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Developing a Small-Scale Experimental Method for Evaluating the Effectiveness of Soil Improvement Using Prefabricated Vertical Drains

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ABSTRACT Soft soils pose significant challenges in infrastructure development due to their low bearing capacity and high compressibility, which cause settlement and deformation over time through consolidation. Despite advancements in soil improvement techniques, faster and more efficient methods for accelerating soil consolidation remain crucial for achieving structural stability in a reasonable timeframe. Prefabricated Vertical Drains (PVD) have been widely adopted to accelerate soil consolidation, with their effectiveness typically evaluated through field-scale studies. However, field experiments can be time-consuming, costly, and influenced by site-specific variables, making controlled assessments challenging. We developed a small-scale laboratory experiment to evaluate the effect of PVD on soil consolidation. Soil samples were collected from the Padang-Pekanbaru Toll Road construction site in West Sumatra, Indonesia. Under controlled laboratory settings, two models were constructed—one with PVD and one without—using PVC pipes (20.32 cm diameter, 3.0 m height) filled with saturated soil to simulate field-scale soil columns. We found that PVD significantly enhanced soil consolidation. The rate of settlement on conditions without PVD was 1.2 times slower than that with PVD, particularly under lower loads. In contrast, PVD-enhanced models exhibit 5.3 times faster and greater settlement than conditions without PVD, along with 7.15 times higher water discharge. Metrics such as the coefficient of consolidation (C_v) and t_{90} values reinforced that PVD accelerated the consolidation process, particularly when subjected to higher loads. This study ultimately supports the development of more reliable laboratory methods for evaluating PVD applications, thereby enhancing design decisions across various consolidation scenarios and providing valuable insights for future infrastructure projects.

KEYWORDS Laboratory experiment; Soil improvement; Prefabricated Vertical Drains; Consolidation; Soft soil

1 INTRODUCTION

The geotechnical challenges posed by soft, compressible soils are significant, especially in coastal zones, floodplains, and reclaimed lands (Tian et al., 2020; Kuganeswaran et al., 2021; Indraratna et al., 2023; Hastomo et al., 2023; Wu et al., 2023). These soils often exhibit a low bearing capacity, high compressibility, and a tendency to settle excessively under applied loads (Das and Dey, 2018; Ding et al., 2019; Olatinsu et al., 2019; Hasan et al., 2020; Saparudin et al., 2022). Such characteristics can lead to structural instability, posing risks to buildings, embankments, roads, and other types of infrastructure. To mitigate these risks, various soil improvement methods have been developed over the years. Among the most common methods is mechanical compaction, which increases soil density through applied physical force (Azadegan et al., 2012; Lie et al., 2024), and chemical stabilization, where additives like lime or cement are mixed into the soil to enhance its strength and stiffness (Azadegan et al., 2012; Alhassani, 2021; Yong Tat et al., 2022). Another widely used approach is preloading, which involves applying a temporary surcharge to induce consolidation of the soft soil (Al-Jubair and Jabir, 2015; Ding et al., 2019; Bhosle and Deshmukh, 2021). For large-scale projects, deep foundation techniques such as piling are commonly employed to transfer loads to more stable soil layers at greater depths (Olatinsu et al., 2019; Isnaniati and Mochtar, 2023). In recent decades, Prefabricated Vertical Drains (PVD) have emerged as an efficient solution for accelerating the consolidation process of soft soils, particularly when combined with preloading techniques (Bergado et al., 2002; Roesyanto, 2018; Zhafirah et al., 2019; Ayeldeen et al., 2021).

Prefabricated Vertical Drains (PVD) are synthetic drainage systems consisting of a plastic core wrapped in. PVD facilitate the vertical movement of water trapped within the soil layers, thereby accelerating the consolidation process (Qi et al., 2020). By shortening the drainage path for pore water, PVD enhance the rate of consolidation in soft soils, improving their load-bearing capacity more quickly than traditional soil improvement techniques such as mechanical compaction or chemical stabilization (Azadegan et al., 2012). Studies by Deng et al. (2017) have shown that compared to untreated soft soil foundations, those improved with

PVD exhibited a total degree of consolidation approximately 20% higher. Additionally, PVD also offer several practical advantages, including lower environmental impact, minimal disturbance to the surrounding soil structure, and ease of installation. These benefits, along with their cost-effectiveness, make PVD a preferred choice for large-scale infrastructure projects (Chu et al., 2008). However, while PVD have been widely adopted in field applications, accurately evaluating their effectiveness remains a complex challenge.

Various methods have been developed to evaluate the effectiveness of PVD in soil improvement. Field-based methods, such as settlement monitoring, pore pressure measurements, and field instrumentation, are commonly used to assess the performance of PVD in large-scale projects (Indraratna et al., 2023). However, these methods are often time-consuming, costly, and influenced by environmental and site-specific variables that are difficult to control (Karunaratne, 2011; Moh and Lin, 2015). Additionally, large-scale field experiments require extensive resources and prolonged monitoring to capture the full consolidation (Kassou et al., 2021). Alternatively, numerical modeling, such as finite element analysis, has been utilized to simulate the behavior of PVD under various soil conditions (Chai et al., 2020). While modeling provides valuable predictive insights, it often relies on assumptions and idealized conditions that may not fully represent real-world soil behavior (Chrismaningwang et al., 2023). As a result, both field and numerical methods, despite their advantages, are often limited by practical constraints and uncertainties (Chu and Yan, 2005). To address these limitations, there is a growing emphasis on developing small-scale experimental methods that can replicate PVD performance in a controlled laboratory environment.

Small-scale experimental methods provide offer a practical and controlled alternative to field testing and numerical modeling. In a laboratory setting, experiments can be conducted under controlled conditions where soil types, moisture content, and loading parameters can be adjusted and monitored precisely (Deng et al., 2017). This experiment setting enables the replication of field conditions in a smaller, more manageable environment while observing PVD behavior within a shorter timeframe (Chrismaningwang et al., 2023). Additionally, small-scale experiments facilitate the testing of PVD performance across various soil types and configurations, aiding in the optimization of PVD design, spacing, and installation techniques. Compared to large-scale field trials, small-scale testing is more cost-effective and yields faster results, making it a valuable method for studying long-term soil consolidation (Baral et al., 2018). Yue-Bao Deng highlighted that small-scale experimental methods are critical for advancing our understanding of soil consolidation mechanisms, as they allow for detailed observations of drainage behavior that are difficult to capture in field studies. Therefore, developing reliable small-scale experimental methods is essential for improving PVD technology and providing more accurate predictions for their performance in real-world applications.

Despite the availability of field studies, numerical models, and some small-scale experiments, significant knowledge gaps remain in understanding the full potential and limitations of PVD, especially at smaller scales. Most existing studies focused on large-scale field applications, where variables such as soil heterogeneity and environmental conditions complicate result interpretation (Saowapakpiboon et al., 2010; Asha and Mandal, 2015; Adriyati et al., 2023). Meanwhile, small-scale experiments have yet to fully replicate the complex interactions between soil particles, water, and PVD observed in field conditions (Deng et al., 2017). The primary objective of this study is to develop a small-scale experimental method for evaluating the effectiveness of PVD in accelerating soil consolidation. By designing a controlled laboratory setup that simulates field conditions, this study provides valuable insights into PVD behavior, optimizes their design, and offers practical recommendations for engineers involved in soil improvement projects. Additionally, this study seeks to contribute to geotechnical engineering by addressing current limitations in small-scale testing methodologies.

2 METHODS

2.1 Study Site

The study site was located along the Padang – Pekanbaru Toll Road Section, specifically in the Padang – Lubuk Alung – Sicincin segment at STA 9+075 in West Sumatra, Indonesia. This region was characterized by a diverse topography and complex geotechnical conditions, making it a critical site for studying soil improvement methods in infrastructure development. According to data from the Central Bureau of Statistics by subdistrict in 2015, the site lay at an approximate elevation of 25-1000 m above sea level, with geographical coordinates -0.665602°S, 100.301594° E (Figure 1a).

The terrain in the area mostly passed through different types of land contours ranging from rivers, forests, hills, rice fields, swamps and uninhabited land. Disturbed soil samples for this study were collected from the ground surface at a depth of 50 cm around the PVD deployment site (Figure 1b). The soil at this site iswas classified as blackish-brown silt with a very soft consistency, a characteristic typical of the area that poses significant challenges for construction projects. Laboratory testing of soil samples revealed an average composition of 8.95% sand, 65.21% silt, and 25.85% clay, with a moisture content of 33.45% and a plasticity in-

Figure 1 (a) Sampling location at Padang – Pekanbaru Toll Road Section, Padang – Lubuk Alung – Sicincin; (b) Sampling location around the PVD embankment; (c) Visualization of soil samples

dex of 21.66%. These properties indicated high compressibility and low shear strength, which were critical factors in this study.

The groundwater conditions at the site played an important role in its geotechnical behavior. The groundwater table was approximately 1 m deep, with seasonal fluctuations ranging from 0.7 to 1 m. These fluctuations influenced soil consolidation and drainage, making it essential to consider groundwater dynamics when designing ground improvement techniques.

The region's climate was tropical, with annual average temperatures ranging from 23°C to 26°C, while monthly averages varied depending on location and altitude. Lowland areas such as Padang tend to be warmer than mountainous regions. The area experiences significant rainfall, particularly during the wet season from October to April, with an annual total of 3,000 to 4,000 mm. This high rainfall further complicated soil conditions, posing challenges for construction and stabilization efforts.

2.2 Experiment Setup

For the experimental setup, the main test equipment included two 8-inch Rucika Wavin (AW) PVC pipes, each 3 m long, and two 6-inch PVC pipes, each 1 m long. The 8-inch pipe served as the primary test columns for soil placement, while the 6-inch pipes provided support for PVD embedding. Additional equipment included iron weights ranging from 3 kg to 96 kg, used to ap-

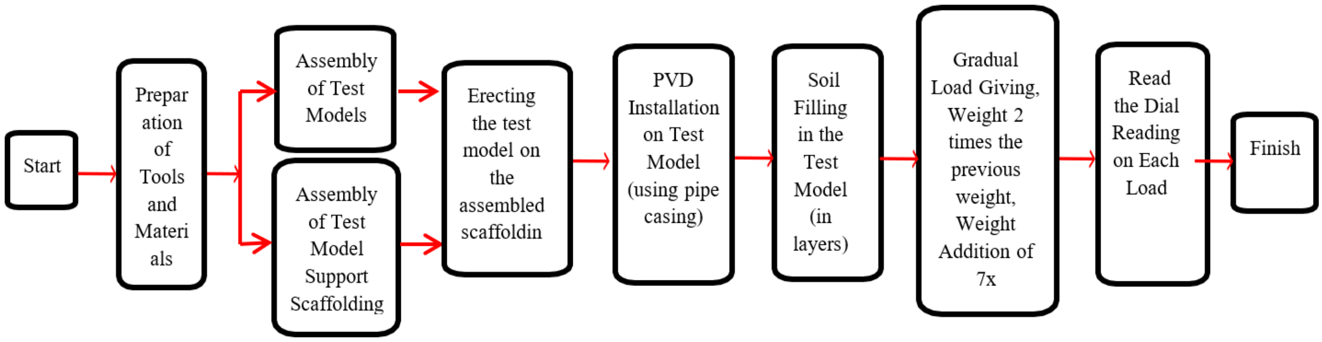

Figure 2 Schematic illustration of the experimental setting

Figure 3 (a) Condition of PVD in the pipe before loading; (b) PVD performed after testing completion

ply normal pressure between 0.85 and 27.21 kPa to the soil column. A settlement indicator dial measured vertical displacement, while a 1.5 mm diameter hose monitored water pressure levels rising due to loading. To facilitate water drainage, pore stones and pore papers were placed at the bottom of the soil column. Scaffolding was used to keep the PVC pipes stable and upright throughout the experiment.

The PVD material used in the test was the AD530 type, a commonly used variant in field applications. It measured 10 cm in width and 0.5 cm in thickness and was supplied by PT. Teknindo Geosystem Unggul. The PVD was installed to match the depth of the soft soil layer, which was 286 cm. The installation pattern and spacing were kept constant, with a single PVD placed centrally within the soil layer. Notably, installing the PVD in soft soil resulted in a smear zone around the drain, as reported in previous studies (Wu et al., 2023).

The soil used in the test was disturbed soil collected from the field. It was then saturated for at least 24 hours before the experiment. This process ensured a uniform, slurry-like consistency similar to mud. While the soil was soaking, an 8-inch PVC pipe was cut to a length of 3 meters. Five holes were drilled at equal intervals along its side, and a 1.5 mm vertical hose was inserted into each hole, extending the full height of the pipe. The pipe was then positioned upright and secured using a Peri system scaffolding.

For Test Model 1 (without PVD), the saturated soil was placed into the 8-inch PVC pipe in layers, with each layer carefully compacted to maintain uniform density throughout the sample depth. The soil was filled to a depth of 2.86 meters, and water was added until it reached the surface. Water levels were monitored through hoses inserted at different depths, and the consistency of these levels indicated uniform pore water distribution.

For Test Model 2 (with PVD), the setup followed a slightly modified procedure (Figure 2). After the 8-inch PVC pipe was positioned upright, a 3 m long PVD sample was inserted into a 4-inch PVC pipe to ensure it remained vertical and did not buckle during installation. The 4-inch pipe, containing the PVD, was then placed inside the 8-inch PVC pipe. Soil was added in layers, similar to Model 1, with each layer compacted. When the soil reached a height of 2.86 meters, the 4-inch pipe was carefully lifted and removed, ensuring the PVD remained embedded without buckling (Figure 3a). The PVD was checked for stability, and the exposed length above the soil surface matched the expected difference between its total length and the embedded depth. The PVD remained straight and did not bend during installation (Figure 3b). Figure 4 shows the laboratory modeling results of the test models with and without PVD.

2.3 Experiment Process

Before initiating the loading process, the soil surface was covered with filter paper to prevent soil particle migration while allowing water to escape freely during consolidation. A lightweight PVC base plate was then

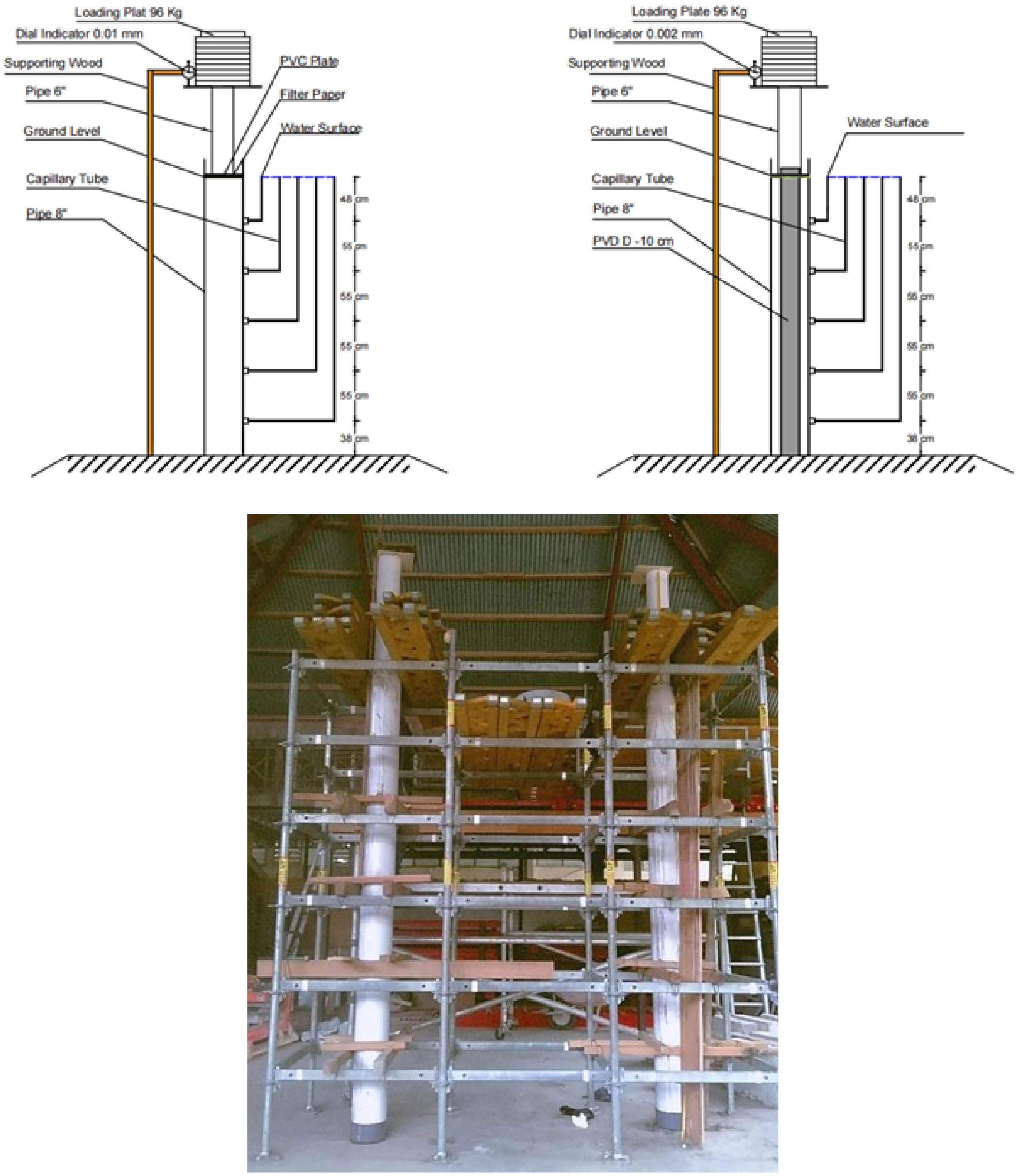

Figure 4 Model test installation results; (a) Ground improvement model without PVD; (b) Ground improvement model with PVD; (c) Visualization of the two models

placed on top of the filter paper. The base plate was perforated at the center, acting as a valve to facilitate water drainage from the soil. A 1 m long, 6" diameter PVC pipe was then placed vertically on top of the base plate. This pipe served as a connection between the soil and the applied load, as well as support for the dial indicator used to measure settlement. With the pipe in position, a 3 kg load was applied on top. Since the combined weight of the base plate and connecting pipe was 2.85 kg, the additional applied load amounted to 0.15 kg. At this stage, the dial indicator was set to record the initial settlement measurement under the 3 kg load.

The loading sequence was carried out over several days. After the first 24 hours, the applied load was doubled. The load increments followed a progression where each subsequent load was twice the previous one, with weights of 3 kg, 6 kg, 12 kg, 24 kg, 48 kg, and 96 kg. Settlement was measured at each loading stage using the dial indicator, while pore water pressure in the hose was closely monitored.

On the seventh day, the load was gradually reduced in reverse order until the applied weight returned to the initial 3 kg. Throughout the experiment, changes in soil layer thickness, or settlement, were observed and recorded for each load application. This sequential loading and unloading process enabled an accurate assessment of the soil's consolidation behavior under varying stress conditions.

2.4 Measurement and Analysis

The rate of consolidation settlement was calculated using the coefficient of consolidation (C_v) estimated using the square root of time method by Taylor Theory. To determine (C_v) the consolidation test results were plotted on a graph showing the relationship between the square root of time and settlement. The resulting curve was linear up to approximately 60% consolidation. A key characteristic of this method is that the degree of consolidation (U) is set at 90%, allowing for the determination of t_{90}, which represents the time required for one-dimensional consolidation settlement to reach 90%.

3 RESULTS

The results indicated a significant difference in soil consolidation behavior for conditions with and without PVD (see Figure 5). In Model 1 (without PVD), the soil exhibited slower and smaller settlement across all pressure levels (Figure 5a). Under higher loads, such as 96 kg cm^{-2}, the dial reading stabilized at approximately 0.75 cm after 60 min, suggesting that most consolidation had occurred. In contrast, lower loads, such as 3 and 6 kg cm^{-2}, resulted in minimal settlement, remaining below 0.15 cm throughout the test period.

In contrast, Model 2 (with PVD) demonstrated that the introduction of PVD significantly enhanced the consolidation process, both in speed and magnitude (Figure 5b). Under the same 96 kg cm^{-2} load, the settlement reached approximately 4 cm after 120 min, indicating a much higher degree of consolidation compared to the no-PVD case. Even at lower loads, the settlement was elevated, with a faster consolidation rate over time. The presence of PVD allowed quicker drainage of excess pore water, leading to accelerated consolidation. This effect is particularly evident under higher loads, where settlement continues beyond 120 min without reaching equilibrium.

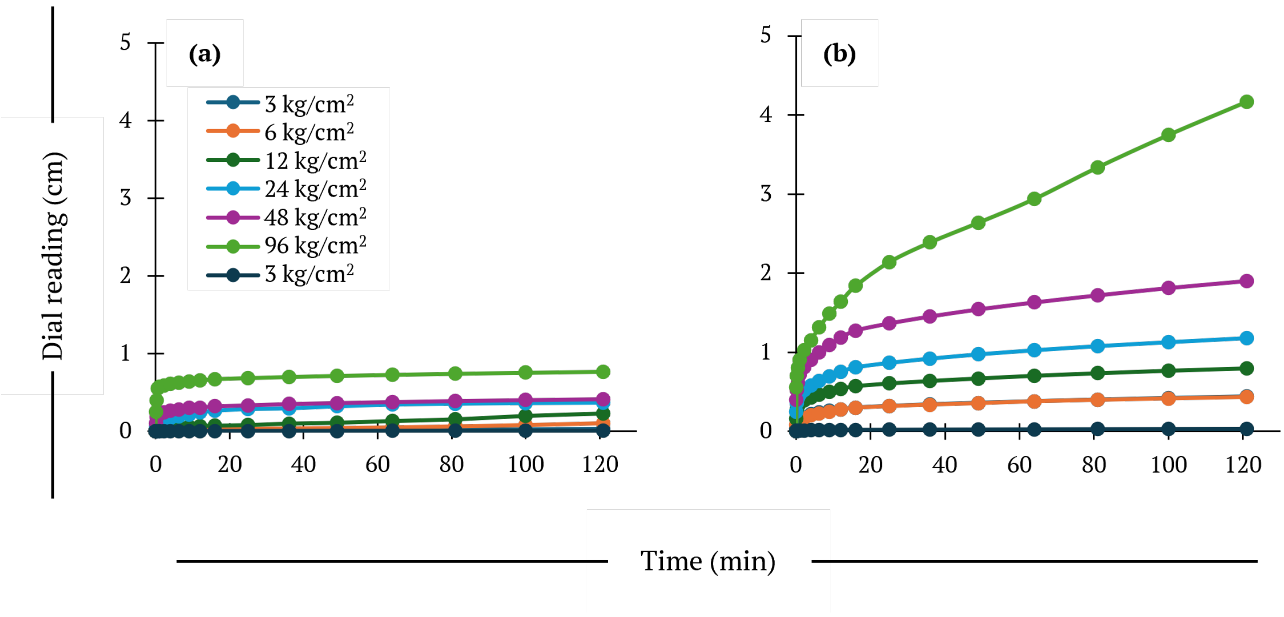

Figure 5 Dial Reading Data for models (a) Without PVD and (b) with PVD

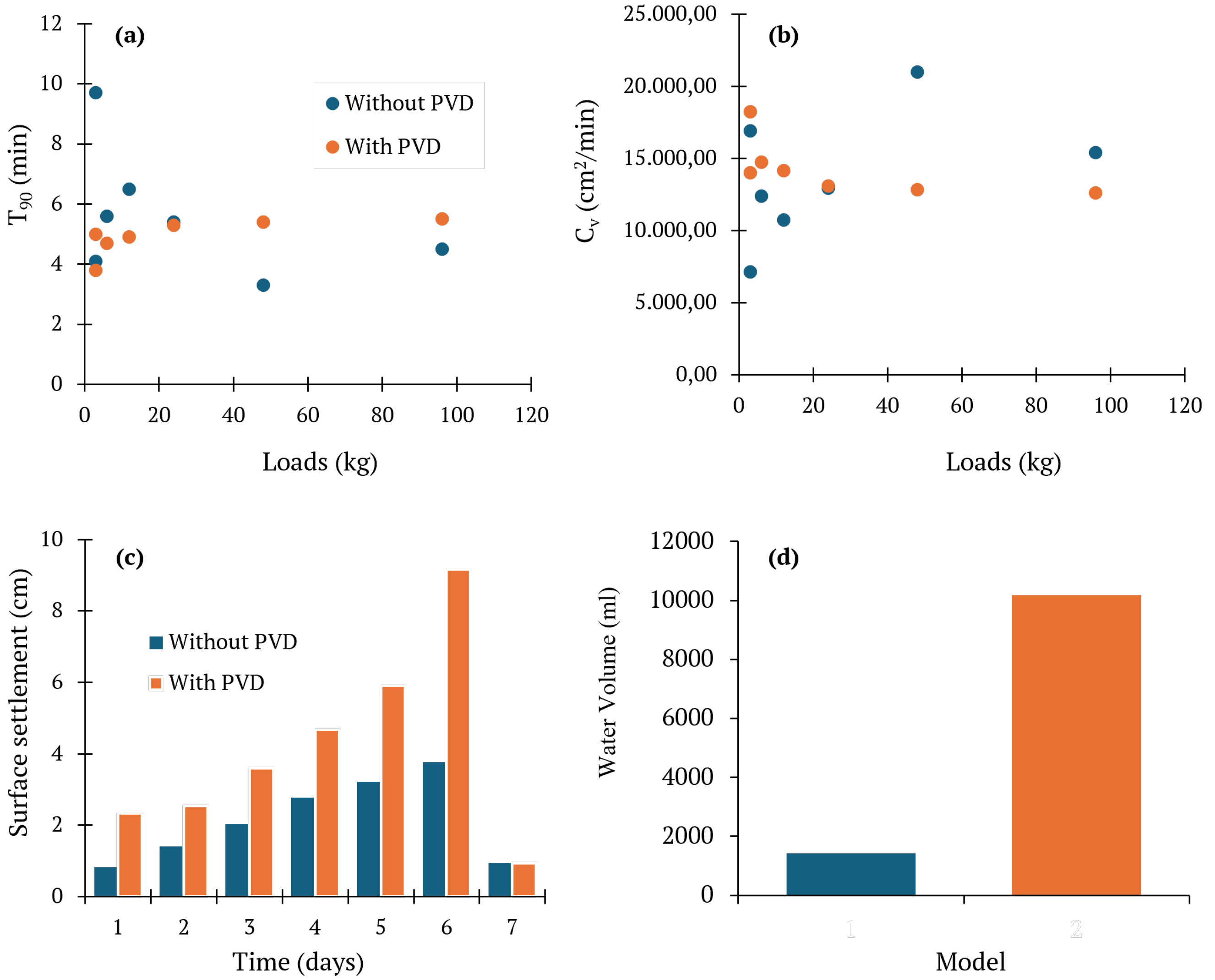

Figure 6 Soil behavior during consolidation process: (a) t_{90}, (b) Cv, (c) Surface settlement, and (d) Water discharge.

The total surface settlement further supported the effect of PVD in accelerating the consolidation process, as shown in Figure 6c. Over seven days, soil with PVD consistently showed greater settlement than that without PVD. On Day 1, the total settlement on soil with PVD reached 2.34 cm, while the soil without PVD generated only 0.827 cm of settlement. This trend continued, with the gap widening significantly by Day 6, where settlement on soil with PVD reacheds a peak of 9.17 cm compared to just 3.767 cm on that without PVD. This stark difference highlighteds how PVD facilitated quicker pore water drainage, leading to faster and more substantial consolidation, especially under higher pressure conditions. By Day 7, both systems stabilized, but the total settlement with PVD remaineds significantly higher throughout the test period.

The t_{90} value, representing the time taken for 90% consolidation, showed a clear distinction between the two models. In Model 1, t_{90} varied significantly with the applied load, ranging from 3.3 min for the 48 kg cm^{-2} load to 9.7 min for the 3 kg cm^{-2} load. These results indicated that without PVD, higher loads facilitated faster consolidation by expelling pore water more efficiently, whereas lower loads resulted in a significantly longer consolidation time. In contrast, Model 2 exhibited more and shorter t_{90} values across all loads, as compared to Model 1. Under conditions with PVD, t_{90} ranged from 3.8 min at 3 kg cm^{-2} to 5.5 min at 96 kg cm^{-2}, indicating a more consistent consolidation process.

The coefficient of consolidation (C_v), which measured how quickly soil consolidated under loads, also showed distinct differences between the two models. In Model 1, C_v values were more variable, ranging from 7,150.83 cm^2 min^{-1} at 3 kg cm^{-2} to 21,019.09 cm^2 min^{-1} at 48 kg cm^{-2}. This variability indicated that consolidation occurred much faster at higher loads due to increased pressure, which forceds water out of the soil pores more efficiently. The lack of vertical drains resulteds in slower drainage, requiring higher pressures to expedite consolidation. In contrast, Model 2 exhibited more consistent C_v values, ranging from 12,611.46 cm^2 min^{-1} at 96 kg cm^{-2} to 18,253.42 cm^2 min^{-1} at 3 kg cm^{-2}. Additionally, the average C_v value in Model 2 was slightly higher than in Model 1, reflecting the enhanced drainage capacity provided by PVD.

The water discharge data shown in Figure 6 further highlighted the significant difference between the two models. In Model 1, the total water discharge was 1,421 ml, whereas that in Model 2 was 10,182 ml. The significantly higher water discharge in Model 2 indicated the enhanced drainage capacity and accelerated consolidation facilitated by the PVD.

4 DISCUSSION

4.1 Effect of PVD on Soil Consolidation Behavior

The introduction of Prefabricated Vertical Drains (PVD) significantly impacts soil consolidation, enhancing both the rate and magnitude of settlement. In Model 2 (with PVD), settlement at a load of 96 kg cm^{-2} was 5.3 times greater compared to Model 1 (without PVD). Similarly, the total volume of discharged water in Model 1 was 7.1 times larger than in Model 2. This result can be attributed to the primary function of PVD: shortening the drainage path for excess pore water, allowing for faster and more efficient water escape (Sakleshpur et al., 2018; Ayeldeen et al., 2021).

The effect of PVD is particularly evident under higher loads, where increased pressure forces water out of the soil more rapidly. These findings align with previous studies by Chrismaningwang et al. (2023) which demonstrated that PVD accelerated consolidation by enhancing water drainage, significantly reducing consolidation time. Other studies, such as Chrismaningwang et al. (2023), further confirmed the effectiveness of PVD in improving consolidation rates, particularly in soft, compressible soils. Additionally, the PVD promoted a better load distribution across the soil structure, preventing excessive pore pressure buildup a common issue during the consolidation process (Chrismaningwang et al., 2023). As a result, consolidation occurred more rapidly under high-pressure loads, as reflected in the 4 fourfold reduction in t90 for the highest load (96 kg cm^{-2}) in Model 2 compared to Model 1.

4.2 The Effectiveness of the Small-Scale Experimental Method for Observing the Consolidation Process on Soils

This experimental method proves to be an effective approach for investigating soil consolidation behavior. Despite being a scaled-down representation of field conditions, the experiment provided clear, measurable differences in settlement rates and water discharge for conditions with and without PVD. Previous studies, such as those by (Deng et al., 2017), have also demonstrated the effectiveness of small-scale models in evaluating the influence of PVD on the consolidation process. These studies highlighted that small-scale tests can reasonably predict the trends observed in field applications, particularly water drainage and settlement acceleration (Mert et al., 2022). However, as noted by prior studies, scaling effects may introduce discrepancies when predicting the time scale of consolidation (Bergado et al., 2002). These effects arise primarily from differences in the geometric and physical properties of the soil PVD system when scaled down (Deng et al., 2017).

While the small-scale model effectively illustrates the differences in the consolidation process of soils with and without PVD, scaling effects must be considered when applying these results to real-world projects. Previous studies, including (Deng et al., 2017), highlighted that drainage path lengths and soil permeability differed in field conditions, potentially leading to slower consolidation times in the field than in the laboratory. Therefore, while small-scale models replicate the consolidation mechanism, full consolidation in the field may take longer due to the larger soil volume and greater spacing between PVD. As a result, scaling effects may introduce discrepancies in predicted consolidation times (Deng et al., 2017), though the overall trends—such as faster and more uniform consolidation with PVD—align with full-scale findings (Théodore et al., 2024). Nevertheless, while the exact magnitudes observed in this small-scale experiment may not directly translate to large scale projects, this study provides valuable insight into the general behavior of soil consolidation, with and without PVD, confirming previous large-scale observations (Cascone and Biondi, 2013; Deng et al., 2013; Roesyanto, 2018; Nguyen and Kim, 2019; Qi et al., 2020; Ibrahim et al., 2022; Chrismaningwang et al., 2023; Wu et al., 2023).

5 CONCLUSION

This study provides insight into advancing small-scale experimental methods for investigating the performance of Prefabricated Vertical Drains (PVD) in soil consolidation. A key challenge in geotechnical engineering studies is replicating large-scale field conditions in a controlled laboratory setting. This study demonstrated the effectiveness of small-scale models in capturing the essential dynamics of the soil consolidation process, both with and without PVD, offering a cost-effective alternative to full-scale experiments. By measuring settlement, water discharge, and t_{90} across different pressure levels, the study illustrated how small-scale setups can simulate the fundamental processes of drainage and consolidation. Furthermore, this study highlighted the importance of considering scaling laws when interpreting results from laboratory models. The ability to replicate trends observed in full-scale field studies, while accounting for differences in time and magnitude, highlights the value of small-scale experiments in validating theoretical models and informing real-world design decisions. This study provides a foundation for future research on small-scale PVD applications, encouraging the development of more reliable laboratory methods that can be adapted to various soil conditions and consolidation scenarios.

DISCLAIMER

The authors declare no conflict of interest.

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