Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1139

Innovative Ground Improvement Strategies for Ultra-Soft Soils in Seismically Active Coastal Reclamation Projects: Insights from the Kalibaru Container Terminal, Jakarta

Agus Himawan
PT Promisco Sinergi Indonesia, Bandung, Indonesia, ahimawan@promisco.com
Institut Teknologi Sains Bandung, Indonesia

Tita Kartika Dewi, Vernanda Yunan Hilmi, Andi Kurnia Setiadi Kartawiria
PT Promisco Sinergi Indonesia, Bandung

Jian Chu
Nanyang Technological University, Singapore

Masyhur Irsyam, Hendriyawan
Bandung Institute of Technology, Bandung, Indonesia

Uun Jayasaputra, Arzena Norega
PT Pelabuhan Indonesia (Persero), Jakarta, Indonesia

Ikhsan Budi Prasetyo
PT PP (Persero) Tbk., Jakarta, Indonesia

Marcello Djunaidy
PT Geotekindo, Jakarta, Indonesia

ABSTRACT: The development of the Kalibaru Container Terminal in Jakarta, Indonesia, presents unique geotechnical challenges, as it involves reclamation over ultra-soft and very soft soils with excessive water content (exceeding the liquid limit) and near-zero shear strength. These conditions, combined with seismic risks and long-term settlement concerns, require the adoption of robust, innovative soil improvement techniques to ensure operational safety and sustainability. This study outlines a two-stage soil consolidation approach integrating vacuum preloading and surcharge preloading techniques with Prefabricated Vertical Drains (PVDs) to overcome these challenges. The initial stage employs shallow PVD installation (5–8 meters) alongside vacuum preloading to stabilize the soil from ultra-soft to very soft consistency, enabling the safe deployment of construction equipment. In the second stage, deeper PVDs (17–25 meters) are combined with vacuum and surcharge preloading to meet stringent design criteria for slope stability, liquefaction mitigation, and long-term settlement limits. Hydraulic filling is used for embankment construction, and dynamic compaction and vibroflotation are applied for deep soil compaction, effectively addressing liquefaction risks in seismic events up to magnitude 8.7. This paper provides critical insights from trial preloading studies, including settlement monitoring, pore pressure dissipation trends, and post-improvement evaluations. The results demonstrate significant reductions in water content, increased undrained shear strength, and improved soil stability metrics. The findings underscore the feasibility and effectiveness of multi-phase soil improvement frameworks for mitigating geotechnical risks in ultra-soft soil environments underlain by high seismic activity, with implications for similar coastal infrastructure projects worldwide.

KEYWORDS: Ultra-soft soil, slurry, ground improvement, vacuum and surcharge preloading, prefabricated vertical drains, liquefaction mitigation, coastal reclamation.

1 INTRODUCTION

1.1 *Background*

Reclamation plans at Kalibaru, Jakarta, have been carried out since 2016 on top of a very soft marine clay area. To contain the reclamation material, a sand-bund embankment was built along the southern side, and a breakwater reinforced with a bamboo mattress and piles was constructed on the northern, eastern, and western sides. Marine clay was dredged using a cutter section dredger from the nearby port development project, which formed a slurry pond as illustrated in Figure 1. This project includes reclamation works of ±83 Hectares on top of the slurry pond for container terminal port development.

The dredged material within the reclamation area has surface elevations ranging from −0.6 m to +2.6 m. To achieve the target grade of +4.00 m and accommodate design loads, filling and ground improvement are necessary. The underlying ultra-soft soil, with water content exceeding the liquid limit and shear strength approaching 0 kPa, poses a high risk of slurry instability under direct fill placement. A structurally stable working platform is therefore required before the mobilisation of heavy equipment, such as Prefabricated Vertical Drain (PVD) rigs, to ensure operational safety and stability during subsequent works.

1.2 *General Soil Condition*

The original seabed consists of 10m –20 m-thick marine clay with varying consistency from very soft to medium stiff. Infilled material dredged from the nearby seabed and pumped into the reclamation area has an initial water content exceeding 100% after pumping. In this study, 'ultra-soft soil' is defined based on physical and mechanical properties consistent with slurries. The criteria used include a liquidity index (LI) greater than 1.0, with natural water content (w_n) significantly exceeding the Liquid Limit (1.5 to 2.0 times LL), and an undrained shear strength (S_u) of less than 5 kPa (often approaching 0 kPa). As shown in Figure 2 and Table 1, the dredged material exhibits an initial w_n of up to 153% against a LL of 89%, confirming its viscous, slurry-like state.

Figure 1. Slurry pond area at Kalibaru, Jakarta.

The consistency of the dredged material is assessed using the liquidity index and undrained shear strength values derived from piezocone penetration tests (CPTu), electric cone penetration tests (CPTe), and vane shear tests (VST). The thickness of the ultra-soft soil layer is estimated at 5-8 meters, taking into account historical deposition of dredged material in the area, influenced by self-weight consolidation and sun drying.

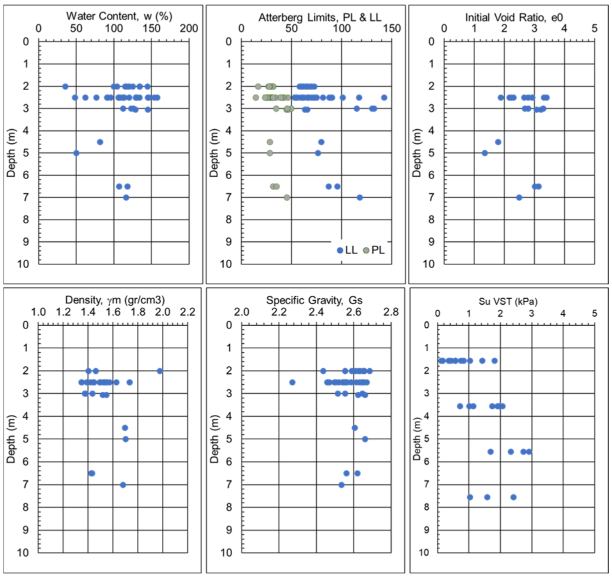

Figure 2. Basic soil properties of ultra-soft soil prior to the first stage vacuum preloading.

Table 1. Basic soil properties of ultra-soft soil prior to the first stage vacuum preloading.

Parameter	Symbol	Value	Unit
Water content	*w*	87 - 153	%
Liquid Limit	*LL*	53 - 89	%
Void ratio	*e*	1.34 – 3.47	-
Specific Gravity	*Gs*	2.27 – 2.69	-

2 DESIGN CONCEPT

The project adopts a two-stage consolidation acceleration approach combining vacuum preloading and surcharge preloading for ground improvement. In the first stage, vacuum preloading is implemented using short Prefabricated Vertical Drains (PVDs) installed to depths of less than 8 m, to reduce the water content of the ultra-soft soil to a very soft consistency and attain sufficient shear strength to support a working platform for the subsequent stage. Only limited consolidation is required during this phase.

The second stage integrates vacuum and surcharge preloading with PVD installed at depths of 17 to 25 meters to increase soil strength and stiffness, accommodating estimated loads of 32 kPa for the inner port road and 82 kPa for the container yard. To guarantee sustained performance, the maximum allowable settlements are designated as 10 cm within one year, 20 cm within ten years, and 30 cm within fifty years.

The PVD spacing of 1.0 m in a square pattern was selected to balance consolidation speed and smear minimization. While closer spacing theoretically accelerates consolidation, in ultra-soft soils, the installation mandrel can cause significant disturbance (smear), reducing the horizontal coefficient of consolidation (c_h). Analytical modeling indicated that a 1.0 m spacing provided the optimal trade-off to achieve the target 90% degree of consolidation within the constrained 6-month timeline.

Reclamation fill is designed utilizing the hydraulic filling method, incorporating deep compaction to mitigate the liquefaction hazard associated with a magnitude of 8.7. A site-specific seismic response analysis is performed to determine the peak ground acceleration at the surface (PGA_M), which is subsequently used to establish the target cone penetration resistance (q_c) from Cone Penetration Test (CPT) data. This target q_c serves as the verification criterion for assessing the effectiveness of the deep compaction process.

3 FIRST STAGE GROUND IMPROVEMENT

The objective of this stage was to reduce the water content of the slurry-dredge material with a 5-8 meter thickness to attain a liquidity index exceeding 1 and an undrained shear strength exceeding 5 kPa, signifying a transition in soil consistency from an ultra-soft to a very soft state. The vacuum preloading was implemented using short PVD.

The short PVD installation in this first stage is carried out using a lightweight PVD rig on top of five layers of a bamboo mattress, which also serves as basal reinforcement to enhance bearing capacity and stability during the subsequent stage. The short PVD is installed in a grid pattern with 1 meter spacing, using a lightweight rig as shown in Figure 3.

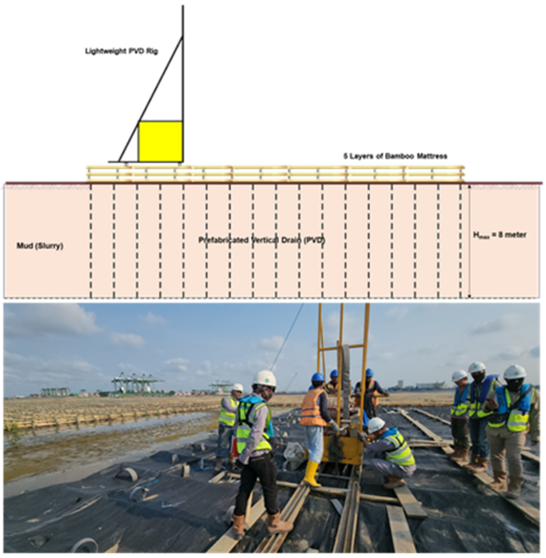

Figure 3. Short PVD installation above ultra-soft soil layer.

The tops of PVDs were linked to a wire-hose perforated horizontal drain (PHD) and a four-sided connector, which in turn connected to the vacuum pump. The entire area was secured with two layers of geomembrane and nonwoven geotextile, with the perimeter sealed in a ditch to prevent leakage of vacuum pressure.

3.1 *Trial Vacuum Preloading (VP)*

To ensure the effectiveness of the first stage of ground improvement, a trial vacuum preloading (trial VP) is conducted in an area of 25 m x 25 m within the project, with PVDs installed to a depth of 7 meters (Figure 4). According to Ang et al. (2019), a case study in Singapore indicates that the reduction of water content from slurry state to the liquid limit was projected to occur after 54 days of vacuum preloading. During the trial, a VP of 70 kPa was applied for a minimum of 60 days.

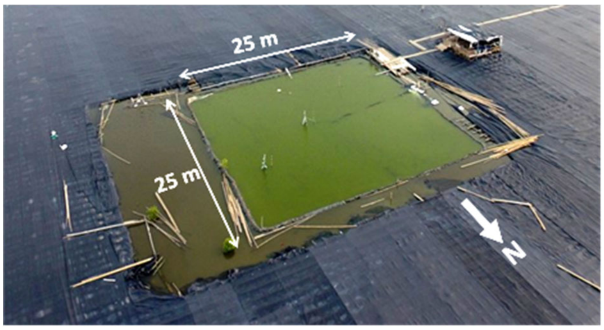

Figure 4. Trial vacuum preloading area.

Figure 5 shows settlement plate monitoring results during the trial VP period of 66 days. The average final settlement across three settlement plates at the end of vacuum consolidation is 914 mm, and the average vacuum pressure was maintained at 82 kPa, indicating that the vacuum system functioned effectively.

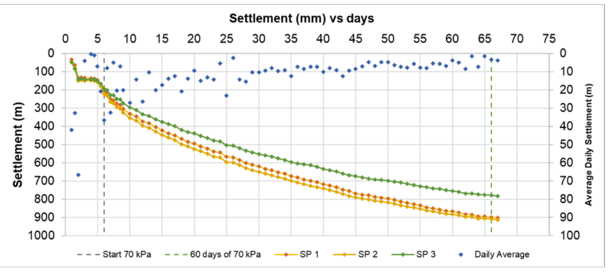

Figure 5. Settlement plate monitoring results during trial VP.

Undrained shear strength from pre- and post-trial VP, VST, and water content test results is shown in Figure 6. From the ground surface to a depth of 4 m, the rate of pore pressure dissipation was relatively low, indicating weaker drainage capacity or reduced vacuum efficiency within the upper soft layer. Correspondingly, the increase in undrained shear strength (S_u) was minimal, and the reduction in water content was also limited, suggesting that consolidation in this zone was not substantial. In contrast, the 4–7 m depth interval exhibited a more noticeable reduction in pore pressure, reflecting more effective transmission of vacuum pressure. This zone also demonstrated a better increase in S_u and a more substantial decrease in water content, indicating more efficient consolidation and dewatering at these depths. The primary cause is likely the variation in pore water pressure reduction during the trial period. In the upper layer, the decrease in pore water pressure caused by suction from the hydrostatic condition progresses more slowly than in the deeper layer. The discrepancy in pore pressure dissipation between the upper (0–4 m) and deeper (4–7 m) layers can be attributed to the formation of a 'smear zone' and to clogging of the PVD filter sleeve. The ultra-soft slurry, having a high fine-grain content, tends to migrate into the PVD filter under high vacuum pressure, creating a cake layer that reduces permeability at the soil-drain interface (Wang et al., 2020; Zhou et al., 2021). This phenomenon restricts the vacuum propagation in the upper layer where the soil is most fluid. In contrast, the deeper layers, influenced by self-weight consolidation before improvement, exhibited higher stiffness and less particle migration, allowing for more effective vacuum transmission

3.2 *Implementation of the first stage ground improvement*

Following the effectiveness of the trial VP, the 1st stage of ground improvement works was subsequently continued. In certain areas on the southern side, initial vacuum preloading was unnecessary. The desiccated dredged material in this area had dried due to sunlight exposure and surface drainage, rendering the soil sufficiently strong to support the construction load. A load test using a water tank was conducted to assess the surface strength of the dredged slurry material. Based on the test results, a zonation scheme was developed to delineate areas requiring initial vacuum preloading improvement, particularly those exhibiting ultra-soft characteristics, including high water content and low undrained shear strength. The area identified as not necessitating initial vacuum preloading and the dredge material condition before ground improvement are shown in Figure 7 and Figure 8.

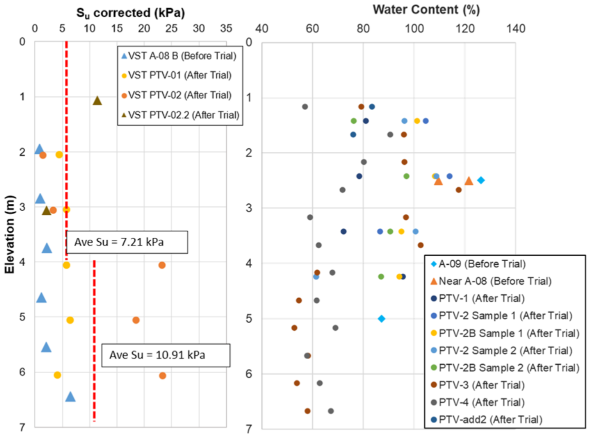

Figure 6. Undrained shear strength and water content before and after the trial VP.

For an area of approximately 73 hectares, the 1st stage of ground improvement was completed in less than nine months. The construction is divided into 18 zones of ground improvement to optimize the applied vacuum pressure during PVD installation at a depth of 5–8 meters (Figure 9). However, the bamboo mattress was installed across the entire 83-hectare area, functioning both as a working platform and as basal reinforcement. Figure 10 shows the implementation of the 1st stage of ground improvement.

Similar to the trial VP area, various monitoring instruments, including settlement plates, vacuum gauges, and piezometers, were installed. After 60 days of vacuum preloading, post-improvement tests—comprising CPTu, VST, and undisturbed soil (UDS) sampling—were performed to evaluate the increase in undrained shear strength and the decrease in water content.

The measured settlements ranged from 0.63 m to 1.87 m, accompanied by increases in undrained shear strength to values exceeding 5 kPa. A comparison of undrained shear strength improvements for Zones 1 to 3 is presented in Figure 11. Overall, the results of the first stage exhibit a trend consistent with the trial vacuum preloading outcomes, in which Stage 1 ground improvement was more effective at depths greater than 4 m.

Figure 7. The area identified as not necessitating intial vacuum preloading.

Figure 8. The dredge material condition prior to ground improvement.

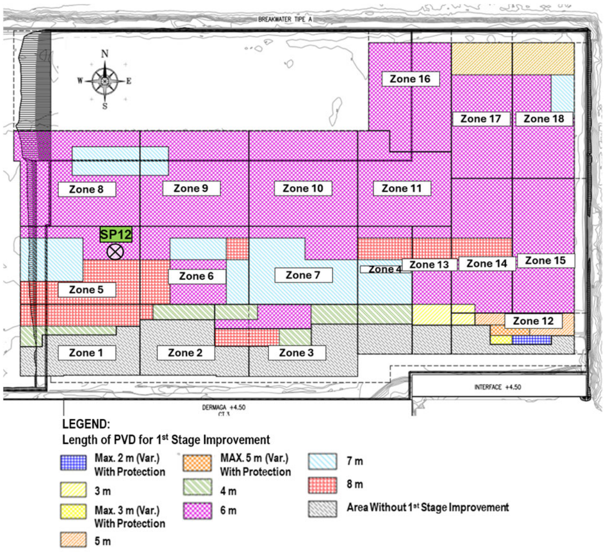

Figure 9. Sub zones of the 1st stage ground improvement.

4 SECOND-STAGE OF GROUND IMPROVEMENT

The next stage of ground improvement commenced with the placement of a 1-meter-thick platform layer, serving as the initial working surface for PVD installation. The successful completion of platform filling and PVD installation, without bearing failures or slurry bursting, confirms the effectiveness of the 1st stage of ground improvement in mitigating construction risks on ultra-soft soil.

Figure 10. Implementation of the 1st stage of ground improvement.

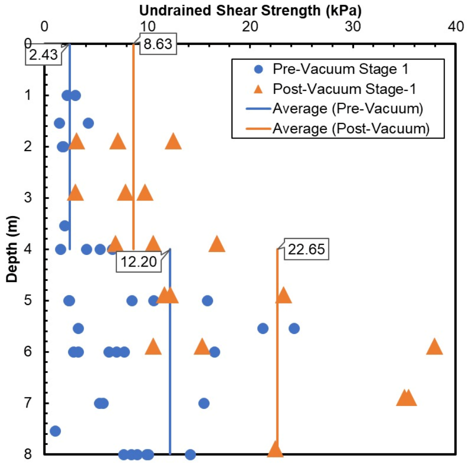

Figure 11. Undrained shear strength before and after the 1st stage of ground improvement.

The 2nd-stage vacuum system was implemented across the entire reclamation area, maintaining a minimum vacuum pressure of 70 kPa and employing surcharge preloading with a thickness of 4-14 m. In the southern section, a 1 m-wide sealing wall was constructed to prevent vacuum pressure losses associated with the underlying sand bund layer (Figure 12). Reclamation fill was placed using the hydraulic filling method, with each stage limited to a maximum height of 3 m. Embankment levelling was carried out using multiple bulldozers, shaping boundary slopes at a 1V:2.5H gradient. The second-stage ground improvement was applied for a minimum duration of 180 to 220 days (Figure 13).

During the 2nd stage of ground improvement, a comprehensive monitoring program was implemented, incorporating settlement plates, vacuum gauges, piezometers, extensometers, and inclinometers. The instrumentation layout comprised one settlement plate and five vacuum gauges for every 0.25 ha, vibrating wire piezometers for every 20 ha, and extensometers for every 10 ha. Inclinometers were installed at 200 m intervals along the toe of the embankment slope.

However, the hydraulic filling method posed a significant challenge to instrument protection. During the filling process, several piezometer and extensometer cables were damaged and could not be repaired, resulting in unreliable pore water pressure (PWP) data.

Figure 12. Implementation of the second-stage vacuum preloading.

Figure 13. Hydraulic filling for embankment and surcharge preloading.

4.1 *Limitations of Monitoring Data*

A critical limitation encountered during the second stage was damage to vibrating-wire piezometers caused by the hydraulic filling process. This resulted in a lack of direct Pore Water Pressure (PWP) data to verify the end of primary consolidation. Consequently, the verification of ground improvement relied heavily on settlement data extrapolation (Asaoka and Chin-Kondner methods) and CPTu verification. While settlement-based methods proved robust (as shown by the convergence of the prediction models in Figure 14), the absence of PWP confirmation underscores the need for more robust instrument protection strategies—such as wireless transmission or protective conduits—in future hydraulic fill projects.

In addition, a complete Loading Trial Embankment at the final grade elevation, simulating the design loads of 32 kPa and 82 kPa, could be performed to verify that residual settlement remains within the allowable post-construction settlement criteria.

Settlement plate measurements across the entire area indicated settlement magnitudes ranging from 2.6 m to 4.9 m. To assess the completion of the ground improvement works, the monitoring data were evaluated against the defined completion criterion, which specified a Degree of Consolidation (DOC) of at least 90%.

Figure 14 presents an example of total settlement estimation at SP12 using three methods: Asaoka (1978), Chin–Kondner, and Decourt extrapolation. The Asaoka method predicts a final settlement of 4.68 m with a Degree of Consolidation (DOC) of 91.6%, whereas both the Chin–Kondner and Decourt methods estimate 4.42 m with a DOC of 97%. The close agreement among these methods validates the observed settlement data and confirms that the majority of consolidation has been completed. These analytical approaches are also helpful for forecasting remaining settlement and determining the need for additional preloading.

Post-construction settlement (PCS), estimated from vacuum preloading and operational load modelling, was 6.0 cm, 11.0 cm, and 14.0 cm at 1, 10, and 50 years, respectively—within allowable PCS limits. The actual consolidation period of 220–285 days exceeded the target of 180–220 days.

The post-treatment soil investigation results, as presented in Figure 15, demonstrate consistent improvement following ground treatment. Post-test data indicate a general reduction in water content, reflecting the effectiveness of consolidation and dewatering. Only minor variations in the Atterberg limits (LL and PL) were observed, indicating that the soil classification remained unchanged while its physical properties improved under vacuum and surcharge preloading. Correspondingly, undrained shear strength (Su) measured from Vane Shear Tests increased substantially after treatment, particularly within the upper 15 m, validating the effectiveness of the combined vacuum and surcharge preloading in improving soft soil conditions.

To mitigate liquefaction risk in the hydraulic-filled sand embankment material under the design earthquake magnitude of 8.7, the deep compaction using vibroflotation and dynamic compaction was adopted. Dynamic compaction was executed using 25–32-ton tampers dropped from 17 m, with a 4 m grid spacing in two phases totaling 11 drops (Figure 16). Site-specific seismic response analysis (SSRA) determined a design surface acceleration of 0.43 g, corresponding to a target CPT cone resistance (qc) of 12.5–16 MPa below the groundwater table (up to 8 m depth) and up to 6 MPa within the upper 3 m for bearing capacity requirements. An example of CPT results at Panel 55 (Figure 17) shows substantial QC gains, especially within the 0 to −3 m depth range, exceeding target thresholds and indicating improved density and strength.

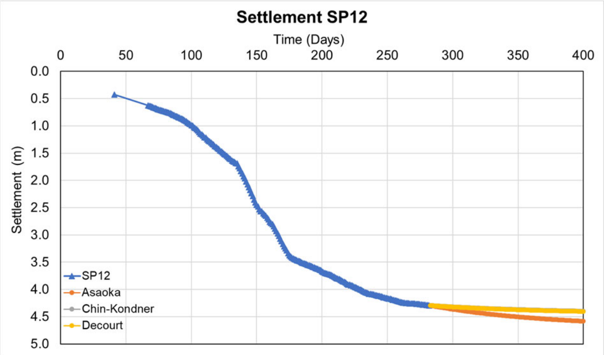

Figure 14. Estimation of total settlement using Chin-Kondner, Decourt Extrapolation, and Asaoka Method.

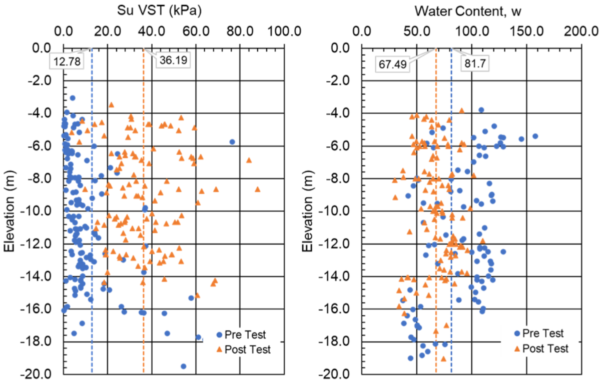

Figure 15. Post-soil investigation result of the 2nd stage of ground improvement.

5 CONCLUSIONS

The two-stage ground improvement program implemented at the Kalibaru Project proved highly effective for treating ultra-soft to very soft soils in a seismic coastal reclamation environment where conventional direct filling was not feasible. The trial vacuum preloading demonstrated depth-dependent performance, with greater pore pressure dissipation, undrained shear strength gain, and water content reduction at 4–7 m depth, validating the method's consolidation potential. Stage 1 vacuum preloading, applied with short PVDs, successfully improved slurry consistency to Su ≥ 5 kPa and enabled safe platform construction across 83 ha, with settlements of 0.63–1.87 m. Stage 2, combining deep PVDs, vacuum, and surcharge preloading, achieved settlements of 2.6–4.9 m, a Degree of Consolidation (DOC) above 90%, reduced void ratio and water content, and substantial Su increases, particularly within the upper 15 m. The deep compaction, using dynamic compaction and vibroflotation, of the hydraulic fill sand embankment further mitigated liquefaction risk for the design earthquake (Mw 8.7), with CPT results exceeding qc targets and indicating a shift toward denser, less compressible soil behavior types. Collectively, these results confirm that the dual-stage vacuum–surcharge preloading strategy, complemented by deep compaction on the hydraulic fill sand embankment, is a robust and effective solution for ground improvement in ultra-soft, seismically active reclamation sites.

(a)

(b)

Figure 16. (a) Vibroflotation (b) Dynamic compaction using 25-32 ton tampers.

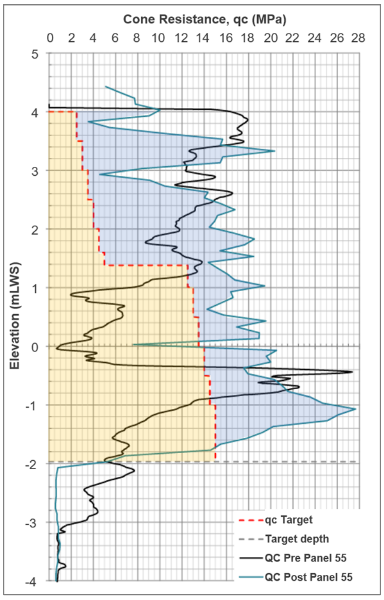

Figure 17. Pre- and post-dynamic compaction CPT.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge PT PP (Persero) Tbk. and PT Pelabuhan Indonesia (Persero) for their invaluable support throughout this research. Appreciation is also extended to PT Promisco Sinergi Indonesia and PT Geotekindo for providing essential resources, data, and technical information that contributed significantly to the completion of this study.

7 REFERENCES

Asaoka, A (1978). Observational procedure of settlement prediction. Soils and Foundations, 18(4): 87–101.

Anda, Rila. et. Al. (2020). Effects of pressurizing timing on air booster vacuum consolidation of dredged slurry. Geotextiles and Geomembranes, 48 (2020): 491-503.

Ang, B., Seet, A. and Chu, J. (2019). Slurry clay as infill material for land reclamation in Singapore. Proceeding of International Conference on Case Histories & Soil Properties, 5 – 6 December 2019. Geotechnical Society of Singapore, Singapore.

Bergado, Dennes T. et. al. (2022). Case study and numerical simulation of PVD improved soft Bangkok clay with surcharge and vacuum preloading using a modified air-water separation system. Geotextiles and Geomembranes, 50 (2022): 137-153.

Chu, J. and Yang, S.W. (2005). Estimation of degree of consolidation for vacuum preloading projects. International Journal of Geomechanics, ASCE, Vol. 5, No, 2, 158-165.

Wang, P. et. al (2020). Apparent clogging effect in vacuum-induced consolidation of dredged soil with prefabricated vertical drains. Geotextile and Geomembrane 38 (2020) 524-531.

Zhou, Y. et. al (2021). Analytical Solution on Vacuum Consolidation of Dredged Slurry Considering Clogging Effects. Geotextile and Geomembrane 49 (2021) 842-851.