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Ground Improvement Design using Prefabricated Vertical Drains at the Container Yard Area of Sunda Kelapa Port, Jakarta

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ABSTRACT

This study investigates the application of Prefabricated Vertical Drains (PVDs) as a ground improvement technique in the Container Yard Area of Sunda Kelapa Port, Jakarta. The site is underlain by thick, soft clay deposits with low shear strength and high compressibility, posing significant risks of settlement under structural loads. The objective of the study is to evaluate the effectiveness of PVD installation at varying depths such as 1/3, 2/3, and full depth of the soft soil layer on consolidation performance and total settlement. The methodology involved site investigation, stratigraphic profiling, and technical calculations based on geotechnical parameters from three designated zones. Settlement outcomes were analyzed for each depth scenario. Results indicate that full-depth PVD installation consistently produced the highest settlement, with maximum values reaching 3.13 meters, demonstrating its superiority in facilitating consolidation across the entire compressible layer. Shallower PVD installations at 1/3 and 2/3 depths resulted in lower settlement values of 1.92 m and 2.64 m respectively, indicating that untreated deeper layers hinder full consolidation. In contrast, full-depth PVDs (34 m) achieved the highest settlement at 3.13 m within 25 weeks, demonstrating their superior effectiveness in accelerating consolidation. The integration of vacuum consolidation further reduced the consolidation time and improved dissipation of excess pore water pressure. These quantitative results confirm that full-depth PVDs, with optimal spacing of 0.862 m, provide a practical and efficient solution for ground improvement, enhancing long-term stability and performance in soft soil infrastructure projects.

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1. INTRODUCTION

Prefabricated Vertical Drains (PVDs) have emerged as a critical ground improvement technique in geotechnical engineering, particularly for accelerating the consolidation of soft, compressible soils [1]. Typically composed of a plastic core encased in a geotextile filter, PVDs function by providing artificial drainage paths that significantly reduce the time required for excess pore water pressure to dissipate under applied loads. This is especially relevant in port and reclamation areas where deep soft clay deposits present major challenges for construction stability and time efficiency. In conventional scenarios, techniques such as surcharge preloading alone often result in excessively long consolidation periods, particularly in thick, low-permeability clay layers. The integration of PVDs into the soil mass can substantially shorten these drainage paths and enhance vertical and radial consolidation rates [2], [3]. Research has consistently demonstrated that the depth and spacing of PVD installations are key parameters that directly influence their effectiveness. Variations in drain penetration depth have been shown to alter consolidation timelines significantly, requiring careful design planning based on subsurface conditions [4], [5].

Moreover, the integration of multiple soil improvement methods has garnered increasing interest as a strategy to optimize consolidation outcomes. A study by Muis and Wulandari [6] demonstrated that the combination of PVDs and stone columns results in a synergistic effect, wherein the drainage function of PVDs is complemented by the load distribution capacity of stone columns. This hybrid approach mitigates the individual limitations of each method, offering an effective and pragmatic solution for soft soils with complex geotechnical properties. In addition, the application of vacuum preloading in conjunction with PVDs has been proven to further enhance consolidation, particularly in multi-layered soil profiles, by increasing the hydraulic gradient and accelerating pore pressure dissipation [7], [8]. Numerical modeling approaches have also contributed to a more accurate prediction of settlement behavior and consolidation performance, aiding engineers in the optimization of design parameters for site-specific conditions [9], [10]. Given the complex stratigraphy and presence of thick, soft clay deposits in the Container Yard Area of Sunda Kelapa Port, the use of full-depth PVD systems is anticipated to significantly improve the consolidation rate and ground stability. This study aims to evaluate the effectiveness of various PVD installation depths through technical analysis, to propose an optimal ground improvement plan for the project site. The findings are expected to contribute to more efficient and sustainable construction practices in soft soil environments.

2. METHOD

This research employs a literature review and case study approach, grounded in planning-related theories such as bearing capacity analysis, soil stability, and the consolidation concept using Prefabricated Vertical Drains (PVD). The study is conducted at the Container Yard Area of Sunda Kelapa Port, located in North Jakarta, Indonesia, which serves as one of the country's oldest and historically significant seaports. This area experiences high loading from container stacking activities and is characterized by soft, compressible alluvial soil deposits with a high groundwater table—conditions that necessitate effective ground improvement to ensure long-term stability and serviceability. The site was selected due to ongoing infrastructure development and the need for soil enhancement to accommodate increased container traffic and storage demands. The project area was divided into several zones based on geotechnical variability and functional layout, which were analyzed individually for appropriate ground improvement strategies. The study objective is analyzing and comparing the technical planning and implementation of ground improvement systems using PVD.

The data sources used in this study are categorized into two types:

1. Primary Data: Obtained directly through field surveys, visual observations, and interviews. These data serve as supporting information to understand the existing conditions of the study site.
2. Secondary Data: Acquired from relevant government or project-related agencies, this includes technical planning data such as soil investigation reports, topographic maps, and other relevant engineering documents.

The collected data encompass project location details, topographic maps, and soil characteristics data across predefined zones within the study area. Data processing and analysis were carried out through technical calculations of consolidation settlement using the PVD methods. Figure 1 presents the project site layout, including zoning boundaries and soil cross-section lines used for stratigraphy analysis and vertical drainage planning.

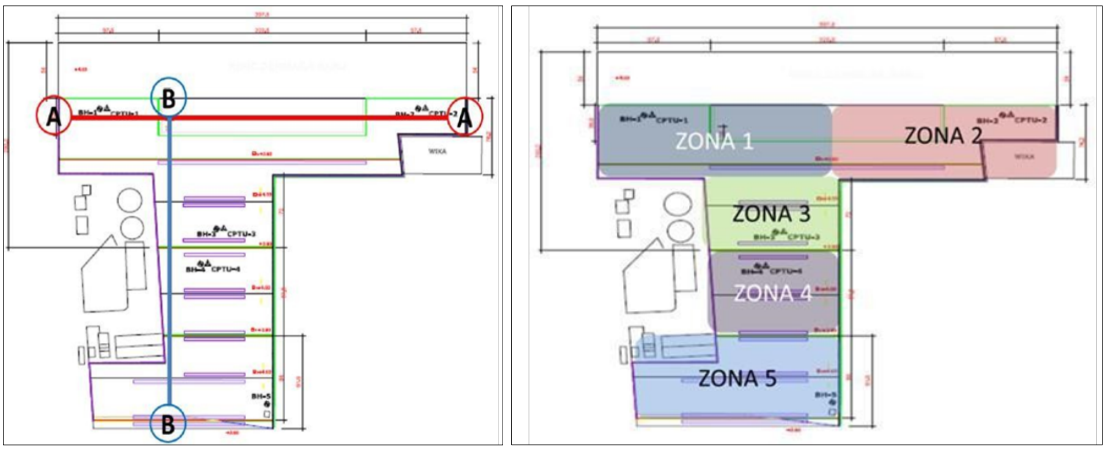

Figure 1. Plan view of section lines and zone identification

The determination of soil parameters through correlations and empirical formulas is a common practice in geotechnical engineering, especially when direct measurements are not feasible or economical. For soil cohesion, the correlation between SPT-N values and undrained cohesion (Cu) is widely used, with the effective cohesion (C') often assumed to be two-thirds of Cu. This approach is supported by various studies, including the one that developed empirical correlations between soil properties and SPT-N values [11]. However, it's important to note that soil cohesion can vary significantly with moisture content, as demonstrated in a study on compacted clay [12]. The internal friction angle (ϕ) estimation based on soil type and laboratory data adjustment is a reasonable approach. Research has shown that ϕ can be correlated with SPT-N values, particularly for sandy soils [13]. However, these correlations may underestimate ϕ for high-quality undisturbed samples, suggesting the importance of laboratory data for refinement. Regarding the compression index (Cc) and swelling index (Cs), while empirical formulas based on natural water content are commonly used, caution is advised. A study on aged solid waste samples found that Cc values varied with void ratio, and Cα (secondary compression index) was more dependent on conditions favorable to microbial activity [14]. This highlights the complexity of soil behavior and the potential limitations of simplified empirical approaches, as illustrated in the table of stratigraphic profile. However, the compression index (Cc), swelling index (Cs), and Cα (secondary compression index) are not presented in the stratigraphic profile table due to their variability and dependence on factors such as void ratio and microbial activity conditions

3. RESULTS AND DISCUSSION

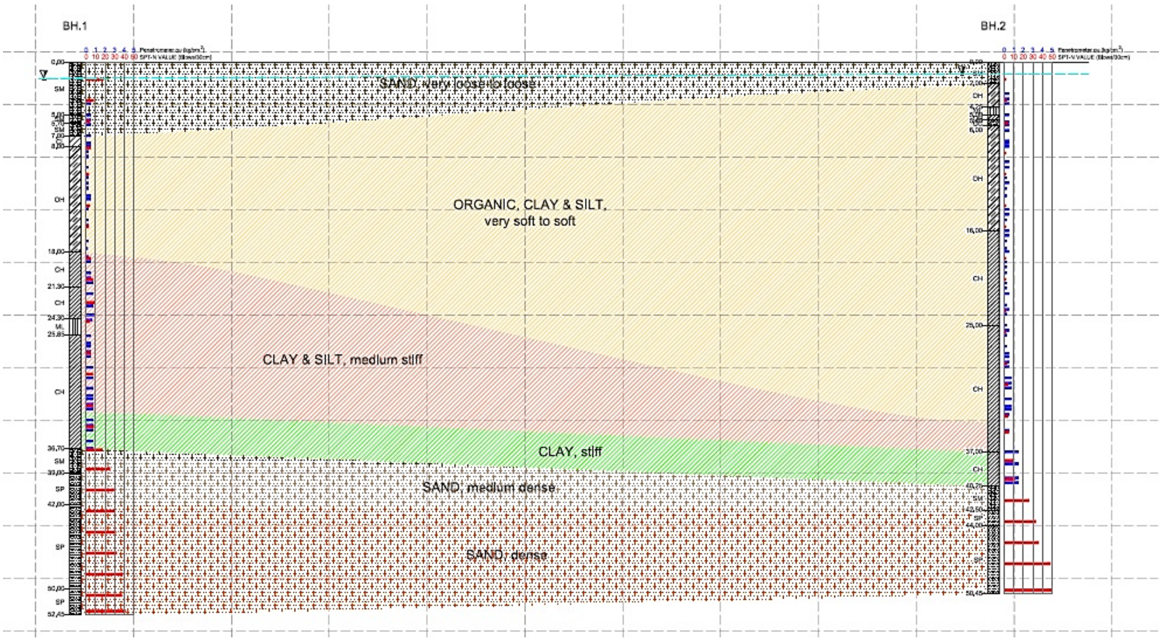

Figure 2. Stratigraphic section A-A

The stratigraphic profiles along sections A–A and B–B, as presented in Figure 2 and Figure 3, provide critical insights into the geotechnical conditions and subsurface variability at the study site. Section A–A illustrates the vertical and lateral distribution of soil layers from the ground surface to the lower bearing strata. The uppermost layer, identified as "sand (very loose to loose)", is a non-cohesive, free-draining sandy deposit with relatively low shear strength and limited load-bearing capacity. With N-SPT values typically ranging from 4 to 18, this layer offers good permeability but lacks structural integrity, making it unsuitable for supporting heavy loads and not a focus in ground improvement planning. Immediately below lies a substantial deposit of "organic clay & silt (very soft to soft)", which dominates the profile and is characterized by high natural water content, elevated plasticity index (PI), and low undrained shear strength. These parameters indicate a highly compressible soil prone to large settlements, particularly under embankment or structural loading. The presence of organic matter further exacerbates consolidation behaviour and time-dependent settlement. This soft soil stratum is therefore targeted for improvement using Prefabricated Vertical Drains (PVD) combined with preload or vacuum consolidation to accelerate dissipation of excess pore water pressure. At greater depths, the profile transitions into "clay & silt (medium stiff)" and "clay (stiff)", indicating a progressive increase in soil stiffness and shear strength with depth. These layers exhibit higher N-SPT values and improved undrained shear strength, offering greater resistance to deformation and more favourable bearing characteristics. The deepest portions of the profile reveal "sand (medium dense)" and "sand (dense)", which serve as the competent bearing layers due to their high density, excellent drainage capacity, and significant shear strength. These sandy layers are essential in determining foundation depth and serve as termination levels for PVDs or pile foundations, ensuring adequate support for overlying structures.

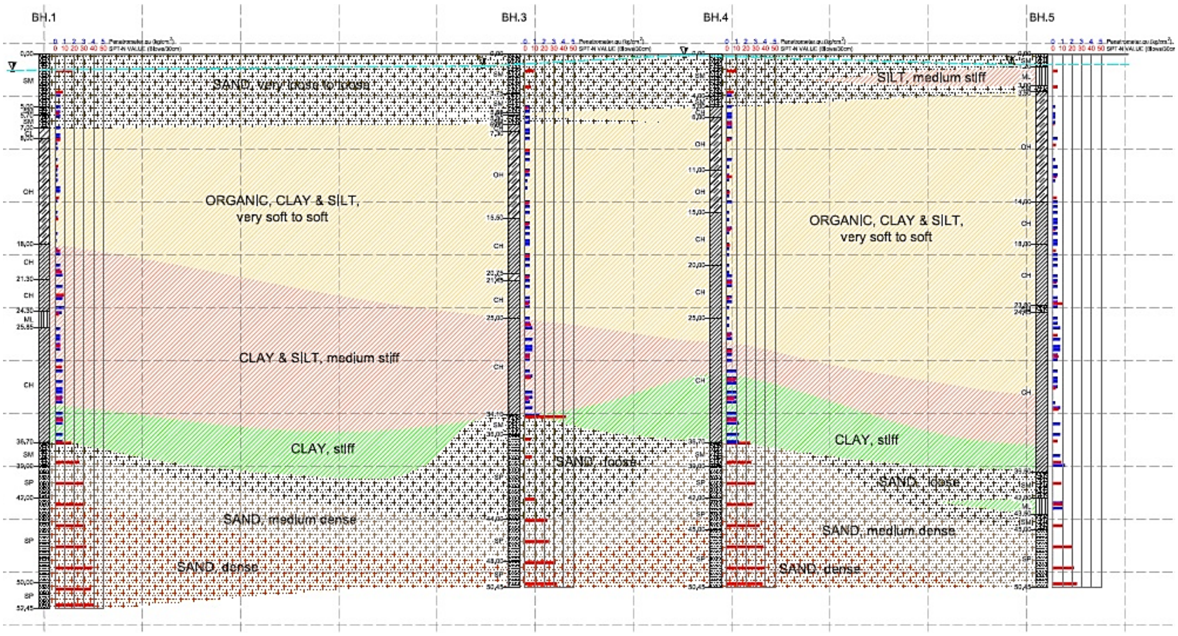

Figure 3. Stratigraphic section B-B

Section B–B (Fig 3) reinforces and complements the observations from section A–A, emphasizing the lateral continuity and variation in depth of each geotechnical layer across the site. The upper sandy layer continues to dominate the surface stratum, although its thickness varies slightly across boreholes. Beneath it, a thick and laterally continuous deposit of "organic clay & silt (very soft to soft)" persists throughout the profile, maintaining similarly poor geotechnical characteristics as those observed in section A–A. This layer demonstrates extremely high-water content (Wc up to 97%), low Cu values (0.125–0.25 kg/cm²), and high PI, making it highly vulnerable to primary and secondary consolidation. Without intervention, this could result in prolonged and uneven settlement post-construction. At depths beyond approximately 27–28 meters, the profile shows a gradual transition to medium stiff and stiff clay layers, though their basal elevations vary significantly between boreholes. These irregularities suggest inclined or undulating hard layers, which can create uneven load distribution and differential settlement if not addressed during the design phase. The profile terminates in dense sand layers, consistent with those observed in section A–A, indicating a well-defined stratigraphic boundary suitable for load transfer and foundation anchorage.

In summary, the subsurface investigation across both sections identifies a widespread and thick deposit of highly compressible, low-strength organic clay and silt as the dominant geotechnical challenge at the site. Installation of PVD on the considerable vertical thickness and lateral continuity of this soft layer, coupled with the undulating nature of the stiffer substrata, call for a carefully engineered ground improvement system to accelerate consolidation and reduce settlement risks. Furthermore, the variability in soil stiffness at deeper levels underscores the importance of tailoring foundation depth, PVD termination, and loading strategies to account for spatial heterogeneity in subsurface conditions. A comprehensive understanding of these profiles is essential to ensuring the stability, durability, and safety of any infrastructure built on this ground.

Table 1 presents the stratigraphic profile of zone 1, indicating that the upper soil layer (0–4 m depth) consists of very loose to loose sand with Standard Penetration Test (N-SPT) values ranging from 4 to 18 and zero cohesion (Cu = 0), signifying a non-cohesive soil with good natural drainage. This layer does not undergo significant consolidation. Beneath this, extending from approximately 5 to 28 meters depth, lies a thick layer of clayey silt with very soft to soft consistency, characterized by N-SPT values between 3 and 5, high natural water content (Wc up to 84%), and a plasticity index (PI) ranging from 76% to 80%. These indicators reflect a highly compressible soil with substantial consolidation potential. At depths exceeding 28 meters, the soil exhibits increased stiffness (medium stiff) with an N-SPT value of 7 and undrained shear strength (Cu) of 0.375 kg/cm², indicating that even deeper layers may still require improvement to prevent long-term settlement.

Table 1. Stratigraphic profiles in zone 1

Depth (m)	Type of Soil	N-SPT	γsat (t/m3)	Wc (%)	Cu (kg/cm2)	C' (kg/cm2)	ϕ	LL (%)	PI (%)
1–2	Sand (very loose to loose)	18	1.5474	29.6	0	0	31.0	0	0
3–4		8	1.6	25.5			31.3		
5–7		4	1.2	46.3			25.0		
8–9	Clay & Silt (very soft to soft)	5	1.44025672	67.3669753	0.25	0.166667	1.8	80.3091385	53.5245848
10–12		3			0.1875	0.125			
13–14		4			0.25	0.166667			
15–16		3			0.1875	0.125			
17–18		5			0.25	0.166667			
19–21	Clay & Silt (medium stiff)	7	1.46861199	84.8810183	0.375	0.25	0.0	110.267606	76.8958285
22–23		9			0.5	0.333333			
24–25		4			0.25	0.166667			
26–28		5	1.50101317	82.0846577	0.25	0.166667		106.074753	74.9726977
29–33		7			0.375	0.25			

Table 2. Stratigraphic profiles in zone 2

Depth (m)	Type of Soil	N-SPT	γsat (t/m3)	Wc (%)	Cu (kg/cm2)	C' (kg/cm2)	ϕ	LL (%)	PI (%)
1–2	Sand (very loose to loose)	18	1.5474	29.6	0	0	31.0	0	0
3–4		8	1.6	25.5			31.3		
5–7		4	1.2	46.3			25.0		
8–9	Clay & Silt (very soft to soft)	5	1.44025672	67.3669753	0.25	0.166667	1.8	80.3091385	53.5245848
10–12		3			0.1875	0.125			
13–14		4			0.25	0.166667			
15–16		3			0.1875	0.125			
17–18		5			0.25	0.166667			
19–21	Clay & Silt (medium stiff)	7	1.46861199	84.8810183	0.375	0.25	0.0	110.267606	76.8958285
22–23		9			0.5	0.333333			
24–25		4			0.25	0.166667			
26–28		5	1.50101317	82.0846577	0.25	0.166667		106.074753	74.9726977
29–33		7			0.375	0.25			

Table 2 shows that zone 2 has stratigraphic characteristics like Zone 1, albeit with slight variations in geotechnical parameters. The upper sandy layer extends to a depth of approximately 4 meters, also with N-SPT values between 4 and 18 and Cu = 0. Below this lies a thick very soft clayey silt layer, ranging from depths of ±5 to 27 meters, with N-SPT values of 3–5, extremely high-water content (Wc up to 97%), and PI values between 53% and 76%. The Cu values are notably low, ranging from 0.125 to 0.25 kg/cm². This soil stratum is highly susceptible to secondary consolidation and long-term settlement. At depths beyond 27 meters, the soil demonstrates improved stiffness with N-SPT values increasing to 7–9 and Cu values reaching 0.375 kg/cm². However, the PI remains high at around 75%, indicating that the soil retains high plasticity and remains a potential contributor to settlement if left untreated.

Table 3. Stratigraphic profiles in zone 3

Depth (m)	Type of Soil	N-SPT	γsat (t/m3)	Wc (%)	Cu (kg/cm2)	C' (kg/cm2)	ϕ	LL (%)	PI (%)
1	Sand (very loose to loose)	9	1.533	29.6	0	0	30.8	0	0
2									
3		6	1.3	39.9			27.3		
4									
5		3	1.3	39.9			28.3		
6									
7	Clay & Silt (very soft to soft)	3	1.44025672	67.3669753	0.1875	0.125	0.0	80.3091385	53.5245848
8									
9		5			0.25	0.166667			
10									
11		4			0.25	0.166667			
12									
13									
14									
15									
16									
17									
18									
19		5			0.25	0.166667			
20									
21		4			0.25	0.166667			
22									
23									
24									
25									
26	Clay & Silt (medium stiff)	6	1.50101317	82.0846577	0.375	0.25	0.0	106.074753	74.9726977
27									
28		5			0.25	0.166667			
29									
30		6			0.375	0.25			
31									
32		4			0.25	0.166667			
33									
34									

Table 3 describes Zone 3, which displays a slightly different stratigraphic profile. The very loose sand layer is thinner, extending only to about 3 meters depth, with lower density reflected by N-SPT values of 1–3. The dominant clayey silt layer extends from 4 to 27 meters and is characterized by high water content (up to 97%), PI as high as 83%, and low Cu values, indicating extremely soft and highly compressible soil conditions. In the deeper zone (>27 m), an increase in soil density is observed, with saturated unit weight (γ_sat) reaching 18.00 kN/m³ and Cu = 0.375 kg/cm². However, the PI remains high, suggesting that the soil at this depth still possesses high plasticity and may continue to experience consolidation if not effectively treated with an extended PVD system.

Table 4 presents the calculated primary consolidation settlements (Sc) for three observation zones (Zone 1, Zone 2, and Zone 3), under three different PVD installation depths: one-third, two-thirds, and full depth of the soft soil layer. The data were derived from analytical consolidation calculations using the classic settlement formula:

$$Sc = \frac{Cc.H}{1+e0}.log\frac{\sigma 0' + \Delta\sigma}{\sigma 0'} \quad (1)$$

Where Sc represents primary consolidation settlement (m), Cc stand for compression index (dimensionless), depends on soil type, H refers to thickness of the compressible soil layer (m), e0 denotes Initial void ratio of the soil (dimensionless), σ0' correspond to initial effective vertical stress (kN/m² or kPa), and Δσ is an increase in effective vertical stress due to loading (kN/m^2 or kPa).

Table 4. Settlement Recapitulation Based on PVD Depth Variation in Zones A, B, and C

Zone	PVD	Depth	H-initial (m)	H-after unloading (m)	H-Final (m)	Sc (m)
a	Full	34	7.6	4.08	1.40	2.08
	2/3 of depth	23	6.7	4.08	1.40	1.26
	1/3 of depth	11	5.9	4.08	1.40	0.46
b	Full	35	7.7	4.08	1.40	2.26
	2/3 of depth	23	6.8	4.08	1.40	1.37
	1/3 of depth	12	6.1	4.08	1.40	0.64
c	Full	39	8.6	4.08	1.40	3.13
	2/3 of depth	26	7.7	4.08	1.40	2.27
	1/3 of depth	13	6.9	4.08	1.40	1.38

The observed parameters include the initial ground height (H-Initial), height after preloading (H-after unloading), final ground height after consolidation (H-Final), and the resulting settlement (Sc).

- Zone 1 (a): With an initial soil height of 7.6 meters, full-depth PVD installation (34 m) resulted in the greatest settlement value of 2.08 m. Shallower installations led to smaller settlements of 1.26 m (two-thirds depth) and 0.64 m (one-third depth).
- Zone 2 (b): Full-depth PVD installation to 35 meters achieved a settlement of 2.26 m, compared to 1.37 m for two-thirds depth and 0.64 m for one-third depth.
- Zone 3 (c): With the greatest initial height of 8.6 meters, full-depth installation resulted in the highest settlement of 3.13 m, while two-thirds and one-third depths produced 2.27 m and 1.38 m, respectively.

These findings confirm that full-depth PVD installation consistently yields the highest settlements, indicating more effective drainage and consolidation in deeper soft layers. The data show a clear trend: as PVD depth increases, settlement increases due to better mobilization of excess pore water pressure at deeper layers. This validates the engineering principle that deeper soft soil layers contribute significantly to total settlement and must be effectively drained. The soft soil stratum is therefore targeted for improvement using Prefabricated Vertical Drains (PVD) combined with preload or vacuum consolidation to accelerate dissipation of excess pore water pressure [15].

4. CONCLUSION

This study has demonstrated that the application of Prefabricated Vertical Drains (PVDs), particularly when installed to full depth, significantly enhances the consolidation performance of soft clay soils in the Container Yard Area of Sunda Kelapa Port. The site investigation revealed that the subsurface profile is dominated by highly compressible organic clay and silt layers, with total thicknesses reaching up to 34–35 meters in Zones 1 and 2, and up to 36 meters in Zone 3. Stratigraphic analysis and analytical settlement simulations showed that full-depth PVD installations resulted in the highest settlements across all zones:

- Zone 1: Settlement of 2.08 m (full depth) compared to 1.26 m (2/3 depth) and 0.64 m (1/3 depth).
- Zone 2: Settlement of 2.26 m (full depth) compared to 1.37 m and 0.64 m.
- Zone 3: Settlement of 3.13 m (full depth) compared to 2.27 m and 1.38 m.

These quantitative findings confirm that full-depth PVDs enable better drainage from deeper compressible layers, accelerating primary consolidation and maximizing settlement. The data also validates the use of PVDs as an effective solution to mitigate long-term settlement risks in port reclamation projects. Additionally, the study highlights the potential benefit of integrating vacuum consolidation techniques to further accelerate pore pressure dissipation and reduce construction timeframes. The performance advantage of full-depth PVDs, particularly in areas with thick marine clay, emphasizes the importance of reaching the bottom of the compressible stratum to ensure uniform and complete ground improvement. The implementation of full-depth PVD systems is therefore strongly recommended for similar soft ground improvement projects, as it enhances consolidation rates, minimizes differential settlement, and contributes to the long-term performance and sustainability of infrastructure. Further research is encouraged to optimize drain spacing, surcharge load configurations, and the integration of hybrid ground improvement methods such as combining PVDs with stone columns or vacuum preloading.

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