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Vacuum-PVD improvement of reclaimed deep excavation pits filled with soft clay lumps

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ABSTRACT: Improvements to settling of soft clay lumps in landfill were investigated using the Vacuum Consolidation Method (VCM) with surcharge loading applied to clay lumps deposited in deep ponds (15–20 m) for housing development. Unlike naturally deposited clays, soft clay lumps are heterogeneous and highly compressible, making settlement predictions challenging. VCM is used widely with natural soft clays but rarely with soft clay lumps in reclaimed or backfilled areas. Thus, site monitoring data were collected and used for back-analysis. The coefficient of horizontal consolidation (C_h) is a crucial parameter; however, existing values are based on naturally deposited layers. The obtained C_h values for soft clay lumps were in the range 1.39–4.13 m^2/year. Furthermore, the study proposed a new empirical approach for calculating settlement in soft clay lumps improved by applying the VCM, estimating that settlement at a 90% degree of consolidation corresponds to 4%–9% of the prefabricated vertical drain installation depth. This finding should enable more accurate pre-construction predictions by improving existing knowledge, as previous equations have been appliable only to naturally deposited clays. Overall, the research should contribute to the planning and design of soft ground improvement projects involving reclaimed or backfilled soft clay lumps.

KEYWORDS: Geosynthetics, Vacuum consolidation method, Soft clay lumps, prefabricated vertical drain, Coefficient of horizontal consolidation, UN SDG 9: Industry, innovation and infrastructure, Ground improvement, Site investigation

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1. INTRODUCTION

From the 1980 s to the 1990 s, Bangkok, the capital city of Thailand, experienced rapid urban expansion, leading to a substantial demand for backfill material to reclaim lowland areas for construction. Several large excavation pits in the outskirts of Bangkok, often 15–20 m deep, were later abandoned and filled with stormwater, forming large lakes. With increasing land prices, these areas have become targets for reclamation and residential development (Anantsuksomsri and Tontisirin 2015; Vichiensan *et al*. 2023; Pongprasert and Benjaanunphong 2025). However, conventional backfill materials, such as inland rock and local sand, are costly and limited in availability (Wang *et al*. 2021).

Using soft clay lumps from the soil excavated in a nearby quarry is considered a practical and cost-effective approach. Despite the geotechnical challenges, these materials are considered a viable alternative for land reclamation. Several studies have examined the consolidation behaviour of clay lumps for land reclamation, highlighting that a clay lump is unlike homogenous natural soil. For example, soft clay lumps exhibit complex settlement behaviour due to their intra- and inter-granular porosity, high compressibility, and heterogeneous composition (Yang *et al.* 2002; Robinson *et al.* 2005; Yang and Tan 2005; Juneja and Chafale 2019). Soft clay lumps have a rapid initial rate of consolidation, which is primarily attributed to the expulsion of water from the voids between the lumps, known as inter-lump voids. During the early stages of loading, these relatively large voids allow water to drain quickly, resulting in a high initial settlement rate. As the inter-lump voids close under load, there is a considerable reduction in the rate of consolidation because the primary mechanism of consolidation (the expulsion of water) diminishes as the clay lumps become more compacted. Once the larger voids are compressed, drainage paths become less effective and further consolidation must occur within the lumps themselves (intra-lump), which is a much slower process due to lower permeability (Li *et al.* 2011).

Consequently, excessive settlement—both short- and long-term—can be substantial in clay lump fill due to the intra- and inter-granular porosity, compressibility, and heterogeneity of the material and these issues could damage road, pavement, and building assets. Additionally, backfilling must be performed while the pond remains fully inundated, as water drawdown could trigger land movement along the lake's boundary, posing risks to adjacent infrastructure. Furthermore, dumping soft clay lumps directly into water results in a highly saturated, non-uniform soil mass with unpredictable properties. Due to this issue, these inter-lump voids are expected to be filled with water and generate excess pore water pressures during dumping (Phakdimek and Soralump 2018). Furthermore, it can be challenging to deduce the settlement rate based on pore-pressure dissipation alone due to the large difference between the permeability of the lumps and the slurry (Federico *et al.* 2015). Often, these lumps are suspended in clay slurry, which makes their response analysis somewhat complex because the strains in the two soil states (solid and slurry) are not the same (Shi and Herle 2016). Thus, the behaviour of soft clay lumps is uncertain because of non-uniformity in their properties. The behaviour of excess pore water pressure dissipation is rather complicated and can cause substantial and long-term settlements. Despite these challenges, the economic feasibility of using clay lumps for backfilling makes it a viable option, provided that effective ground improvement techniques are implemented. Preloading is one of the most effective ground improvement techniques for mitigating excessive settlement and enhancing the strength of soft clay soils.

Currently, preloading is widely applied in ground improvement projects involving soft clay, particularly through the use of the Vacuum Consolidation Method (VCM) combined with Prefabricated Vertical Drains (PVDs). Originally, the use of conventional PVDs was proposed in 1952 by Kjellman (1952) and has since been studied and developed continuously. Surcharge preloading remains one of the most widely adopted techniques due to its effectiveness in reducing the consolidation time by shortening the drainage path and facilitating more efficient water flow toward permeable drainage layers. In particular, the vacuum-PVD technique is advantageous due to its faster consolidation performance, less lateral displacement, environmental compatibility, and cost efficiency, making it effective from both geotechnical engineering and construction management perspectives. This method accelerates the consolidation process by applying vacuum pressure to reduce pore water pressure and increase effective stress without requiring additional surcharge loading (Chai *et al.* 2005, 2006, 2008, 2013, 2020; Indraratna *et al.* 2005, 2010a, 2012; Cai *et al.* 2018; Hayashi *et al.* 2021; Zhang *et al.* 2021; Zhou *et al.* 2022; Soralump *et al.* 2024). This ground improvement technique using PVDs with VCM has been adopted successfully in infrastructure projects throughout Asia and other parts of the world. In Thailand, it has been applied in large-scale developments such as the Suvarnabhumi International Airport and major highway construction projects (Balasubramaniam *et al.* 1995; Bergado *et al.* 1998, 1999; 2002; Balasubramaniam *et al.* 2005; Abuel-Naga *et al.* 2015; Bergado *et al.* 2021, 2022).

The VCM (involving vacuum preloading) uses atmospheric pressure as a temporary surcharge. Vacuum preloading combined with PVDs and the soil surcharge load can shorten the consolidation period considerably (Chu *et al.* 2000; Chai *et al.* 2005; Yan and Chu 2005). Vacuum consolidation preloads the soil by reducing the pore pressure with constant total stress instead of increasing the total stress. The effective stress increases by reducing the pore water pressure in the soil mass. The height of the surcharge load can be reduced by several metres if a vacuum pressure of at least 70% of the atmospheric pressure is applied and sustained (Rujikiatkamjorn *et al.* 2008; López-Acosta *et al.* 2019; Alditra *et al.* 2020; Phakdimek *et al.* 2020). When the soil has densified or gained greater stiffness and strength through consolidation, the settlement from post-construction will be greatly reduced, thereby eliminating any risk of differential settlement. In Thailand, soil surcharge preloading with PVD has been applied in several large infrastructure projects, such as the Suvarnabhumi Airport (Second Bangkok International Airport; SBIA) (Balasubramaniam *et al.* 1995; Bergado *et al.* 2002) and the Second Bangkok Chonburi Highway Project (Bergado *et al.* 1999). Vacuum preloading was first implemented in a trial area in Thailand in the SBIA Project by Bergado *et al.* 1998, where the method was applied to improve very soft-to-soft clay layers beneath the proposed site of a test track facility at the Asia Industrial Estate. Two decades later, VCM was applied successfully, again on Bangkok soft clay, as a part of the runway extension project at SBIA (Bergado *et al.* 2021, 2022, 2024a, 2024b). In addition, other South-east Asian countries with widespread soft clay deposits have adopted the VCM for infrastructure development. Notable examples include the Cai Mep International Terminal (CMIT), the North-South Expressway (NSEW), and the PM3-Ca Mau (PM3-CM) projects in Vietnam (Long *et al.* 2013). Numerous case studies have documented the successful application of VCM to improve naturally deposited soft clays. However, its use in deep excavation pits and reclaim areas, particularly those involving soft clay lumps, remains relatively rare in practice and the published literature.

However, research on the use of VCM for improving soft clay lump fills in deep excavation pits remains scarce. This gap raises essential questions about the potential challenges and methods for improving non-natural deposit soil conditions using VCM. Typically, empirical guidelines and consolidation parameters are available for naturally deposited clay layers; however, they are inadequate for the accurate prediction of settlement in areas containing soft clay lumps. Therefore, the current research aimed to address this gap by providing practical guidelines for the estimation of settlement, utilizing the back analysis of consolidation parameters from field data collected at 4 sites, where VCM was applied to soft clay lumps in deep excavated pits.

This paper considers VCM to improve the soft clay lumps in deep excavation pits full of water. Improvements in behaviour and effectiveness were investigated by analyzing field instrumentation data on settlement and pore water pressure, assessing the evolution of soil properties before and after improvement, and empirical correlation development for settlement estimation. The findings provide practical insights and design guidance for applying VCM to heterogeneous fill materials in deep excavated pits full of water, contributing to sustainable land reclamation practices in Thailand and similar environments.

2. SOFT CLAY LUMPS CHARACTERISTIC AND SITE CONDITION

Several abandoned ponds located in Bangkok are being used for building assets whose boundaries are indicated in red in Figure 1. Field observations were made at four housing projects in Bangkok—Burasiri Watcharapol (BPW), Noble Wisdom (NOBLE), Burasiri Panyaindra (BPI), and Narasiri&Setthasiri (NSR&SSR)—each containing approximately 16.00 to 20.00 m thick soft clay lump layers within deep excavation pits or lakes, as shown in Figure 2. The land reclamation process began by filling soft clay lumps into a pond without pumping the dewatering, followed by VCM to accelerate the consolidation and improve shear strength. The construction durations and lake characteristics, and details of the land reclamation and ground improvement processes at each location are summarized in Table 1.

The soil investigations conducted at each site prior to VCM application identified a 1.50 m-thick top crust overlying a very soft to medium silty clay (the soft clay lumps layer), extending approximately 18.50 m below the ground surface. Underneath the medium clay, there was greyish-brown stiff clay from depths in the range 18.50–22.00 m, below which there was brown, medium dense silty sand. The site's soft clay lumps profile and properties are plotted in Figure 3.

The soft clay lumps consisted of very soft to soft high-plasticity clay (CH) from 0.00–18.50 m depth with an average undrained shear strength of 13.00 kPa, a unit weight of 16 kN/m^3, a water content of 76.24%, a compression index (C_c) of 0.40–1.00, a pre-consolidation pressure (P_c) of 10–100 kPa, and a void ratio of 1.00–3.00 as determined following (ASTM D2166-24, ASTM D2487-25) standards. The findings from the soil investigation revealed that the compression index and void

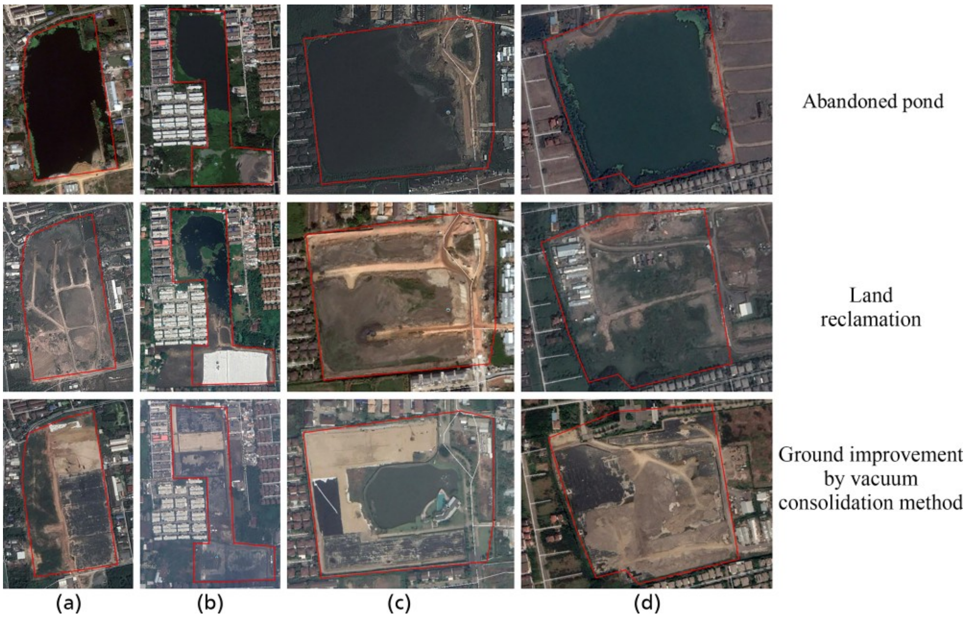


Figure 1. Reclamation and ground improvement process layout (a) BPW site (b) NOBLE site (c) BPI site (d) NSR & SSR site

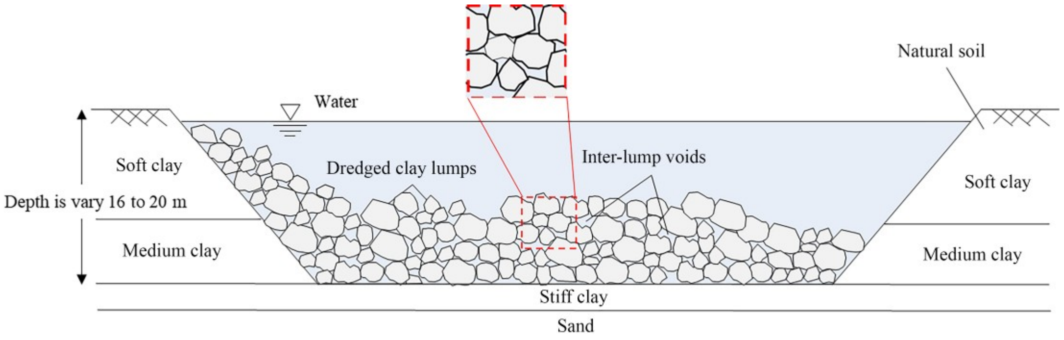


Figure 2. Schematic profile of reclaimed large excavation pit filled with soft clay lumps

Table 1. The construction durations and lake characteristics

		Site			
	Description	BPW	NOBLE	BPI	NSR&sSR
Land Reclamation process	Backfill Year	2014	2018	2013	2018
	Year of VCM	2017	2019	2018	2020
	Self-consolidation period	3 years	1 year	5 years	2 years
Lake or pond characteristics	Depth of pond	20 m	15 m	22 m	22 m
	Area of pond	73 452 m^2	25 886 m^2	27 393 m^2	70 507 m^2
	Site location	Bangkok, Thailand			

ratios were higher than those of naturally deposited clay layers. Conversely, the undrained shear strengths and pre-consolidation pressures are lower than those of naturally deposited clay layers and did not increase with depth.

To further quantify the heterogeneity of the soft clay lumps, a statistical analysis was performed on the geotechnical parameters. The results showed that the unit weight exhibited a relatively low standard deviation of 0.87 and a coefficient of variation (COV) of 5.22%, indicating minor variation in density. In contrast, undrained shear strength (S_u) showed substantial spatial variability, with a standard deviation of 8.83 kPa and a COV of 50.01%, suggesting significant strength heterogeneity. Water content and initial void ratio (e_0) displayed moderate variability (COV of 20.49% and 22.53%, respectively), C_c and P_c exhibited high variability (COV of 34.00% and 43.36%, respectively). These results confirm that the soft clay lumps are highly heterogeneous materials, likely resulting from the random nature of excavation and backfilling processes during reclamation as illustrated in Figure 4. This heterogeneity can strongly influence consolidation behaviour, settlement response, and interpretation of back-calculated parameters.

Additionally, the high values for the water content, void ratio, and compression index, and low shear strength suggested that the properties of the soft clay itself could pose problems in housing estate construction. In addition to these unfavorable soil properties, the collapse of inter-lump voids within the clay lumps contributed to large amounts of settlement, further complicating ground improvement conditions.

3. PROBLEMATIC SOFT CLAY LUMPS USING THE CONVENTIONAL PRELOADING METHOD

Soft clay lumps obtained from dredging and excavation can be reused for land reclamation projects, providing both economic and environmental benefits. When these clay lumps are placed in water, they form a matrix consisting of the clay lumps and inter lump voids. The collapse of the inter lump voids can lead to large amounts of settlement and needs to be overcome before the site is suitable for house construction. One kind of settlement is caused by the collapse of the inter-lump voids that include: (1) large settlement due to the closure of inter-lump voids, (2) primary consolidation, and (3) secondary settlement or creep, which involves the fusing of clay within both inter-lump and intra-lump structures. Preloading is an effective method for reducing the inter-lump voids and accelerating consolidation settlement. To confirm the effectiveness of preloading on soft clay lumps, the current study applied both centrifuge testing and a full-scale trial site with conventional preloading. Figure 5 presents the conditions of the soft clay lumps before and after preloading in the centrifuge test. Based on the results, the inter lump voids were closed and settlement occurred suddenly during the initial stage, consistent with the findings from other studies (Leung *et al.* 2001; Karthikeyan *et al.* 2004; Li *et al.* 2011; Kostkanová *et al.* 2014). Based on the centrifuge testing, preloading was an applicable method for reducing settlement in soft clay lumps before construction. On the other hand, at the trial site, when conventional preloading using surcharge loading was applied, there was a problem of soft clay lumps throughout the site

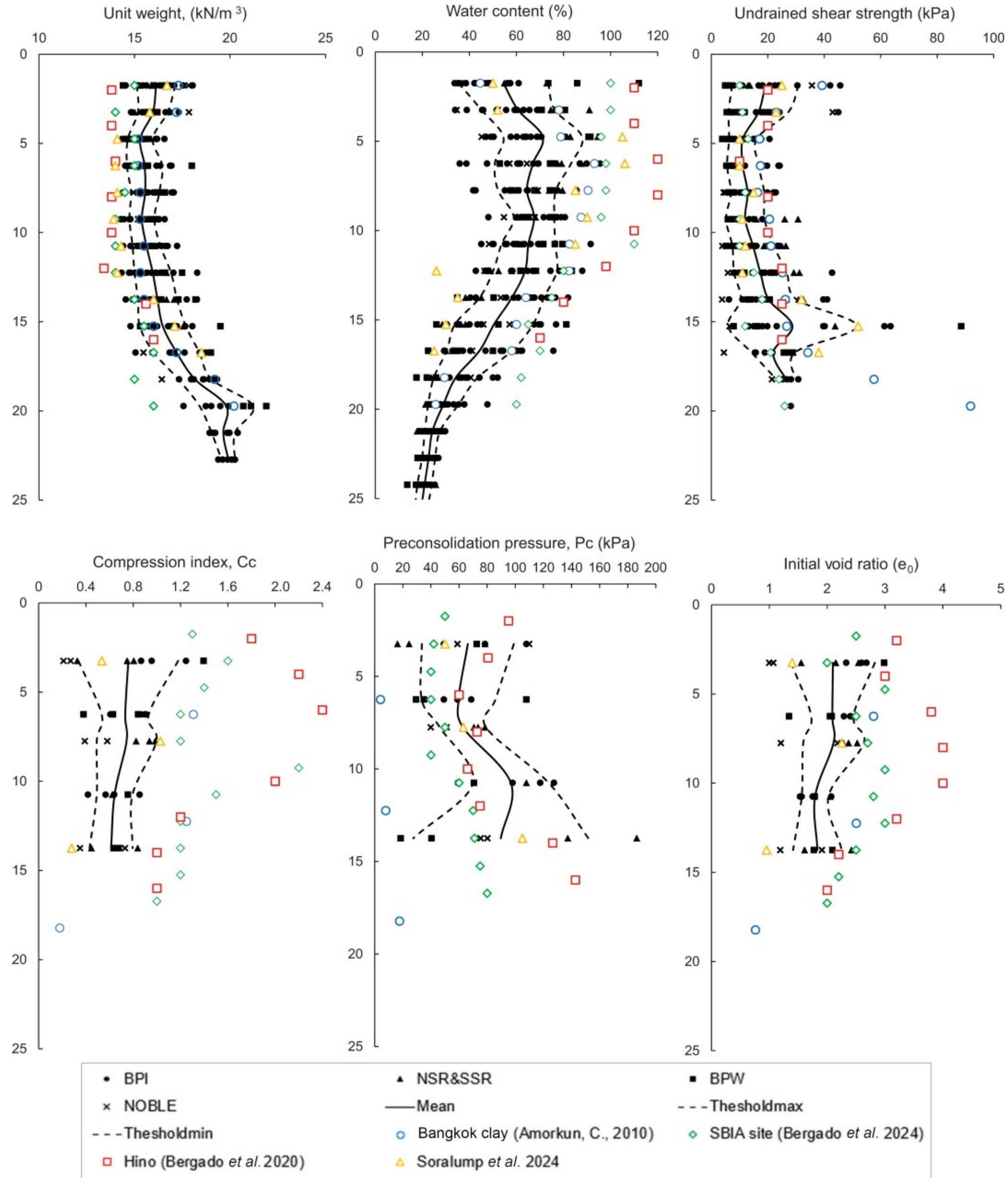


Figure 3. Properties of soft clay lumps and natural soft Bangkok clay

Figure 4. Heterogenous soft clay lump layer collected from bore hole

monitoring and in the observation data, as shown in Figures 6 and 7, respectively. The applied surcharge load induced a distribution of shear stress within the soft clay lump layer, where the shear stress exceeded the shear strength of soft clay lump. This stress imbalance led to lateral deformation in the form of shear flow. There was great deformation in the settlement pattern along the edges of the embankment compared to its centre, indicating lateral displacement. This was accompanied by surface cracking, as shown in Figure 6. Figure 7 shows that the excess pore water pressure increased slightly due to the surcharge. However, it dissipated gradually and the dissipation rate was sluggish because of low permeability and a very long drainage path in the underlying soft clay lump layer. Nevertheless, the excess pore water pressure at 18.00 m dissipated quickly because the piezometer was installed near the sand layer with high permeability. This sand


(a) (b)

Figure 5. Soft clay lumps with 20 kPa loading during centrifuge test (a) Before test and (b) After test

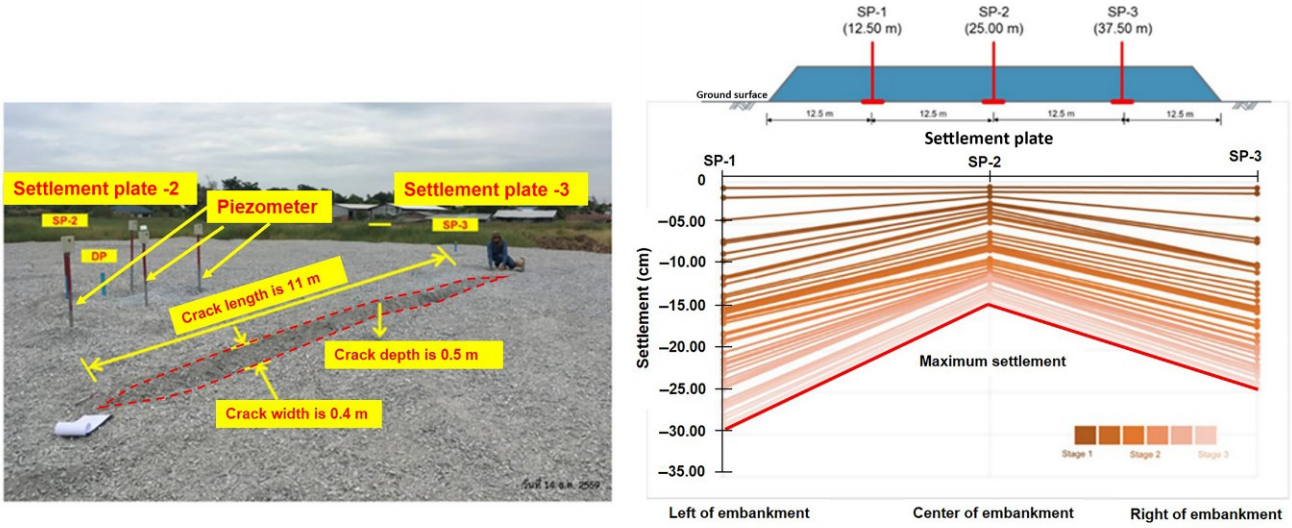


Figure 6. Cracks generated by shear flow and differential settlements at trial conventional preloading site

layer was affected by the excessive groundwater pumping in the past, which led to the piezometer drawdown in this layer.

Based on the issues discussed above, the conventional preloading method may adversely affect nearby housing construction areas, as the surcharge load induces lateral displacement in the underlying soft clay lumps, potentially causing structural damage to nearby buildings. In addition, this lateral movement hinders the effectiveness of ground improvement, as the soft clay lump layer cannot consolidate uniformly and effectively. Analysis of instrumentation data from the trial site revealed excessive settlement, considerable lateral displacement, and a slow rate of pore water pressure dissipation. These issues could be attributed primarily to the compression of the saturated inter-lump voids and the soft clay lumps themselves. Consequently, the conventional preloading method is not applicable for improving soft clay lumps. This challenge was addressed by implementing PVDs combined with the VCM. This approach, commonly referred to as the Vacuum-PVD method, has been identified as a more appropriate ground-improvement technique for land reclamation involving problematic soft clay lump soils. It effectively accelerates consolidation and mitigates lateral displacement. Notably, the application of vacuum pressure in the VCM induces inward lateral displacement into the improvement area, thereby counteracting the outward movement typically observed in conventional preloading methods (Chai *et al*. 2006; Chai *et al*. 2013; Indraratna *et al*. 2010a 2010b; Koirala *et al*. 2022; Soralump *et al*. 2024).

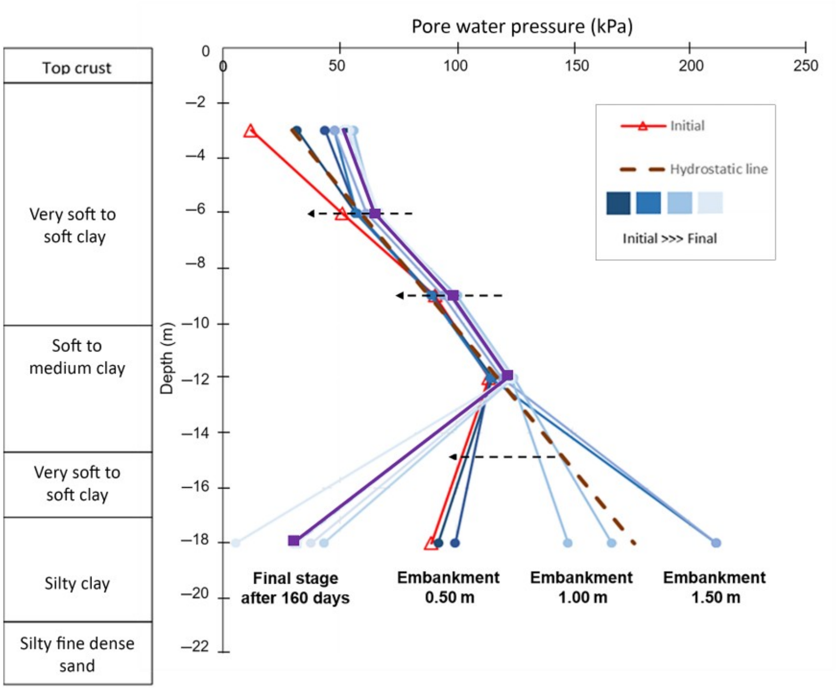


Figure 7. Pore water pressure for different periods at trial site using conventional preloading

4. VACUUM PRELOADING WITH SOFT CLAY LUMPS

Initially, vacuum preloading was proposed by Kjellman (1952). The vacuum pressure from the vacuum pump is distributed by PVDs and a horizontal drainage pipe (HDPE) into a soft clay lump fill that induced negative pressure (compared to atmospheric pressure). The sealing system prevents leakage of vacuum pressure by using a geomembrane on top of the sand blanket. The PVDs are installed within a sand blanket in the ground under treatment. Vacuum pressures as high as 70.00–80.00 kPa can be achieved to accelerate the soft clay consolidation rate. Combining vacuum pressures with surcharge load can expedite consolidation compared to using only vacuum pressures.

This paper presents the research performed over 4 sites. The preload consists of a surcharge combined with a vacuum (a vacuum-PVD with an airtight membrane (VCM-MB)) and the sand blanket. The lake was filled with soft-to-medium stiff clay lumps for construction without pumping the water out. The sand blanket with a thickness of 0.5 m was built using clean medium to coarse sand. The sand blanket's permeability was tested based on field permeability and was greater than 1.00×10^{-3} m/sec, confirming that the sand blanket provided adequate drainage capacity for efficient pore pressure dissipation during the VCM process. These site-specific test results are consistent with the design assumption and are presented in Supplementary A. The PVDs were installed at 1.00 m (triangular pattern) and 1.20 m (square pattern) spacings in the vacuum area. The HDPE was installed so that the vertical PVDs and horizontal PVDs were connected. The airtight area membrane was installed for the vacuum area. The vacuum pump operated at 70.00–80.00 kPa until the average degree of consolidation (DOC) reached 90.00%. From the 1.00–1.50 m embankment preloading, the wet and saturated unit weight of embankment fill after compaction was 17.00 kN/m^3.

During the improvement, settlement under the embankment and pore water pressure in the soil layer were measured using settlement plates and piezometers. These two parameters were used to monitor performance during the operation. Piezometers were installed at mid-depth within the soft clay lump fill using two types of instruments: push-in and standpipe (borehole) with vibrating wire piezometers (PK45I model, SISGEO). Both types were calibrated under atmospheric pressure and verified at multiple elevations before installation, as shown in Supplementary B, while the settlement plate was installed below the sand blanket. Vacuum pressure was measured at 2 locations, at the pump and beneath the airtight membrane using vacuum gauges.

4.1. Information of site improved by VCM

The soft clay lump behaviour was observed using a settlement plate and piezometer during the VCM operation to determine settlement and pore pressure, respectively. The soil investigation and monitoring after the VCM were used to evaluate its effectiveness. Table 2 shows the construction duration and VCM specifications, including ground improvement processes at each location.

4.2. Vacuum preloading observation

That the behaviour of the soft clay lumps improved following using the VCM was observed over time based on field instrument measurements. The surface and

Table 2. VCM specifications and preloading periods

		Site			
	Description	BPW	NOBLE	BPI	NSR&sSR
Land reclamation process	PVDs Spacing (m)	1.2 × 1.2	1.0 × 1.0	1.2 × 1.2	1.2 × 1.2
	PVDs pattern	square	triangular	square	square
	PVDs length (m)	17–20	10–14	15–20	15–24
	Vacuum pressure (kPa)	80	70	80	90
	Additional soil surcharge (m)	1.0–1.5	—	1.0–1.5	1.0–1.5
	Improvement time (days)	227–247	180	240–270	330

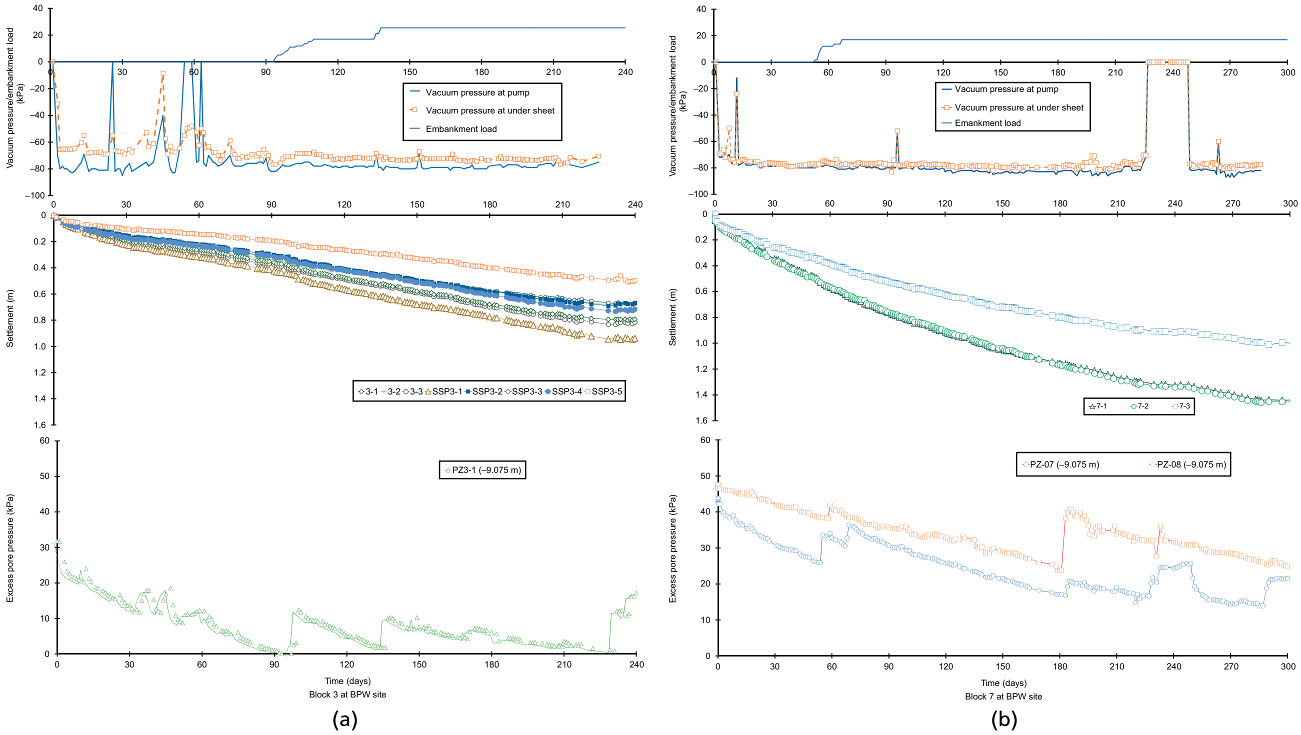
subsurface settlements, pore pressures, and vacuum were monitored during improvement using the VCM.

4.2.1. *Vacuum pressure of pump system and under air-tight sheet*

The vacuum pumps were operated for 180–330 days, as shown in Figure 8, with difference between the vacuum pressure measured under the air-tight sheet and at the pump loss of vacuum pressure between the pump and under the air-tight sheet. The vacuum pump's efficiency depends on the quality of the sand blanket, which should be clean and medium-to-coarse-grained. In Block 3 at the BPW site (Figure 8(a)), the sand blanket consisted of clayey and silty sand, which affected the pump efficiency. For the clean and coarse sand blanket, the vacuum pressure at the pumping system and under the airtight sheet were almost identical, and the pump efficiency was acceptable, as shown in Figure 8(b). Similar figures for BPI (Figure 9) and Nobel (Figure 10) sites are provided the clean and coarse sand blanket, which exhibits the good efficiency of the vacuum pump. Additionally, airtight sheet leakage is a critical factor in vacuum consolidation. Leakage was tested by filling the geomembrane sheets with water and observing any air bubble formation. Potential punctures or gaps were repaired using small pieces of geomembrane, which were sealed with hot glue and a heat dryer. The repaired sheets were retested with water, and no significant leakage was observed, confirming the effectiveness of the sealing method and ensuring the airtight performance of the geomembrane during vacuum preloading.

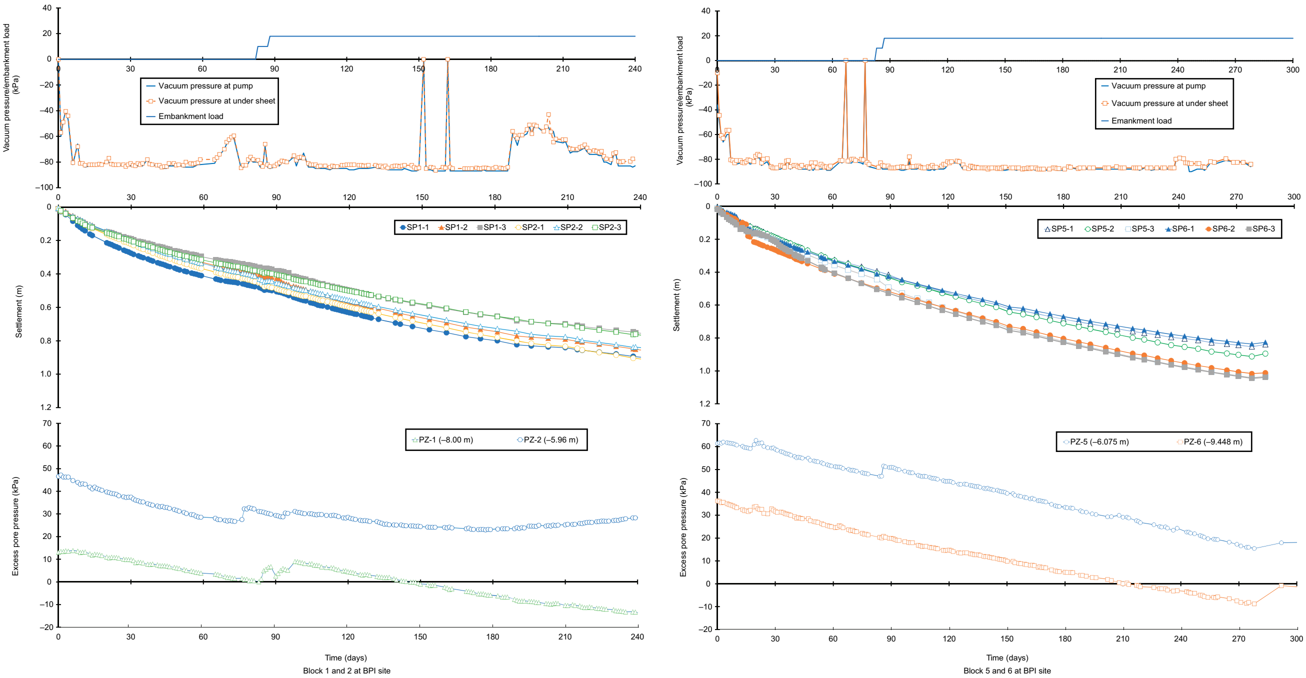
4.2.2. *Pore water pressure*

The pore water pressure was monitored using the push-in through soft clay lumps and a borehole as a standpipe piezometer by vibrating wire piezometers (PK45I model, SISGEO). The push-in method piezometers (PZ) were installed at the centre of the PVD spacing and the middle of the PVD length. The push-in piezometer recorded the excess pore water pressure caused by two factors: the installation of the piezometer (during the penetration through the soil) and the remaining pore pressure during backfill of the pond, which increased about 20 to 50 kPa (Figures 8, 9, and 10). The borehole method piezometers (BPZ) or standpipe piezometers were placed at depths of 2 m, 6 m, 10 m, 14 m, and 18 m for the BPW



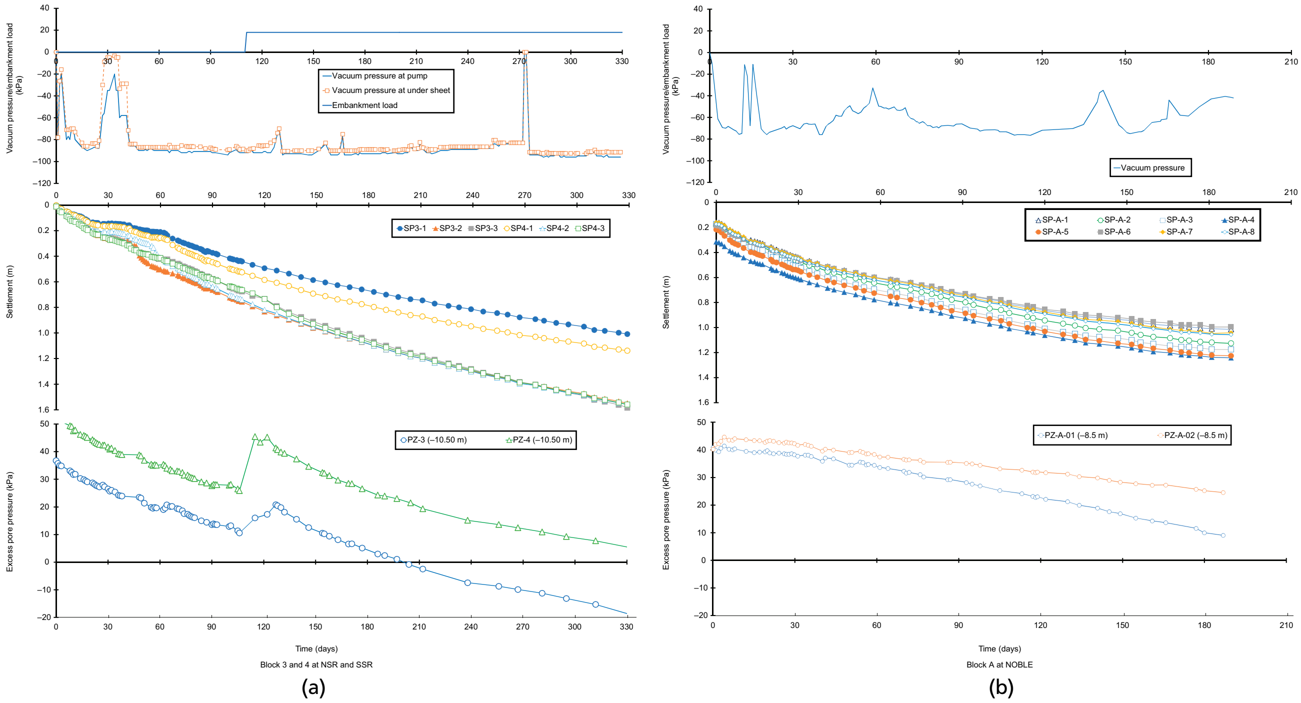
(a) (b)

Figure 8. Vacuum pressure, embankment load, settlement, and excess pore pressures versus time for Blocks 3 and 7 at BPW site



(a) (b)

Figure 9. Vacuum pressure, embankment load, settlement, and excess pore pressures versus time for Blocks 1, 2, 5, and 6 at BPI site



(a) (b)

Figure 10. Vacuum pressures, embankment load, settlement, and excess pore pressures versus time for Blocks 3 and 4 at NSR & SSR site and Block A at NOBLE site

site and at 6 m, 12 m, and 25 m for the BPI site to estimate the pore pressure profile in the vacuum consolidation stage, as illustrated in Figure 11.

Figures 8, 9, and 10 show all the site information and indicate that the VCM method effectively improved the soft clay lumps through monitoring measurements. The settlement graph shows the response to the pumping pressure as the settlement increased with vacuum application over time. The pore water pressure graph shows the pore water reduction with the vacuum application over time. All the information in the figures was consistent with the theory of soil improvement by preloading. This information was used for the back analysis to determine the C_h value. Usually, soil improvement based on the VCM is carried out in areas with natural soft clay. Since it is rare to use the VCM in areas backfilled with clay lumps, many questions exist about whether such areas could be improved. Based on the

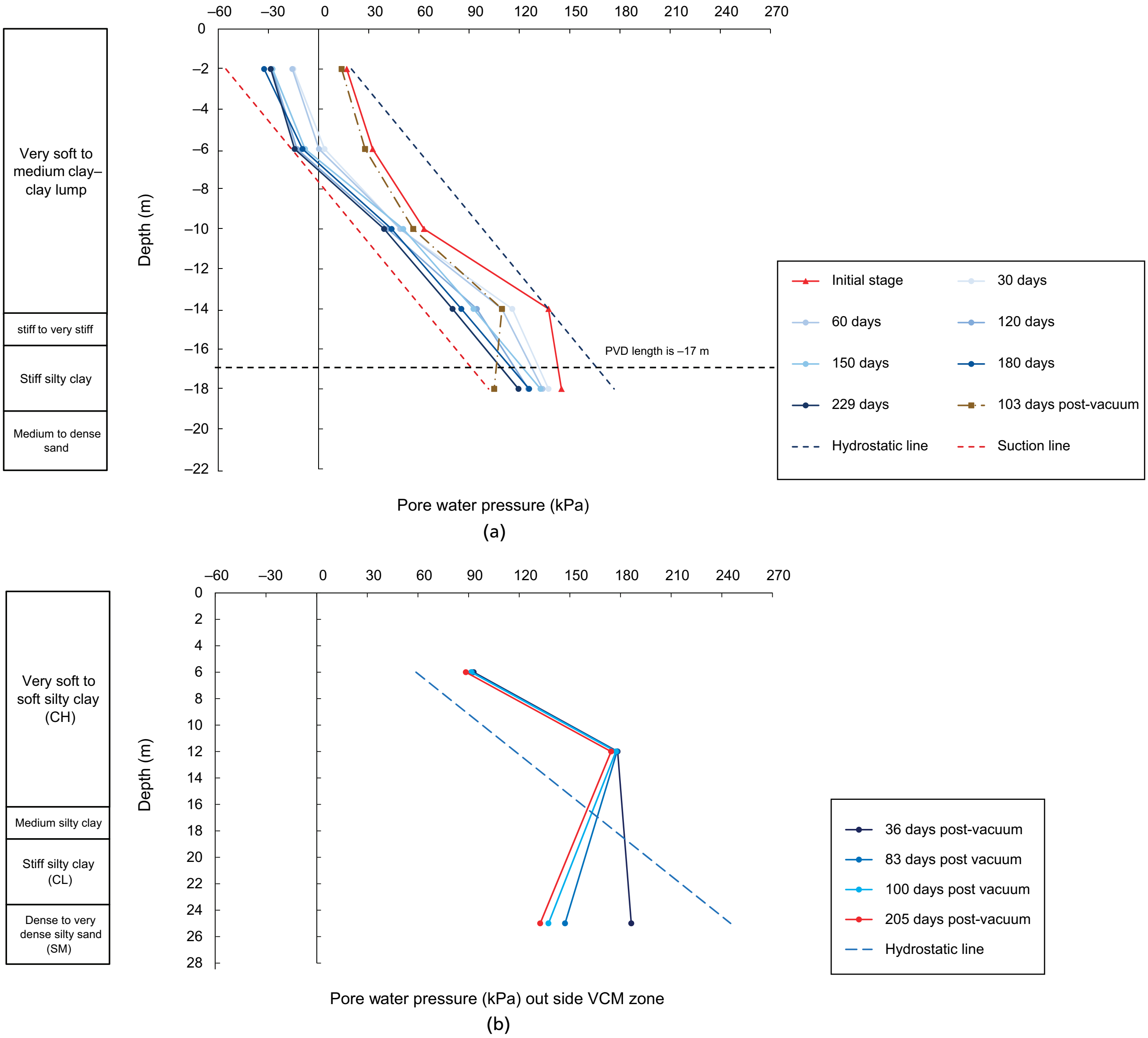


Figure 11. Pore water pressure profile for different periods during VCM at (a) BPW, and (b) BPI

results of the current study, it was possible to improve the area, even though the soil consisted of clay lumps.

Excess pore water pressure due to the backfilling process at the VCM area at the BPW site can be seen in Figure 11(a). The sandpipe piezometers could not detect the initial excess pore pressure because the piezometer installation involved drilling and filling with sand at the proposed depth. Once the borehole has been drilled to place the standpipe, the excess pore water pressure was dissipated, especially near the borehole. Consequently, for this situation, the piezometer could not measure the pore water pressure. Hence, the piezometer reading immediately after installation was not reliable. However, the increased pore water pressure dissipated and became stable over time, after which the piezometer reading was considered reliable. Although the measured pore water pressure obtained from the two methods differed, the trend was the same in both cases. The pore pressure behaviour is related to the construction activities in construction areas, such as the starting of the vacuum pump, backfilled surcharge load (embankment load), interruption in the vacuum pump, and electricity shutdown, which were studied by Phakdimek and Soralump (2018). In the current study, the readings were corrected for settlements at the piezometer tips. Compared to the initial pore water pressure, the excess pore water pressure decreased gradually during the improvement based on vacuum consolidation (Figure 11(a)). Specifically, the pore water pressure lines (days 30–229) moved further away from the initial pore water pressure line and hence moved closer towards the suction line, without actually reaching it, as the suction line is a theoretical concept. On releasing the vacuum pressure (indicated by the day 403 line), the pore water pressure line tries to rebound to the initial pore water pressure line. However, the excess pore pressure at the bottommost part cannot rebound, perhaps because of the piezometric drawdown effect. The excess pore water pressure was not entirely dissipated because of the influence of the distance from the PVDs and the permeability of the soil in the layer. The observed differential pore pressures at the end of preloading were 30–50 kPa, depending on the location and other factors such as piezometric clogging. A similar profile of the excess pore water pressure can be observed near the VCM area at the BPI site in Figure 9(b). Figure 9(b) shows the variation of the pore water pressure with depth. Notably, the piezometric drawdown near the sand layer reduced the pore water at that depth compared to other depths.

4.2.3. *Surface settlement and deep settlement*

The settlement data were collected from settlement plates installed at the centre and edge of the block in the VCM area, as shown in Figures 8, 9, and 10. The settlement trends were very similar with the settlement occurring more rapidly during the initial stage of consolidation using the VCM. The magnitude of settlement depends on the thickness of the layer of soft clay lump, the vacuum pressure, the embankment height, and the time for natural consolidation. The time for natural consolidation is the period between backfilling the soil and improving the soil using the VCM, where no improvement is made. A more extended period indicates a longer time for the soil to consolidate naturally by its self-weight. The highest settlement was observed at the NSR&SSR site, where the thickness of the soft clay lumps was greatest (15.00–24.00 m), and the height of the embankment load was 1.00–1.50 m. The lowest settlement was measured at the NOBLE site, where the soft clay lump was relatively thin (10.00–14.00 m) with no embankment load. The idle period after backfilling at the NOBLE site was less than 1 year before improvement with settlements of 0.20–0.30 m observed during the initial stage due to self-weight consolidation without any external load. The settlement trends were similar when vacuum pressure was applied to the other sites. After an increase in the embankment surcharge load, the settlement rate increased abruptly, resulting in greater settlement. The settlement continued until late in the period of improvement.

Although settlement plates were installed only below the sand blanket, the multiple deep settlement was measured at BPW Block 3 as shown in Figure 12, providing valuable insight into the efficiency of vacuum preloading in transmitting stress throughout the soft clay lumps. The settlement occurs consistently with depth, indicating effective mobilization of vacuum pressure along the PVDs. This observation confirms that the vacuum pressure is efficiently distributed, contributing to the overall consolidation behaviour of the backfilled material.

5. DATA ANALYSIS

5.1. Predictions of settlements, degrees of consolidation, and back-calculation of C_h values

Asaoka's graphical method describes the between S_n and S_{n-1} for surface settlement (Asaoka 1978). In the current study, the theoretical values of final settlement (S_f) were 1.05 m, 1.11 m, 0.92 m, and 1.75 m for the BPW, NOBLE, BPI and NSR&SSR sites, respectively, which were analysed using a time interval (Δt) of 7 days based on Equations (1) and (2).

$$S_n = \beta_0 + \beta_1 S_{n-1} \tag{1}$$

From Equation (1), the values of β_0 and β_1 can be obtained as the intercept and the slope of the best-fitted straight line of the S_n and S_{n-1} plot, where S_n is a settlement at time $t = t_n$, S_{n-1} is a settlement at time $t = t_n - \Delta t$, Δt is the time interval, and corresponding β_1 values were obtained as 0.87 to 0.95. The final primary settlement can be calculated using Equation (2):

$$S_f = \beta_0/(1 - \beta_1) \tag{2}$$

where S_f is the intersection between the S_n and S_{n-1} graph and the 45-degree line. Thus, the average degree of consolidation at EOP for BPW, NOBLE, BPI, and NSR&SSR sites was 90.11%, 90.34%, 90.37%, and 89.32%, respectively, as shown in Figure 13.

The C_h value was calculated using Equations (3)–(13):

$$\boldsymbol{C_h} = \frac{(\mathbf{1} - \boldsymbol{\beta_1})\boldsymbol{d_e^2 F}}{\mathbf{8} \times \boldsymbol{\beta_1 \Delta t}} \tag{3}$$

$$U_h = 1 - exp(-8T_h/F) \tag{4}$$

$$T_h = C_h t/d_e^2 \tag{5}$$

$$\mathrm{F} = \mathrm{F_n} + \mathrm{F_s} + \mathrm{F_r} \tag{6}$$

$$\boldsymbol{F_n} = \frac{\boldsymbol{n^2}}{\boldsymbol{n}-\mathbf{1}} \boldsymbol{log_e(n)} - \frac{\mathbf{3}\boldsymbol{n^2}-\mathbf{1}}{\mathbf{4}\boldsymbol{n^2}} \tag{7}$$

$$F_s = (k_h/k_s - 1)log_e(d_s/d_w) \tag{8}$$

$$F_r = \pi z(2L–z)k_h/q_w \tag{9}$$

$$\mathrm{d_w} = (\mathrm{a} + \mathrm{b})/2 \tag{10}$$

$$n = d_e/d_w \tag{11}$$

where U_h is the degree of horizontal consolidation (a time factor for horizontal consolidation), F is the factor of PVD influence (Equation 6), summarized by F_n, F_s, and F_r, d_e is the equivalent diameter of a unit of the PVD influence zone, k_h is the horizontal permeability of the soft soil, k_s is the horizontal permeability of soft soil in the smear zone, z is the distance from the drainage end of the drain, L is the length of the PVD for one-way drainage and is half of the PVD length for the drainage boundary at both ends of the PVD, q_w is the in-situ discharge capacity of the PVD. d_w is the equivalent diameter of the PVD, a and b are the thickness and width of the PVD, respectively, n is the ratio of the equivalent diameter of a unit of the PVD influence zone and the equivalent diameter of PVD, and d_s is the diameter of the smear zone due to PVD installation that can be related to the equivalent diameter of the mandrel (d_m), as

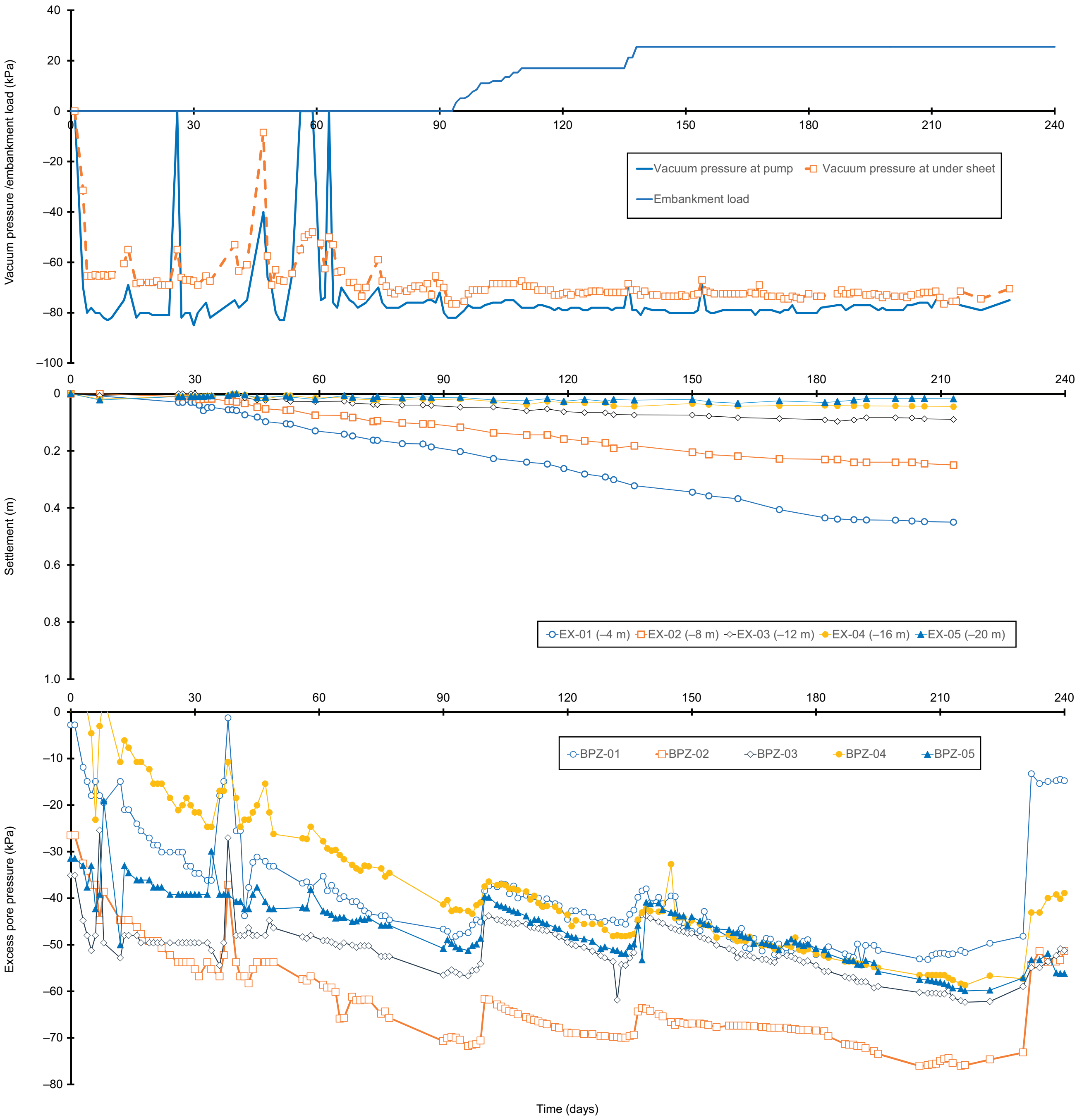


Figure 12. Multiple settlements with vary depths and vacuum pressure versus time Block 3 at BPW site

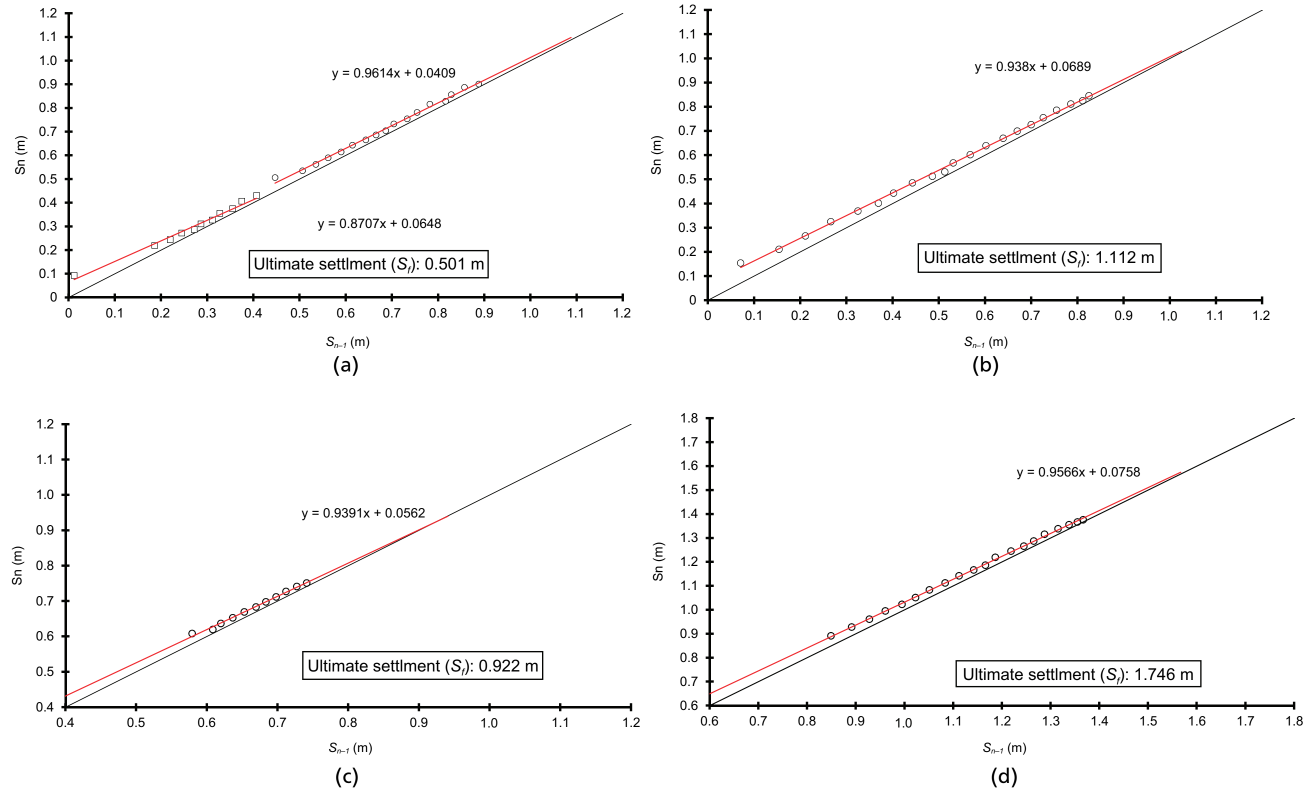
recommended by Hansbo (1979) and Bergado *et al.* (1991) that can be obtained using Equations (12) and (13):

$$d_s = 2d_m \tag{12}$$

$$d_m = 2(w.l/\pi)^{0.5} \tag{13}$$

where w and l are the width and thickness of the mandrel, respectively.

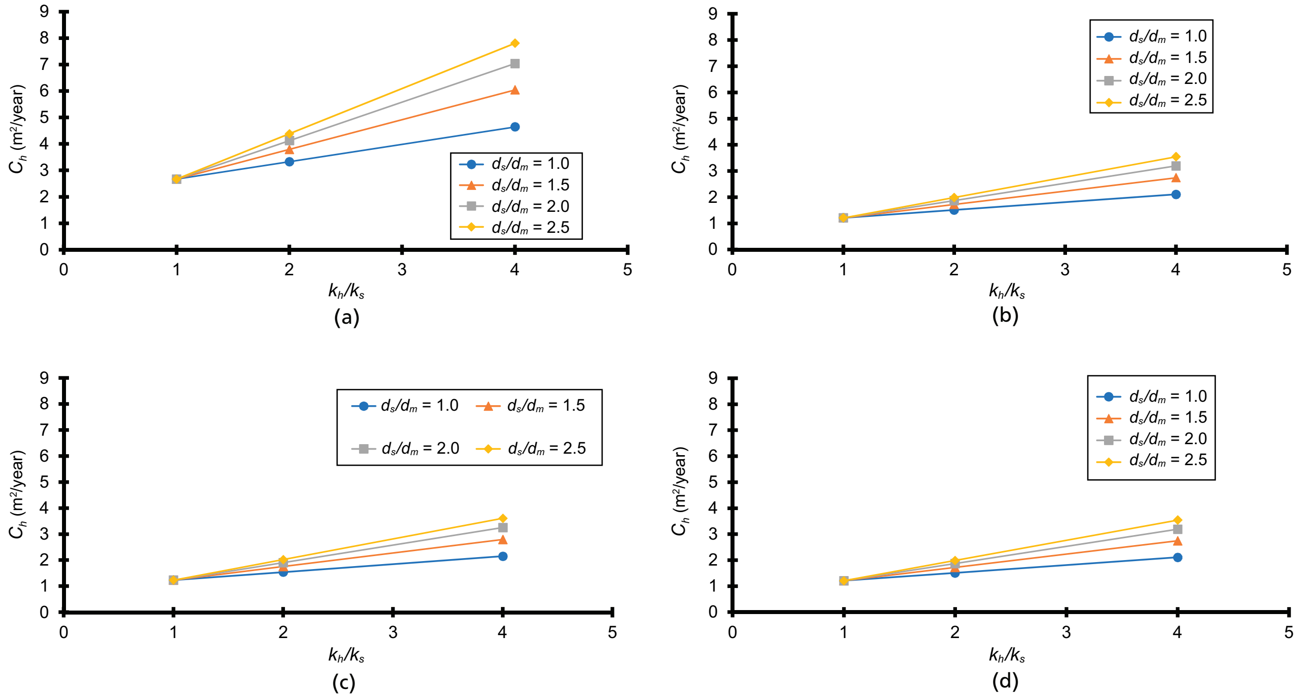
Long *et al.* (2013) noted that the value of k_h/q_w in Equation (9) is less than 0.0001 for most practical cases. Thus, the value of the well resistance F_r becomes negligible in comparison with the values of F_n and F_s. Balasubramaniam *et al.* (1995), Bergado *et al.* (1998, 2002, 2021), and Long *et al.* (2006) indicated that good resistance had very little effect when the q_w is greater than 50 m^3/year. It should be noted that the Asaoka method is based on small-strain consolidation theory. However, for field applications under vacuum loading, the large-strain effects are often implicitly accounted for through back-analysis of observed settlement data. Previous studies (Chai *et al.* 2005; Geng and Yu 2017; Indraratna *et al.* 2017a, 2017b) developed large-strain consolidation solutions for PVD-installed deposits featuring vacuum preloading to address the well resistance issue. However, these solutions did not consider the well-resistance effects of the drain or the discharge



(a) (b) (c) (d)

Figure 13. Final settlement prediction using Asaoka method (a) BPW, (b) NOBLE, (c) BPI and (d) NSR&SSR

capacity reduction over time and they have confirmed that the Asaoka method remains effective for interpreting consolidation parameters when calibrated with field measurements. Therefore, with a known PVD spacing, the main parameters influencing the calculated consolidation rate are the values of horizontal coefficient of consolidation (C_h, m^2/year), k_h/k_s, and d_s/d_m which have to be assumed in design practice. The current study assumed values of k_h/k_s and d_s/d_m were assumed within the ranges of 1.00–4.00 and 1.00–2.50,



(a) (b) (c) (d)

Figure 14. (a) Back calculated values if C_h for k_h/k_s from BPW (b) Back calculated values if C_h for k_h/k_s from BPI (c) Back calculated values if C_h for k_h/k_s from NOBLE (d) Back calculated values if C_h for k_h/k_s from NSR&SSR

respectively, as shown in Figure 14. Verification of the assumed $d_s = 2\ d_m$ was conducted using field monitoring data and back-analysis of settlement behaviour. Figure 14 compared the predicted settlement with field measurements, demonstrating that the assumption of $d_s = 2\ d_m$ provides the best agreement with observed consolidation. A sensitivity analysis was also performed on q_w by varying it from 50 to 200 m^3/year. The results, illustrated in Figure 15, indicate that the variation in q_w had a minor effect on the predicted settlement. This confirms that the influence of F_r is negligible for the tested range of discharge capacities. Therefore, the assumptions of $d_s = 2\ d_m$ and negligible F_r are both supported by field data, ensuring the reliability of the numerical prediction and the back-calculated consolidation parameters.

The C_h was calculated based on Equations (3), with the β_1 values derived from the Asaoka plots. They assumed $d_s = 2\ d_m$ and negligible F_r. The values of C_h were obtained as 1.17–4.13 m^2/year by back-calculation. The C_h values of 1.39–4.13 m^2/year were back-calculated at the initial stage without any soil surcharge load, while the C_h values of 1.17–2.08 m^2/year were obtained by vacuum pressure with soil surcharge near the end of preloading (Table 3). The back-calculated C_h values in this study, ranging from 1.00–3.00 m^2/year, indicated the presence of weak soil conditions. These values decreased substantially with an increase in the DOC, consistent with the findings of Bergado *et al.* (2002). The C_h values obtained in the current study were notably lower than those reported in previous studies, which found values ranging from 3.96 to 5.57 m^2/year for Bangkok soft clay (Bergado *et al.* 1998, 2002, 2021, 2024a; Voottipruex *et al.* 2014). Furthermore, the anisotropy of permeability was assessed by comparing the C_h (1.17–4.13 m^2/year) from back-analysis, with C_v (1.05–2.12 m^2/year) from oedometer tests. Since permeability and the coefficient of consolidation are directly related, the ratio C_h/C_v provides a reasonable approximation of the permeability anisotropy (k_h/k_v) governing radial drainage behaviour (Bergado *et al.* 1998; Bo *et al.* 2003; Seah and Koslanant 2003; Seah *et al.* 2004). This comparison resulted in an estimated anisotropy ratio of 1.2–4.1. For comparison, Bangkok clay reported by Bergado *et al.* (1998) exhibited a k_h/k_v 4–10, whereas less anisotropic clay studied by Bo *et al.* (2003) had a ratio of 1–2. The relatively lower C_h values and ratio of C_h/C_v observed in the current study may be attributed to the heterogeneous characteristics of the soft clay lump material, less anisotropic, the inter lump voids, and the soil disturbed by the backfilling process as well as due to vacuum preloading that increased the k_s in the smear zone. Consequently, the lower C_h values in the soft clay lumps resulted in slower dissipation of the excess pore water pressure, leading to a longer consolidation period compared to natural Bangkok clay.

Table 3. Comparison degree of consolidation (DOC, %) and horizontal coefficient of consolidation (C_h, m^2/year) of soft clay lumps

VCM site	Field settlement (m)	Ultimate settlement at U = 100% (m)	DOC (%)	C_h (m^2/year)
BPW	0.90	1.06	90.11	4.17
BPI	0.75	0.92	90.37	1.97
NSR&SSR	1.38	1.75	89.32	1.39
NOBLE	0.85	1.11	90.34	2.08

5.2. Properties of the soft clay lumps before and after improvement

The soils at the sites were investigated for the index and consolidation properties of the soft clay lumps after improvement. The water contents, undrained shear

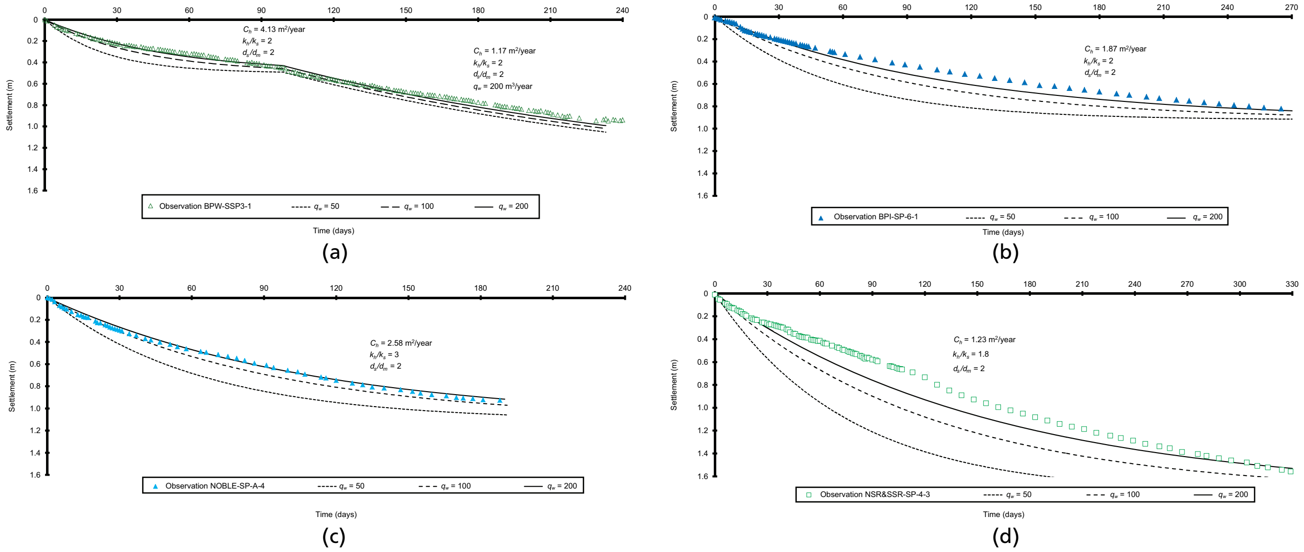


Figure 15. (a) Comparison of predicted and observed field settlements for BPW (b) Comparison of predicted and observed field settlements for BPI (c) Comparison of predicted and observed field settlements for NOBLE (d) Comparison of predicted and observed field settlements for NSR&SSR

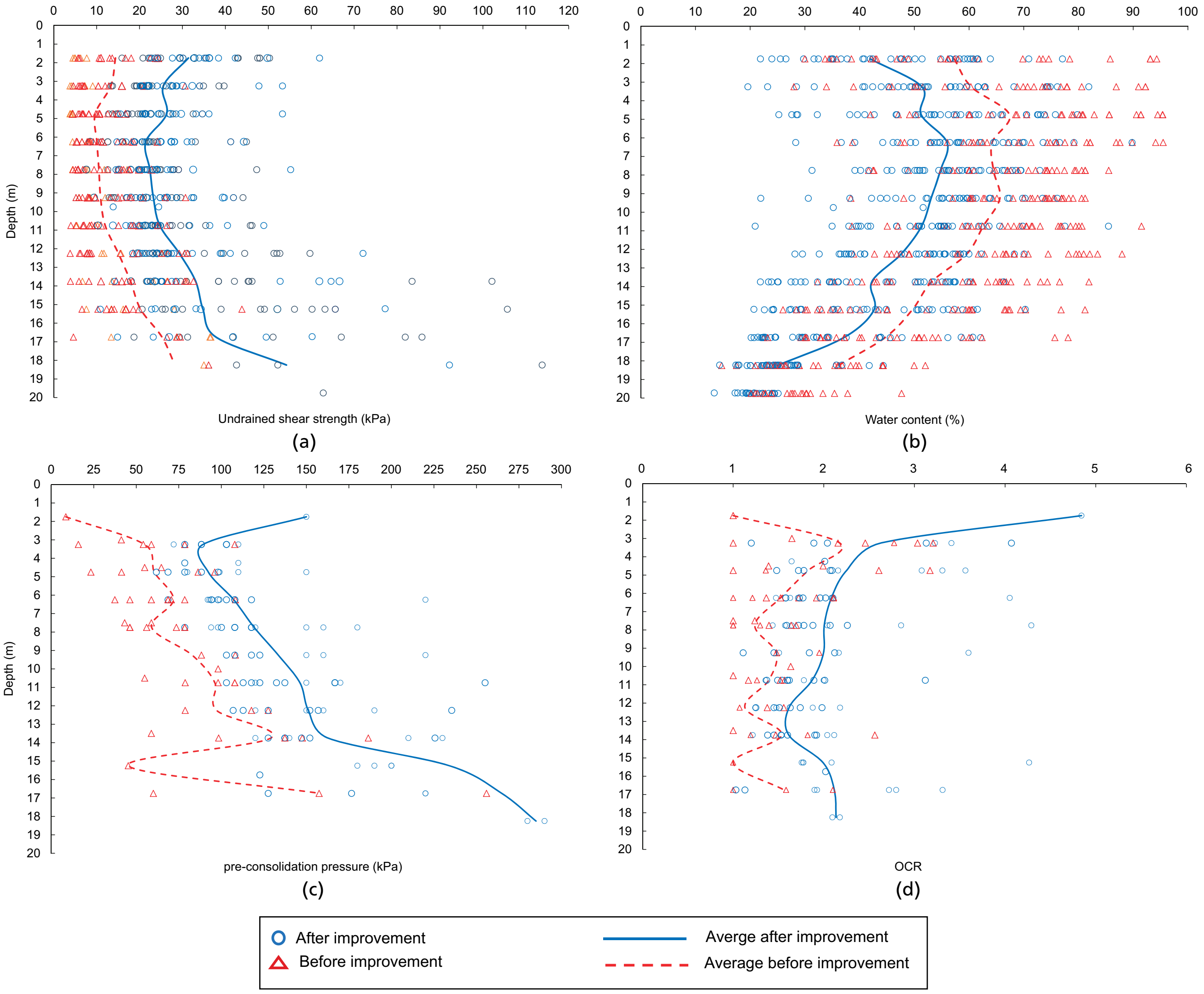


Figure 16. Soft clay lumps properties before and after improvement (a) Undrained shear strength, (b) Water content (%), (c) Pre-consolidation pressure and (d) OCR

strengths, pre-consolidation pressures, and OCR, before and after improvement for BPW, BPI, NOBLE, and NSR&SSR sites are plotted in Figure 16. After improvement, the undrained shear strength of the soft clay lumps increased by about 200% for depths in the range 0.00–10.00 m and by 150% for depths in the range 10.00–18.00 m, while water content reduced by 80% for depths in the range 0.00–10.00 m and by 70% for depths in the range 10.00–18.00 m. Likewise, the pre-consolidation pressures increased from 30 to 60 kPa and the OCR increased from 1 to greater than 1.5. The development and increment of properties were caused by vacuum pressure and soil surcharge in the top and middle sections. These effects could be reduced by the installation of the PVD at greater depth.

5.3. Soft clay lumps settlement behaviour under vacuum preloading

Settlements during 180–330 days were estimated using the strain percentage shown in Table 4. Since the percentage of strain is the ratio of the change in settlement to the

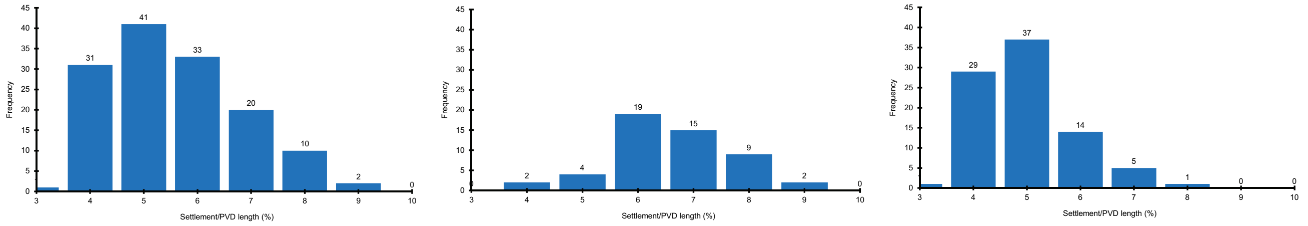
Table 4. Comparison of compressive strain of soft clay lumps

VCM site	Idle time between backfill and before starting VCM (years)	D (m)	% strain	P_{vac} (kPa)
BPW	3	17.00–20.00	4.00–7.30	80
BPI	5	15.00–20.00	4.60–6.30	80
NSR&SSR	2	15.00–24.00	4.00–9.00	90
NOBLE	1	10.00–14.00	5.20–7.80	70

Remark: D = thickness of soft lump clay (m) as the length of PVD (m), $S_{f,\ EOP}/D$ is a compressive strain of soft clay lumps, and P_{vac} is vacuum pressure initial length, converted into a percentage, the initial length here is the thickness of the improved soil or the PVD length. The amount of settlement from each settlement plate in the block depends on the thickness of the soft soil layer and the PVD lengths below the settlement plate. For soft clay lumps with thickness 10.00–21.00 m, the average compressive strain was 6.14%, with a range of 4.00%–9.00%. This was one of the crucial findings of the current research as it provides a rule of thumb to estimate the value of settlement of soft clay lumps improved by applying the VCM before detailed analysis. Usually, it requires approximately 180–330 days for the VCM to complete the improvement of soft clay lumps, which is longer than the typical 150–200 days required for natural soft clay improvement (Soralump *et al.* 2024; Bergado *et al.* 2024b). The value of settlement after applying the VCM is used to calculate the depth of compensation fill (the depth of soft clay lumps that needs to be added above the ground level to compensate for the reduced depth due to the VCM improvement). This settlement value is calculated from the strain percentage at the end of soil improvement. While empirical guidelines for estimating such settlement values exist for naturally deposited clay layers, limited data are available for soft clay lumps. Therefore, the current study determined an estimated settlement value corresponding to 90% DOC for soft clay lumps improved by applying the VCM. The estimated settlement ranges from approximately 4.0% to 9.0% of the soft clay lump thickness, depending on the depth of improvement and the installation depth of the PVDs.

The settlement and PVD length ratio is shown in Figures 14(a), 14(b), and 14(c). These sites have different idle periods between soil reclamation and the application of VCM. As a result of settlement per the PVD length on all the VCM sites, the median values were 5, 6, and 5% for BPW and BPI, NOBLE and NSR&SSR, and all VCM sites, respectively (Figure 17(a)). Notably, for the NOBLE and NSR & SSR sites (Figure 17(b)), the VCM was conducted 1–2 years after the land had been reclaimed, while for the BPW and BPI sites (Figure 17(c)), it was conducted 3–5 years after the land reclamation. It was found that the result obtained before the VCM idle period affected the settlement magnitude.

The rate of settlement is plotted in Figure 18. After the vacuum pump had been activated, the settlement rate was approximately 23.00 mm/day during the initial stage of consolidation. This rapid settlement was likely due to the collapse of inter-lump voids and the high compressibility of soft clay lumps. The rate of settlement decreased greatly after approximately 3 months of vacuum pressure application. When the embankment surcharge load was applied, the settlement rate increased again, followed by a gradual reduction. Notably, settlement decreased after the vacuum pump was shut off. The vacuum preloading operation was terminated when



(a) (b) (c)

Figure 17. Comparison of before VCM idle period time using settlement per PVD length (a) All VCM site on soft clay lump, (b) before VCM waiting period time 1–2 years (NOBLE and NSR&SSR), (c) Before VCM waiting period time 3–5 years (BPW and BPI)

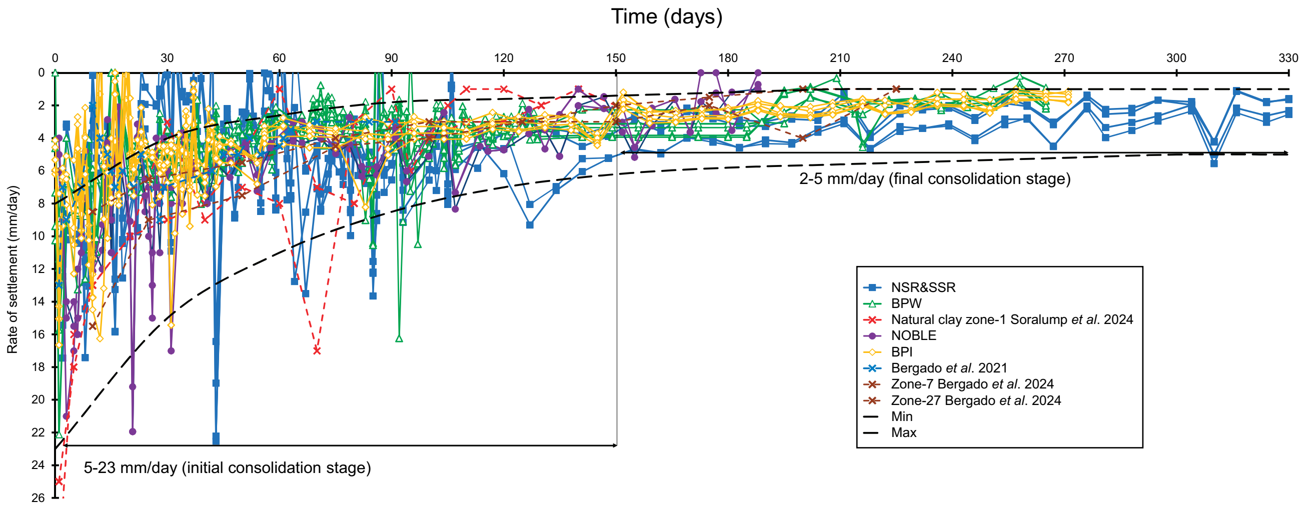


Figure 18. Rates of soft clay lump fill settlement improved using VCM

the settlement rate declined to 2.00–5.00 mm/day. This range of settlement rate indicated that the consolidation process had reached approximately 90% DOC, with further settlement expected to be minimal. The observed settlement behaviour was consistent with another study on soft clay lumps where there was improved settlement based on using the VCM method (Soralump *et al.* 2023) but differed from other research on naturally deposited Bangkok soft clay, where the initial settlement rate was reported in the range of 6 to 10.00–14.00 mm/day and gradually reduced to approximately 3.00–4.00 mm/day (Bergado *et al.* 2021, 2024a). This comparison highlighted the distinctive difference between the settlement behaviour of soft clay lumps and that of natural Bangkok clay, primarily due to material composition, inter lump voids, and consolidation characteristics. Consequently, the current study proposed an empirical guideline for monitoring and determining the appropriate timing to terminate the VCM improvement system specifically for soft clay lump ground conditions.

5.4. Effect of vacuum pump shut down on pore pressure behaviour

During the vacuum preloading process, several temporary shutdowns of the vacuum pump occurred due to maintenance and power interruptions. These shutdowns caused a temporary loss of vacuum pressure, resulting in partial rebound of excess pore water pressure, particularly in the upper and middle layers. The rebound magnitude was generally small and dissipated rapidly once the vacuum system resumed operation. However, these interruptions temporarily slowed consolidation and introduced minor fluctuations in recorded pore pressure data. Despite these short-term effects, the overall consolidation trend remained consistent with theoretical expectations. This indicates that the system effectively re-established vacuum conditions, and the long-term dissipation of pore pressure continued toward the target DOC. Therefore, pump shutdowns introduced transient measurement fluctuations but did not significantly affect the long-term consolidation performance or accuracy of interpretation.

5.5. Environmental and economic implications

The use of soft clay lumps as fill material in land reclamation and foundation improvement projects presents environmental and economic advantages. From an environmental standpoint, reusing dredged or excavated clay reduces the need for disposal and minimizes the extraction of natural borrow materials, thereby conserving resources and reducing carbon emissions associated with transportation and quarrying. This approach provides a sustainable alternative for urban development projects in regions with limited fill materials, such as Bangkok as the capital city. Moreover, the reduction in settlement time achieved through vacuum preloading helps accelerate construction schedules, further improving project cost efficiency.

5.6. Limitations and future studies

Although the present study provides comprehensive field observations, several limitations should be acknowledged. Rainfall during the preloading period may have influenced pore pressure readings and localized variations in vacuum efficiency, especially where sealing conditions were imperfect. The variability in placement methods, such as differences in clay lump size and compaction degree, could also have contributed to spatial heterogeneity in soil response. Mitigation of lateral displacement from the surcharge load should be assessed in conjunction with inclinometer monitoring, enabling the development of guidelines for determining the optimal surcharge magnitude. Furthermore, long-term post-VCM performance, including creep settlement and potential vacuum-induced microstructural changes, warrants further investigation. Future studies should focus on quantifying these effects through extended monitoring, laboratory-based simulation of field consolidation, and advanced numerical modeling that accounts for soil heterogeneity and anisotropy. Such research would refine the predictive capability for large-scale land reclamation using soft clay lumps under vacuum preloading.

6. CONCLUSIONS

The performance was investigated of applying the VCM with PVDs and an airtight sheet membrane on abandoned pond areas filled with soft clay lumps for housing estate construction in Bangkok. Specifically, data were analyzed based on the characteristics of the soft clay lumps, the field monitoring and the improved soil properties results, as well as the back-calculated parameters. Based on these results, the following conclusions and recommendations can be made:

1. The characteristics of the soft clay lumps consisted of heterogeneous properties, low undrained shear strength, high water content, and high compressibility. In addition, there was intra-lump porosity within the soft clay lumps and inter-lump porosity between the soft clay lumps.
2. The effective vacuum pressure depended mainly on the quality of the sand blanket, the efficiency of the vacuum pump, and controlling airtight sheet leakage. Based on the different quality of the sand blankets investigated, the vacuum pressure could be fully transferred to PVDs in a clean sand blanket but not in a dirty sand blanket, The vacuum pressure dropped after leakage from the airtight sheet and the rate of settlement decreased, which affected the vacuum consolidation method and extended the improvement time.
3. The excess pore pressure of the soft clay lumps was higher than for the naturally deposited clay layers. Initially, the excess pore pressures generated in the clay lumps and the naturally deposited clay layers were in the ranges 20–50 kPa and 5–10 kPa, respectively. When primary consolidation had been completed,

the excess pore pressure of the naturally deposited clay layers had almost dissipated, remaining in the range 10–15 kPa for the soft clay lumps. The excess pore pressure could not be dissipated completely because of the piezometric draw-down effect. In addition, the soft clay lumps were backfilled into the pond without first draining the water.

4. The undrained shear strength of the soft clay lumps after improvement by applying the VCM increased by 200% at depths of 0.00–10.00 m and by 150% at depths of 10.00–18.00 m while the water content was reduced by 80% at depths of 0.00–10.00 m and by 70% at depths of 10.00–18.00 m. The pre-consolidation pressure increased by 45% and the OCR value was greater than 1 for all samples after improvement. Improvement in the bottom part was affected by the vacuum pressure and the withdrawal of groundwater.
5. The back-calculated results suggested that values of $d_s/d_m = 2$, $k_h/k_s = 2$ and the value of the well resistance F_r became negligible in comparison to the values of F_n and F_s and so the latter two could be used for PVD improvement in soft clay lumps. The value of C_h for vacuum pressure varied in the range 1.39–4.13 m^2/year, and C_h for a vacuum with a surcharged load varies between 1.17–2.08 m^2/year. However, the value of C_h for a vacuum with a surcharged load after the application of vacuum at about 98 days was less than the C_h values, when only vacuum pressure was applied due to the application of the surcharge load during the consolidation process. This was similar to the C_h value from Bergado *et al.* (2002), which indicates 1–3 m^2/year for weaker soil. The k_h/k_s value in the current study was less than that reported by Bergado *et al.* (1991) ($k_h/k_s = 2 < 5$) because in the current study, the soft clay lumps had heterogeneous properties, were less anisotropic, and were disturbed during the backfilling process. In addition, k_h/k_s decreased due to vacuum preloading because k_s increased in the smear zone.
6. This research established an essentially empirical approach for calculating the settlement of soft clay lumps improved by applying the VCM, with this approach being crucial for determining the depth of the compensation fill required. The study findings revealed that settlement values at 90% DOC were 4.00%–9.00% of the PVD installation depth, derived from the percentage of strain at the end of soil improvement. Such estimates for clay lumps represent a considerable advancement, as such equations previously existed only for naturally deposited clay layers. The current development allows for more accurate pre-analysis predictions, ensuring effective soil improvement planning. The observed settlement behaviour supported the proposed methodology. An initial settlement rate of 23.00 mm/day was recorded, likely due to inter-lump void collapse and high compressibility. After 3 months of vacuum pressure, the rate declined, before rising with surcharge loading and then gradually decreasing. The VCM operation was terminated when the settlement rate reached 2.00–5.00 mm/day, indicating 90% consolidation.

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NOTATION

Basic SI units are given in parentheses.

a	thickness of PVD (m)
b	width of PVD (m)
C_c	compression index (dimensionless)
C_h	horizontal consolidation coefficient (m^2/s)
COV	coefficient of variation (dimensionless)
D	soft clay lumps thickness (m)
DOC	degree of consolidation (dimensionless)
D_w	equivalent diameter of PVD (m)
d_m	equivalent diameter of the mandrel (m)
d_s	equivalent diameter of the smear zone (m)
EOP	end of preloading (dimensionless)
F_n	spacing factor (dimensionless)
F_r	well resistance factor (dimensionless)
F_s	smear zone factor (dimensionless)
k_a	active earth pressure coefficient (dimensionless)
k_h	horizontal permeability of the undisturbed zone (m/s)
k_s	permeability of the smear zone (m/s)
k_v	vertical permeability of the smear zone (m/s)
L	length of PVD (m)
n	ratio of the equivalent of a unit PVD influences zone and equivalent diameter of PVD (dimensionless)
OCR	overconsolidation ratio (dimensionless)
P_c	pre-consolidation (Pa)
P_{vac}	vacuum pressure (Pa)
q_w	in-situ discharge capacity of PVD (m^3/s)
S_f	ultimate settlement (m)
S_n	settlement at time n (m)
S_{n-1}	settlement at time n-1 (m)
S_u	undrained shear strength (N/m^2)
U_h	degree of horizontal consolidation (dimensionless)
z	distance from drainage end of the drain (m)
γ_t	total unit weight of soil (N/m^3)
γ_w	unit weight of water (N/m^3)

ABBREVIATIONS

BPI	Burasiri Panyaindra
BPW	Burasiri Watcharapol

CMIT	Cai Mep International Terminal
HPDE	high-density polyethylene
NOBLE	Noble Wisdom
NSEW	North-South Expressway
NSR&SSR	Narasiri&Setthasiri
PM3-CM	PM3-Ca Mau project
PVD	prefabricated vertical drain
SBIA	Second Bangkok International Airport
VCM	vacuum consolidation method

REFERENCES

Abuel-Naga, H. M., Bergado, D. T. & Gniel, J. (2015). Design chart for prefabricated vertical drains improved ground. *Geotextiles and Geomembranes*, **43**, No. 6, 537–546.

Alditra, D. F., Chaiprakaikeow, S. & Soralump, S. (2020). Study of VCM improved soft soil properties using non-destructive and destructive techniques. *Geosciences*, **10**, No. 8, 300.

Anantsuksomsri, S. & Tontisirin, N. (2015). The impacts of mass transit improvement on residential land development values: Evidence from the Bangkok metropolitan region. *Urban Policy and Research*, **33**, No. 2, 195–216.

Asaoka, A. (1978). Observational procedure of settlement prediction. *Soils and Foundations*, **18**, No. 4, 87–101.

ASTM D2166-24. *Standard test method for unconfined compressive strength of cohesive soil*, ASTM International, West Conshohocken, PA, USA.

ASTM D2487-25. *Standard practice for classification of soils for engineering purposes (Unified Soil Classification System*, American Society for Testing Materials, West Conshohicken, PA, USA.

Balasubramaniam, A. S., Bergado, D. T. & Phienwej, N. (1995). The full scale field test of prefabricated vertical drains for the second Bangkok international airport (SBIA). *Final Report, Division of Geotechnical and Transportation Engineering*, **AIT**, 259.

Balasubramaniam, A. S., Oh, E. Y. N., Bolton, M. W., Bergado, D. T. & Phienwej, N. (2005). Deep-well pumping in the Bangkok plain and its influence on ground improvement development with surcharge and vertical drains. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, **9**, No. 4, 149–162.

Bergado, D. T., Asakami, H., Alfaro, M. C. & Balasubramaniam, A. (1991). Smear effects of vertical drains on soft Bangkok clay. *Journal of Geotechnical Engineering*, **117**, No. 10, 1509–1530.

Bergado, D. T., Chai, J. C., Miura, N. & Balasubramaniam, A. S. (1998). PVD improvement of soft Bangkok clay with combined vacuum and reduced sand embankment preloading. *Geotechnical Engineering*, **29**, No. 1, 95–122.

Bergado, D. T., Balasubramaniam, A. S., Chishti, I. A., Ruenkrairergsa, T. & Taesiri, Y. (1999). Evaluation of the PVD performance at the second Bangkok-Chonburi highway (SBCH) project. *Lowland Technology International*, **1**, No. 2, 55–75.

Bergado, D. T., Balasubramaniam, A., Fannin, R. J. & Holtz, R. D. (2002). Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok international airport project. *Canadian Geotechnical Journal*, **39**, No. 2, 304–315.

Bergado, D. T., Jamsawang, P., Kovittayanon, N., Baez, F. & de Zwart, P. T. (2021). Vacuum-PVD improvement: a case study of the second improvement of soft bBangkok clay on the subsiding ground. *International Journal of Geosynthetics and Ground Engineering*, **7**, No. 4, 1–20.

Bergado, D. T., Jamsawang, P., Jongpradist, P., Likitlersuang, S., Pantaeng, C., Kovittayanun, N. & Baez, F. (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**, No. 1, 137–153.

Bergado, D. T., Jamsawang, P., Voottipruex, P., Jongpradist, P., Rementilla, J. & Dicker, S. (2024a). First and second vacuum-PVD improvement of soft Bangkok clay for the third runway of suvarnabhumi international airport Thailand. *Innovative Infrastructure Solution*, **9**, 348.

Bergado, D. T., Nghia-Nguyen, T., Jamsawang, P., Kovittayanon, N., Rementilla, J. & Chao, K. C. (2024b). Numerical simulation of effects of previous PVD treatment on second vacuum-PVD improvement. *Geosynthetics International*, **32**, No. 4, 484–503.

Bo, M. W., Chu, J., Low, B. K. & Choa, V. (2003). *Soil improvement: prefabricated vertical drain technique*, Thomson Learning, Singapore.

Cai, Y. Q., Xie, Z. W., Wang, J., Wang, P. & Geng, X. Y. (2018). New approach of vacuum preloading with booster PVDs to improve deep marine strata. *Canadian Geotechnical. Journal*, **55**, No. 10, 1359–1371.

Chai, J., Carter, J. & Hayashi, S. (2005). Ground deformation induced by vacuum consolidation. *Journal of Geotechnical and Geoenvironmental Engineering*, **131**, No. 12, 1552–1561.

Chai, J. C., Carter, J. P. & Hayashi, S. (2006). Vacuum consolidation and its combination with embankment loading. *Canadian Geotechnical Journal*, **43**, No. 10, 985–996.

Chai, J. C., Miura, N. & Bergado, D. T. (2008). Preloading clayey deposit by vacuum pressure with cap-drain: Analyses versus performance. *Geotextiles and Geomembranes*, **26**, No. 3, 220–230.

Chai, J. C., Ong, C. Y., Carter, J. P. & Bergado, D. T. (2013). Lateral displacement under combined vacuum pressure and embankment loading. *Géotechnique*, **63**, No. 10, 842–856.

Chai, J. C., Fu, H. T., Wang, J. & Shen, S. L. (2020). Behavior of a PVD unit cell under vacuum pressure and a new method for consolidation analysis. *Computers and Geotechnics*, **120**, 103415.

Chu, J., Yan, S. & Yang, H. (2000). Soil improvement by the vacuum preloading method for an oil storage station. *Géotechnique*, **50**, No. 6, 625–632.

Federico, A., Vitone, C. & Murianni, A. (2015). On the mechanical behaviour of dredged submarine clayey sediments stabilized with lime or cement. *Canadian Geotechnical Journal*, **52**, No. 12, 2030–2040.

Geng, X. & Yu, H.-S. (2017). A large-strain radial consolidation theory for soft clays improved by vertical drains. *Géotechnique*, **67**, No. 11, 1020–1028.

Hansbo, S. (1979). Consolidation of clay by band-shaped prefabricated drains. *Ground Engineering*, **12**, No. 5.

Hayashi, H., Hatakeyama, O. & Hashimoto, H. (2021). Reducing the secondary consolidation of peat ground using vacuum consolidation. *Proceedings of the Institution of Civil Engineers Ground Improvement*, **174**, No. 3, 173–184.

Indraratna, B., Rujikiatkamjorn, C. & Sathananthan, I. (2005). Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. *Canadian Geotechnical Journal*, **42**, No. 4, 994–1014.

Indraratna, B., Geng, X. Y. & Rujikiatkamjorn, C. (2010a). Review of methods of analysis for the use of vacuum preloading and vertical drains for soft clay improvement. *Geomechanics and Geoengineering*, **5**, No. 4, 223–236.

Indraratna, B., Rujikiatkamjorn, C., Kelly, R. & Buys, H. (2010b). Sustainable soil improvement via vacuum preloading. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, **163**, No. 1, 31–42.

Indraratna, B., Rujikiatkamjorn, C., Balasubramaniam, A. S. & McIntosh, G. (2012). Soft ground improvement via vertical drains and vacuum assisted preloading. *Geotextiles and Geomembranes*, **30**, 16–23.

Indraratna, B., Zhong, R., Fox, P. & Rujikiatkamjorn, C. (2017a). Recent advances in vertical drains and vacuum preloading for soft ground stabilisation. In *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul*, ISSMGE, London.

Indraratna, B., Zhong, R., Fox, P. & Rujikiatkamjorn, C. (2017b). Large-strain vacuum-assisted consolidation with non-Darcian radial flow incorporating varying permeability and compressibility. *Journal of Geotechnical and Geoenvironmental Engineering*, **143**, No. 1.

Juneja, A. & Chafale, A. S. (2019). Consolidation behaviour of double-porosity clay using flexible wall permeameter. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, **172**, No. 3, 179–191.

Karthikeyan, M., Dasari, G. R. & Tan, T.-S. (2004). In situ characterization of land reclaimed using big clay lumps. *Canadian Geotechnical Journal*, **41**, No. 2, 242–256.

Kjellman, W. (1952). Consolidation of clay soil by means of atmospheric pressure. *Proc. of Conf. on Soil Stabilization*.

Koirala, N., Soralump, S. & Phakdimek, S. (2022). Observations from ground improvement using vacuum consolidation method. *Civil Engineering and Architecture*, **10**, No. 3, 771–783.

Kostkanová, V., Herle, I. & Bohác, J. (2014). Transitions in structure of clay fills due to suction oscillations. *Procedia Earth and Planetary Science*, **9**, 153–162.

Leung, C. F., Wong, J. C., Manivanann, R. & Tan, S. A. (2001). Experimental evaluation of consolidation behavior of stiff clay lumps in reclamation fill. *Geotechnical Testing Journal*, **24**, No. 2, 145–156.

Li, B., Wu, S. F. & Chu, J. (2011). Consolidation behaviour of clay slurry and lumpy soil as observed from model tests. In *Proceedings of the 4th Pan-Am CGS Geotechnical Conference*, ON, Canada.

Long, P. V., Bergado, B. T., Giao, P. H., Balasubramaniam, A. S. & Quang, N. C. (2006). Back analyses of compressibility and flow parameters of PVD improved soft ground in Southern Vietnam. *Proceedings of the 8th International Conference on Geosynthetics*, Yokohama.

Long, P. V., Bergado, D. T., Nguyen, L. V. & Balasubramaniam, A. S. (2013). Design and performance of soft ground improvement using PVD with and without vacuum consolidation. *Geotechnical Engineering Journal of the SEAGS and AGSSEA*, **44**, No. 4, 36–51.

López-Acosta, N. P., Espinosa-Santiago, A. L., Pineda-Núñez, V. M., Ossa, A., Mendoza, M. J., Ovando-Shelley, E. & Botero, E. (2019). Performance of a test embankment on very soft clayey soil improved with drain-to-drain vacuum preloading technology. *Geotextiles and Geomembranes*, **47**, No. 5, 618–631.

Phakdimek, S. & Soralump, S. (2018). Pore pressure behavior of clayey backfilled soil in a pond improved by vacuum consolidation method. *Proceedings of the 8th Regional Symposium on Infrastructure Development in Civil Engineering (RSID8),* Quezon City, Philippines.

Phakdimek, S., Ngernbumrung, P. & Soralump, S. (2020). Estimated Strength Properties of Soft Clay Lump Backfilled in a Pond Improved by Vacuum Consolidation Method. *Paper presented at the The 25th National Convention on Civil Engineering*, Chonburi, Thailand.

Pongprasert, P. & Benjaanunphong, R. (2025). Determinants of new condominium prices near MRT orange line stations: case study of estimating housing affordability in Bangkok, Thailand. *Hong Kong Journal of Social Sciences*, **64**, No. 64.

Robinson, R. G., Tan, T.-S., Dasari, G. R., Leung, C. F. & Vijayakumar, A. (2005). Experimental study of the behavior of a lumpy fill of soft clay. *International Journal of Geomechanics*, **5**, No. 2, 125–137.

Rujikiatkamjorn, C., Indraratna, B. & Chu, J. (2008). 2D and 3D numerical modeling of combined surcharge and vacuum preloading with vertical drains. *International Journal of Geomechanics*, **8**, No. 2, 144–156.

Seah, T. H. & Koslanant, S. (2003). Anisotropic consolidation behavior of soft Bangkok clay. *Geotechnical Testing Journal*, **26**, No. 3, 266–276.

Seah, T. H., Tangthansup, B. & Wongsatian, P. (2004). Horizontal coefficient of consolidation of soft Bangkok clay. *Geotechnical Testing Journal*, **27**, No. 5, 430–440.

Shi, X. & Herle, I. (2016). Structure transition of lumpy landfills with increasing stress level. *Quarterly Journal of Engineering Geology and Hydrogeology*, **49**, No. 4, 336–343.

Soralump, S., Shah, A. & Phakdimek, S. (2023). Consideration of multiple factors for quality control of improved clay from vacuum consolidation method. *Proceedings of the 21st Southeast Asian Geotechnical Conference and 4th AGSSEA Conference (SEAGC-AGSSEA 2023)*.

Soralump, S., Koirala, N. & Phakdimek, S. (2024). Mitigation of lateral slope movement and soil improvement using the vacuum-PVD scheme. *Geosynthetics International*, **31**, No. 4, 372–387.

Vichiensan, V., Wasuntarasook, V., Prakayaphun, T., Kii, M. & Hayashi, Y. (2023). Influence of urban railway network centrality on residential property values in Bangkok. *Sustainability*, **15**, No. 22, 16013.

Voottipruex, P., Bergado, D. T., Lam, L. G. & Hino, T. (2014). Back-analyses of flow parameters of PVD improved soft Bangkok clay with and without vacuum preloading from settlement data and numerical simulations. *Geotextiles and Geomembranes*, **42**, No. 5, 457–467.

Wang, A. Q., Hu, Y. Y., Zhou, W. H. & Liu, X. W. (2021). Analysis of one-dimensional nonlinear consolidation of a saturated lumpy porous clay layer. *Computers and Geotechnics*, **140**, 104458.

Yan, S.-W. & Chu, J. (2005). Soil improvement for a storage yard using the combined vacuum and fill preloading method. *Canadian Geotechnical Journal*, **42**, No. 4, 1094–1104.

Yang, L.-A., Tan, T.-S., Tan, S.-A. & Leung, C.-F. (2002). One-dimensional self-weight consolidation of a lumpy clay fill. *Géotechnique*, **52**, No. 10, 713–725.

Yang, L.-A. & Tan, T.-S. (2005). One-dimensional consolidation of lumpy clay with non-linear properties. *Géotechnique*, **55**, No. 3, 227–235.

Zhang, D., Fu, H., Wang, J., Zhu, D., Hu, X., Du, Y., Gou, C., Wang, C., Li, M. & Wu, H. (2021). Behaviour of thick marine deposits subjected to vacuum combined with surcharge preloading. *Marine Georesources & Geotechnology*, **39**, No. 10, 1147–1156.

Zhou, Y., Yang, H., Wang, P., Yang, X. T. & Xu, F. (2022). Vacuum-induced lateral deformation around a vertical drain in dredged slurry. *Geosynthetics International*, **29**, No. 5, 495–505.