\sigma' = \Delta(u_a - u_w)$, where u_a and u_w represent pore air pressure and pore water pressure, respectively. Under ideal conditions, the applied vacuum pressure, $-\Delta u_{vac}$, translates directly into a corresponding increase in effective stress, underscoring the method's efficiency. Compared to conventional surcharge preloading, the vacuum-based approach offers several distinct advantages: it eliminates the risk of shear failure, achieves faster consolidation rates, and minimizes lateral displacement—sometimes even inducing inward movement that enhances the stability of adjacent slopes and excavations [3,4].

The effectiveness of conventional vacuum preloading depends critically on the efficient transmission of vacuum pressure to deeper soil layers. This is typically accomplished using prefabricated vertical drains (PVDs), which serve as preferential pathways for pore water flow. These PVDs are connected to a horizontal drainage layer, such as a sand blanket or geosynthetic drainage composite, and the entire system is sealed beneath an impermeable membrane to maintain the vacuum [5]. Over recent decades, extensive research and field applications—particularly in China—have demonstrated the successful performance of this PVD-enhanced vacuum preloading method in projects involving land reclamation, embankment construction, and airport runway development [6,7].

Despite its widespread use, the conventional vertical PVD system presents certain limitations. A particularly well-documented issue is the “vacuum pressure loss” observed along the drain depth [8,9]. This attenuation stems mainly from well resistance of the PVD itself, the smear zone effect caused by mandrel installation, and the inherent permeability of the soil. As a result, the upper soil layers often experience greater consolidation than the deeper layers, leading to non-uniform improvement [10]. This inconsistency can trigger differential settlement and suboptimal stabilization over the full treatment depth. Furthermore, soil consolidation under vacuum pressure is inherently a complex three-dimensional process involving coupled hydro-mechanical behavior, which cannot be adequately captured by simplified one-dimensional theoretical models.

To address these shortcomings and enhance the performance of vacuum preloading, researchers have begun exploring innovative drain configurations, among which inclined drains represent a promising alternative. Unlike conventional vertical installations, inclined drains are installed at a specific angle to form a networked drainage system. Theoretically, this configuration provides shorter and more uniform drainage paths. Studies suggest that inclined drains intersect a larger soil volume, creating an efficient “drainage network” that reduces the average horizontal distance pore water must travel to reach a drain. This arrangement is expected to mitigate the well resistance and vacuum pressure loss commonly associated with long vertical drains, thereby promoting a more uniform distribution of vacuum pressure and effective stress with depth.

Meanwhile, computational methods for analyzing vacuum preloading have advanced considerably. Classical analytical solutions, such as Barron's radial consolidation theory, have been extended to incorporate vacuum effects. However, these solutions often rely on simplifying assumptions—including equal strain conditions, ideal drain behavior, and neglect of true three-dimensional flow—which become particularly limiting when analyzing inclined drains. The development of powerful finite element software has enabled more sophisticated numerical simulations of these complex processes. Advanced constitutive models, such as the Modified Cam-Clay model, can now be implemented in coupled flow-deformation analyses to realistically simulate the elasto-plastic behavior of soft soils under vacuum loading [11–13].

Numerical modeling has become an indispensable tool for investigating the consolidation mechanisms of inclined PVD systems [14,15]. Three-dimensional finite element models can explicitly incorporate the geometry of inclined drains, simulate the progressive dissipation of pore water pressure, and compute the resulting settlements and lateral deformations. For instance, some studies using 3D models have shown that herringbone-patterned inclined drains can increase the average degree of consolidation by approximately 15–20% compared to traditional vertical drains over the same period. Additionally, such models facilitate parametric studies to optimize key design parameters, including drain inclination angle, spacing, and layout patterns (e.g., V-shaped, X-shaped, or herringbone). They also allow for detailed examination of the interaction between inclined drains and the horizontal drainage layer, providing valuable insights into overall system efficiency and potential failure mechanisms.

Despite these promising developments, the application of inclined drains in vacuum preloading remains at a relatively early stage of research. There is a noticeable lack of comprehensive studies that systematically compare the performance of different inclination schemes against conventional vertical drain systems using field-validated, fully coupled 3D numerical simulations. Moreover, the interaction between drain inclination and smear zone characteristics remains poorly understood, and a robust quantitative design framework—capable of reliably predicting consolidation settlement and its time-dependent behavior—has yet to be established.

In summary, vacuum preloading combined with prefabricated vertical drains (PVDs) has matured into a widely used ground improvement technique, supported by substantial theoretical, experimental, and field evidence. Recent research efforts have focused largely on design optimization, combined techniques, environmental sustainability, and performance monitoring. Nevertheless, challenges such as vacuum pressure attenuation, smear zone effects, and long-term durability continue to demand further investigation. This study focuses on a novel drain configuration—inclined PVDs—and aims to contribute to this ongoing research through theoretical derivation and numerical simulation. We develop a governing consolidation equation for inclined PVDs, compare the improvement effectiveness of inclined and vertical PVD vacuum preloading, and investigate the influence of key parameters such as drain spacing and inclination angle. The findings are expected to provide new insights into the design and implementation of vacuum preloading techniques under challenging ground conditions, thereby contributing to the advancement of geotechnical engineering practice.

2. Vacuum Preloading with Inclined Drainage Plates

2.1. Design Philosophy and Mechanism

The core design philosophy of this method is to install drainage plates into the soft soil foundation at a specific inclination angle (denoted as θ , measured from the vertical direction) and predetermined spacing in a symmetrical pattern, thereby forming an efficient drainage system, as shown in Figure 1. This system enhances the ground improvement effect through the following mechanisms.

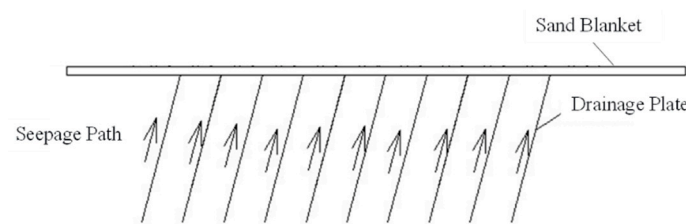


Figure 1. Vacuum Preloading with Inclined Drainage Plates.

Optimization of Seepage Paths and Acceleration of Consolidation: In conventional vertical drain systems, pore water must undergo a lengthy horizontal flow path to reach the vertical drainage channels. In contrast, inclined drainage plates decompose the prolonged horizontal seepage path into a series of shorter radial flow paths directed towards the inclined drains. According to Terzaghi's consolidation theory, the consolidation time is proportional to the square of the drainage path. Consequently, the significantly shortened horizontal drainage paths can substantially accelerate the dissipation of excess pore water pressure, thus reducing the construction period.

Enhancement of Vacuum Pressure Transfer Depth and Uniformity: Vertical drains are subject to the "Well Resistance Effect" with depth, leading to a significant attenuation of vacuum pressure as depth increases. Inclined drainage plates, by virtue of their slanted geometry, function analogously to inserting "straws" obliquely into deeper and broader zones of the soil mass. This provides a more direct and lower-resistance transmission pathway for the vacuum pressure. Consequently, higher vacuum degrees can be achieved even in deeper soil layers, improving the uniformity of the improvement effect and increasing the overall depth of stabilization.

2.2. System Composition and Construction Procedure

The composition of the vacuum preloading system with inclined drainage plates is similar to the conventional method, primarily comprising: a vacuum pump system, a sealing system (e.g., sealing membranes, clay slurry walls), a horizontal drainage layer (sand blanket), and the newly designed inclined drainage plate system.

The key construction sequence is as follows:

Site Leveling and Placement of Drainage Blanket: The soft ground surface is leveled, followed by the placement of a medium-coarse sand blanket which acts as the horizontal drainage conduit.

Surveying, Setting Out, and Equipment Positioning: Precise surveying and setting out are conducted to determine the planar position and design angle for each drainage plate. Modified installation equipment, whose mast or guide frame can be precisely adjusted to the predetermined angle θ , is used.

Installation of Inclined Drainage Plates: The drainage plates, fed through a mandrel, are installed by the casing to the design depth sequentially row-by-row, adhering to the design angle θ and spacing, typically in a symmetrical pattern.

Installation of Vacuum System: Filter pipes are laid within the sand blanket and connected to the main collection pipes and vacuum pumps. The sealing membrane is then deployed, and vacuum pressure sensors are installed beneath the membrane for monitoring.

Vacuum Pumping and Monitoring: Vacuum pumping commences and continues with ongoing monitoring of parameters such as surface settlement, deep settlement, pore water pressure, and lateral soil displacement until the design requirements are met.

3. Analysis of Improvement Effect with Inclined Drainage Plates

3.1. Consolidation Mechanism

Conventional drainage consolidation methods primarily employ vertical or horizontal drainage plates. In contrast, inclined drainage plates, as a novel drainage approach, possess unique drainage paths and consolidation characteristics. Existing consolidation theories are mainly developed for vertical or horizontal drains, resulting in a relative lack of research on the consolidation mechanism of inclined drainage plates. Therefore, this paper aims to establish a theoretical vacuum consolidation model with inclined boundaries specifically for the drainage consolidation method using inclined plates, and to systemati-

cally analyze their consolidation mechanism, thereby providing theoretical guidance for engineering applications.

Basic Assumptions: (1) The soft soil foundation is a saturated, anisotropic porous medium. (2) The drainage plate is an ideal drainage body, with pore water pressure uniformly distributed along its length. (3) The vacuum negative pressure is uniformly distributed along the drainage plate. (4) Soil deformation is solely caused by the expulsion of pore water, neglecting the compression of the soil skeleton. (5) Seepage follows Darcy's law. (6) The small strain assumption is valid.

For anisotropic soft soil, the three-dimensional consolidation equation is:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} + c_h \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (1)$$

where u is the excess pore water pressure, t is time, and x, y, z are the horizontal and vertical coordinates, respectively.

When the drainage plate is inclined, a coordinate transformation is introduced:

- (1) Along the direction of the drainage plate: $s = x \sin \theta + z \cos \theta$.
- (2) Perpendicular to the drainage plate projection in the x - z plane: $\eta = -x \cos \theta + z \sin \theta$.
- (3) Horizontal direction perpendicular to the η -axis: $y = y$.

After this coordinate transformation, the governing equation can be expressed as:

$$\begin{aligned} \frac{\partial u}{\partial t} = & (c_v \cos^2 \theta + c_h \sin^2 \theta) \frac{\partial^2 u}{\partial s^2} + (\sin 2\theta (c_v - c_h)) \frac{\partial^2 u}{\partial s \partial \eta} + \\ & (c_v \sin^2 \theta + c_h \cos^2 \theta) \frac{\partial^2 u}{\partial \eta^2} + c_h \frac{\partial^2 u}{\partial y^2} \end{aligned} \quad (2)$$

Assuming axisymmetric flow around the drainage plate (i.e., u depends only on s and the radial distance r , where $r^2 = \eta^2 + y^2$), under axisymmetric conditions:

$$\frac{\partial^2 u}{\partial s \partial \eta} = 0 \quad (3)$$

In the plane perpendicular to the drainage plate, the Laplace operator can be expressed as:

$$\frac{\partial^2 u}{\partial \eta^2} + \frac{\partial^2 u}{\partial y^2} = \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \quad (4)$$

Considering the drainage plate as an ideal drain where the pressure gradient along its length can be neglected under uniform pressure distribution, yields:

$$\frac{\partial^2 u}{\partial s^2} = 0 \quad (5)$$

Substituting Equations (3)–(5) into Equation (2) gives:

$$\frac{\partial u}{\partial t} = c_r \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \quad (6)$$

where c_r is the equivalent consolidation coefficient, $c_r = \sqrt{(c_v \sin^2 \theta + c_h \cos^2 \theta) \cdot c_h}$.

From Equation (6), it can be observed that the consolidation behavior of inclined drainage plates is analogous to traditional radial consolidation, but the equivalent consolidation coefficient c_r varies with the inclination angle θ .

When $\theta = 0$ (vertical drain) $c_r = c_h$.

When $\theta = 90^\circ$ (horizontal drain), $c_r = \sqrt{c_v c_h}$.

When $0 < \theta < 90^\circ$, c_r lies between c_h and $\sqrt{c_v c_h}$, capturing the effects of both anisotropy and the inclination angle.

A comparison between vacuum preloading with inclined PVDs and the conventional method is presented in Table 1.

Table 1. Comparison of Drainage Characteristics for Different Vacuum Preloading Systems.

Feature	Vertical Drain	Horizontal Sand Blanket	Inclined Drain
Drainage Path	Short, predominantly vertical path	Long, horizontal-only path	Optimized spatial composite path
Consolidation Coefficient	c_h	$\sqrt{c_v c_h}$	$c_r(\theta)$, optimizable via θ
Soil Column Shape	Vertical cylinder	Horizontal slab	Inclined cylinder
Theoretical Model	Classical Barron's theory	One-dimensional consolidation theory	Inclined boundary vacuum consolidation theory

3.2. Comparative Analysis of Improvement Effects

A specific vacuum preloading section of a project was selected for analysis, with a preloading duration of 60 days. The strata in this area consist, from top to bottom, of hydraulically filled soil and normally deposited soft clay. The hydraulically filled soil is the primary target for improvement, characterized by its high clay fraction content, high water content, high void ratio, high compressibility, and low strength.

The numerical models established for this study are illustrated in Figure 2 (vertical drains) and Figure 3 (inclined drains). The overall model domain measures 60.0 m in length and 30.0 m in height, containing a treated zone measuring 10.0 m in length and 15.0 m in depth. Appropriate boundary conditions were applied to realistically represent field conditions: roller supports along the left and right boundaries restrict horizontal movement while allowing vertical displacement, a fully fixed condition at the bottom prevents both vertical and horizontal movements, and the top surface remains free to simulate the ground surface.

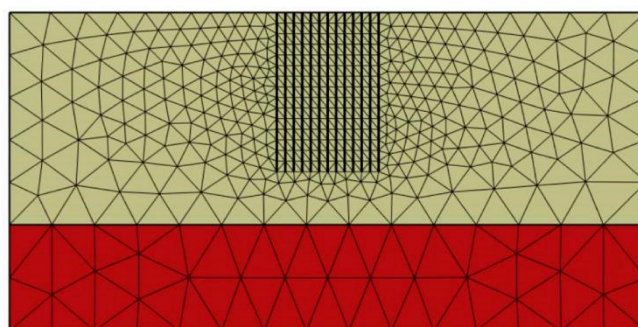


Figure 2. Numerical Model for Vacuum Preloading with Vertical Drains.

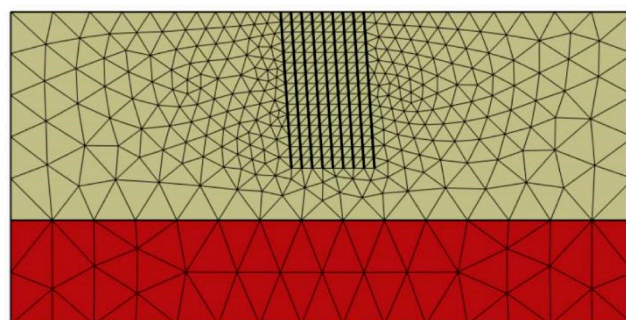


Figure 3. Numerical Model of Vacuum Preloading with Inclined PVDs ($\theta = 4^\circ$).

To accurately capture the large deformation behavior expected during consolidation, the Updated Lagrangian formulation was adopted for the strain calculation. This advanced numerical approach accounts for geometric nonlinearity by continuously updating both the finite element mesh configuration and the corresponding stiffness matrix at the commencement of each load increment throughout the iterative solution process.

The analysis was conducted under plane strain conditions, representing the long-section behavior of the preloading area. Both soil strata—the hydraulically filled soil and the underlying soft clay—were characterized using the Mohr–Coulomb constitutive model, with their respective material parameters summarized in Table 2.

Table 2. Model Parameters.

Model Parameter	Hydraulically Filled Soil	Soft Clay
Natural Unit Weight	17.11 kN/m ³	18.73 kN/m ³
Elastic Modulus	1500 kPa	3200 kPa
Initial Void Ratio	1.47	1.05
Cohesion	4.32 kPa	14.41 kPa
Internal Friction Angle	6.20°	7.41°
Horizontal Permeability Coefficient	0.78×10^{-3} m/d	0.76×10^{-3} m/d
Vertical Permeability Coefficient	0.78×10^{-3} m/d	0.58×10^{-2} m/d
Poisson's Ratio	0.35	0.32

To validate the model correctness and analyze the improvement effect of inclined drainage plates, a comparative analysis was conducted between the settlement monitoring data and the numerical simulation results, as shown in Figure 4. The settlement at the foundation center increases with time. The field monitoring results agree well with the simulation results of the traditional vacuum preloading with vertical drains. At a preloading time of 60 days, the measured field settlement was 22.1 cm, while the numerically simulated settlement for the traditional method was 21.7 cm, resulting in an error of −1.81%. This close agreement validates the rationality of the model and parameters. In contrast, the settlement for vacuum preloading with inclined drainage plates reached 25.5 cm at 60 days, representing a 15.4% improvement in the stabilization effect compared to the traditional technique.

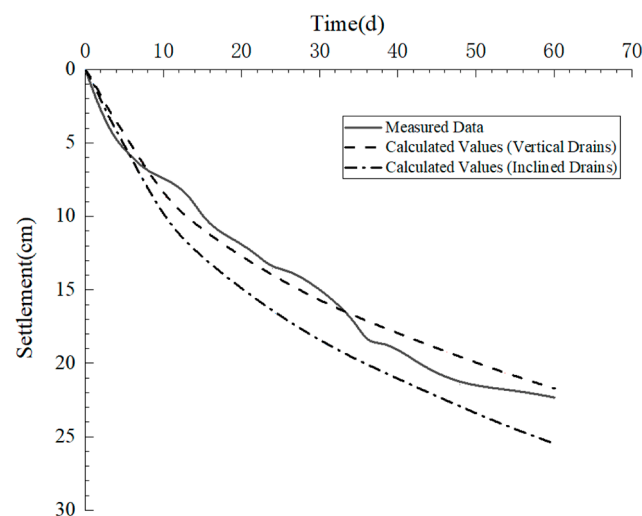


Figure 4. Comparative Settlement Curves.

3.3. Analysis of Influencing Factors

3.3.1. Influence of Drainage Plate Inclination Angle

Models with inclined drainage plates were established for the working conditions listed in Table 3, with a vacuum pressure of 80 kPa and a vacuum duration of 180 days.

Table 3. Working Conditions (Drainage Plate Angle).

Working Condition	Drainage Plate Angle (°)	Drain Spacing (m)	Installation Depth (m)
1	0		
2	1		
3	2		
4	3		
5	4		
6	5		
7	6	1	15
8	8		
9	10		
10	12		
11	14		
12	16		

Figures 5 and 6 present the settlement contour maps corresponding to drainage plate inclination angles of 3° and 12°, respectively. These contours reveal a characteristic funnel-shaped settlement pattern, with the maximum magnitude consistently developing within the central region of the treated area. This distribution arises from the stress state induced by the vacuum pressure: the foundation soil inside the improved zone experiences a three-dimensional stress condition under the applied vacuum, while the effective stress level diminishes toward the periphery due to attenuation during vacuum transfer. Direct vacuum suction acts most effectively on the soil adjacent to the drainage plates, with its influence decreasing in zones farther from the drains. This mechanism of differential stress application provides a clear explanation for the development of peak settlement at the center of the foundation.

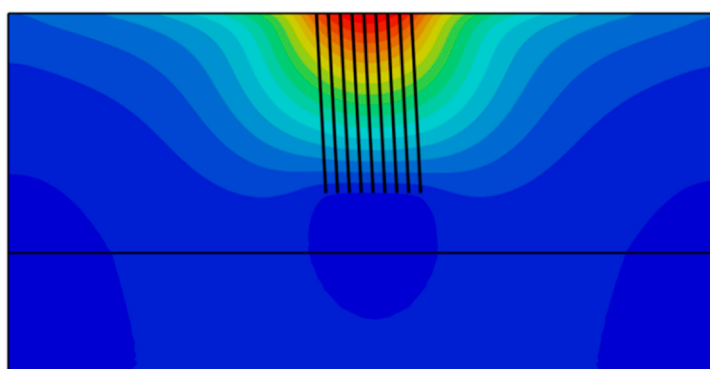


Figure 5. Settlement Contour Plot ($\theta = 3^\circ$).

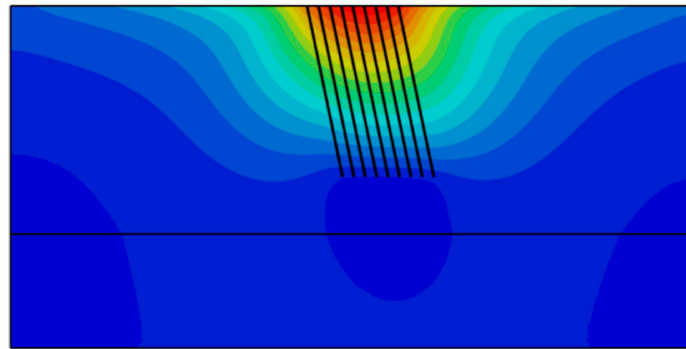


Figure 6. Settlement Contour Plot ($\theta = 12^\circ$).

Figure 7 illustrates the correlation between maximum surface settlement and drainage plate inclination angle, revealing a clear non-monotonic relationship. The settlement demonstrates an initial ascending trend with increasing inclination, reaching an optimal value before transitioning to a descending phase, ultimately approaching a stable value at larger angles. Notably, the peak settlement of 42.9 cm is achieved at 4° inclination, representing a significant 16.6% enhancement compared to conventional vertical drains (0°). This performance improvement underscores the importance of inclination angle optimization. Analysis of the data indicates that for the specified 1.0 m drain spacing, the optimal inclination range yielding substantially improved settlement performance falls between 3° and 5° . Beyond this range, the settlement efficiency gradually diminishes, suggesting the existence of an optimal geometric configuration for drainage path optimization.

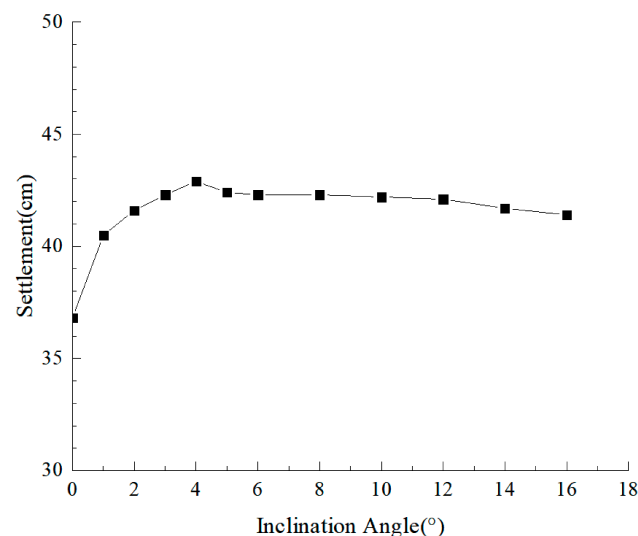


Figure 7. Settlement versus Drainage Plate Angle.

3.3.2. Influence of Drainage Plate Spacing

To systematically evaluate the influence of drain spacing on system performance, a series of numerical models incorporating inclined drainage plates were developed according to the working conditions detailed in Table 4. All simulations maintained a constant vacuum pressure of 80 kPa and a consolidation period of 180 days to ensure consistent comparative basis.

Figure 8 presents the comparative settlement relationships between traditional vacuum preloading (utilizing vertical drains) and the proposed method with inclined drains under varying drainage spacings. The results demonstrate an inverse correlation between drain spacing and improvement effectiveness for inclined drain systems: reduced spacing yields

enhanced consolidation performance. Specifically, at spacings of 0.8 m, 1.0 m, and 1.2 m, the corresponding settlements reach 45.7 cm, 42.3 cm, and 40.2 cm, respectively.

Table 4. Working Conditions (Drainage Plate).

Working Condition	Drain Spacing (m)	Drainage Plate Angle (°)	Installation Depth (m)
1	0.8	0	15
2		3	
3		0	
4	1.0	3	
5		0	
6	1.2	3	

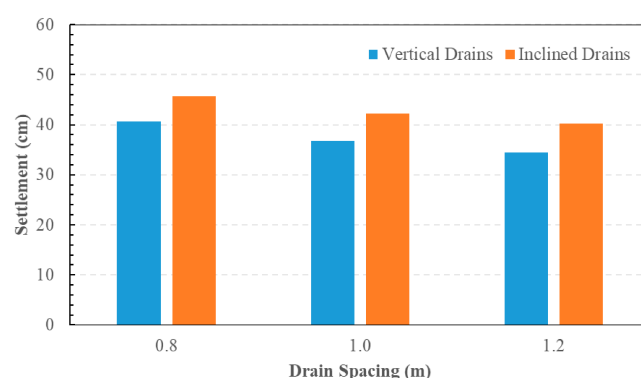


Figure 8. Settlement Comparison under Different Drain Spacings.

The superior performance of inclined drains is particularly evident at the 1.0 m spacing condition. After 180 days of preloading, the inclined configuration achieves 42.3 cm of settlement, compared to 36.8 cm for traditional vertical drains—representing a substantial 14.9% enhancement.

Further analysis reveals a counterintuitive yet significant pattern: although absolute settlement values decrease with increasing spacing, the relative improvement percentage of inclined drains versus traditional methods exhibits a positive correlation with spacing enlargement. The settlement enhancement rates corresponding to 0.8 m, 1.0 m, and 1.2 m spacings are 12.6%, 14.9%, and 16.5%, respectively, forming a clearly ascending trend. This phenomenon suggests that the advantages of inclined drainage configurations become progressively more pronounced as drainage density decreases, highlighting their particular value in scenarios where practical constraints necessitate wider drain spacings.

4. Conclusions

This paper presents a vacuum preloading method utilizing inclined prefabricated vertical drains (PVDs) and compares its improvement effect with that of the traditional method using vertical PVDs. The results demonstrate a settlement-based improvement exceeding 10%. The influence of the drain inclination angle and spacing on vacuum preloading efficiency was analyzed. The settlement initially increases with the inclination angle, then decreases, and finally stabilizes, with the optimum angle influenced by the drain spacing. For a drain spacing of 1.0 m, the optimal inclination angle range is 3° to 5°. Regarding the inclined PVD method, a smaller drain spacing yields a better improvement effect. Furthermore, under identical conditions, the rate of settlement increase compared to traditional vacuum preloading becomes more pronounced as the spacing of the inclined PVDs increases.

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Conflicts of Interest: All authors was employed by the company CCCC First Harbor Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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