

# Assessment of Prefabricated Vertical Drains and Surcharge for Accelerated Consolidation of Soft Marine Clay beneath an Embankment

Semala Raman<sup>1</sup>, Mahmud, M.S.M<sup>1</sup>, Hii, E.J.P. <sup>1</sup>, Bakhtiar Affandy Othman<sup>1,2</sup> and Dayang Zulaika Abang Hasbollah<sup>1,2</sup>

<sup>1</sup>Centre of Tropical Geoengineering, Faculty of Civil Engineering Technology, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

<sup>2</sup>Centre of Tropical Geoengineering (GEOTROPIK), D03 Level 2, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor.

**\*Corresponding Author:**

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## ABSTRACT

This study assesses the use of prefabricated vertical drains (PVDs) combined with surcharge preloading for accelerating consolidation of a thick soft marine clay deposit beneath an embankment in Kuala Langat, Selangor, Malaysia. The site comprises approximately 20–25 m of soft clay beneath fill, creating a significant settlement and construction-time constraint. A field investigation consisting of five boreholes and laboratory testing was used to establish the subsoil and consolidation parameters. PVDs were installed to approximately 25 m depth at 1.0 m spacing in a triangular arrangement, and a 3.5 m fill comprising platform fill and surcharge was considered. One-dimensional consolidation theory was used to estimate settlement, while the radial consolidation response of the PVD system was assessed using the Hansbo modification of Barron's solution. The calculated total settlement for the 3.5 m fill was 1419 mm, with 90% of the predicted primary consolidation settlement corresponding to 1277 mm. The analysis indicated that the 90% consolidation target could be achieved in approximately four months under the adopted PVD and surcharge arrangement.

**Keywords:** Soft soil; Marine clay; Prefabricated vertical drains; PVD; Surcharge preloading; Consolidation; Settlement; Ground improvement

## INTRODUCTION

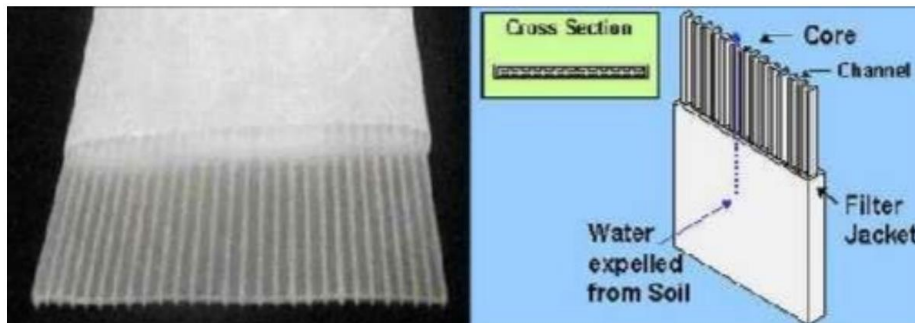
Soft soils are characterised by low shear strength, high compressibility and a tendency to undergo substantial deformation under construction loading [1,2]. These characteristics create difficulties for infrastructure founded on soft deposits, particularly where long-term settlement and construction time are critical considerations [3,4].

Prefabricated vertical drains (PVDs) are widely used to improve soft ground by providing short drainage paths for excess pore water and thereby accelerating consolidation [5,6,12]. Previous studies have examined settlement prediction, numerical simulation and analytical solutions for embankments improved using PVDs [7,8,9]. Installation spacing, smear effects, drain discharge capacity and the hydraulic properties of the soil are among the factors governing PVD performance [11,11,13,14].

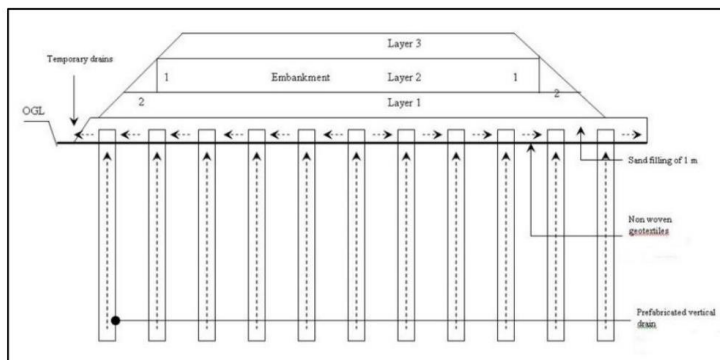
The objective of this paper is to analytically assess the predicted consolidation settlement and time required to achieve 90% consolidation under the adopted treatment scheme.

## LITERATURE REVIEW

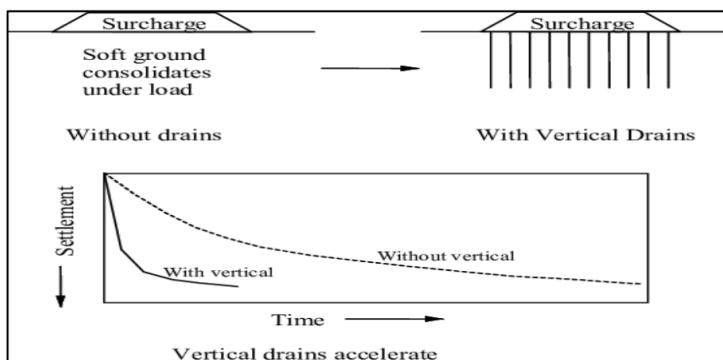
Prefabricated vertical drains (PVDs), also known as wick drains or strip drains, are geosynthetic materials engineered to expedite consolidation in soft soils, thereby enhancing soil strength and stability [15][16][17]. Their primary function is to provide efficient drainage pathways, expediting pore water expulsion from compressible soils and consequently reducing consolidation time and improving load-bearing capacity [18][19][20]. PVDs consist of a plastic core, typically corrugated or channelled polypropylene, encased within a geotextile filter. The core facilitates water flow and resists deformation [17][18][21], while the geotextile filter (woven or nonwoven) prevents soil particle ingress [15][17][18][19]. Advanced PVD designs utilize heat-melted core-filter integration for superior tensile strength and discharge capacity [22].



**Figure 1 PVD Appearance [17]**



**Figure 2 Typical Cross Section Using PVD [20]**



**Figure 3 Effect on The Settlement With and Without PVD [20]**

PVD installation entails vertically embedding the material using a hollow steel mandrel, which anchors the PVD at the specified depth before removal [18]. Installation employs vibratory or static methods, with pre-drilling potentially required for dense soils [18]. While some soil disturbance is inherent, properly managed installations typically minimize horizontal permeability reduction [20][23]. PVDs are arranged in square or triangular patterns; spacing is crucial for consolidation rate [23]. Applications are widespread, encompassing

roads, railways, airports, and land reclamation projects [19][20][22]. To optimize performance, PVDs are often integrated with preloading techniques, including surcharge fills [18][24], vacuum pressure [15][21][24][25], or heat preloading [15][24], which accelerate consolidation by increasing stress or reducing water viscosity to improve hydraulic conductivity. Electro-osmotic treatment may also be implemented to enhance soil drainage [26].

Advantages of employing prefabricated vertical drains (PVDs) include expedited consolidation [15][17], improved soil strength and stability [20][24], cost-effectiveness [15][21], and installation versatility [18]. Furthermore, they minimize soil disturbance relative to alternative methodologies [20][21]. Critical PVD properties, such as discharge capacity, tensile strength, filter characteristics, and dimensions, are paramount to performance. Specifically, discharge capacity must be adequate for site-specific conditions, and sufficient tensile strength is crucial to ensure PVD integrity during installation [22][26][27]. Filter design must effectively balance soil exclusion with unimpeded water flow [15][16]. PVDs represent a reliable and adaptable solution for enhancing soft soil conditions in construction projects [23]. By accelerating consolidation and optimizing soil performance, PVDs facilitate efficient and stable infrastructure development in challenging geotechnical environments.

### Mechanism of PVD In Improving Soft Clay

Prefabricated vertical drains (PVDs) accelerate the consolidation of soft clay by providing short and efficient drainage paths for excess pore-water dissipation [16][18][24][27]. When installed vertically through the compressible soil layer, PVDs provide preferential drainage pathways that allow pore water to flow horizontally from the surrounding soil towards the drain and subsequently flow vertically along the drain [15][17][24][28]. This process reduces the drainage distance and accelerates the dissipation of excess pore-water pressure.

The effectiveness of PVDs is closely related to the horizontal permeability of soft clay, as horizontal drainage towards the PVD is generally more efficient than vertical drainage through the soil layer [15][21][24]. As excess pore-water pressure dissipates, effective stress increases, resulting in progressive consolidation and improvement in the shear strength of the soft clay [15][20][21][29].

PVD installation is commonly carried out using a mandrel. The installation process may disturb the surrounding soil and form a smear zone, which can reduce the local horizontal permeability and consequently affect the rate of consolidation [11][15][21][25]. Therefore, smear effects and the characteristics of the disturbed zone should be considered in PVD design.

PVD performance is also influenced by drain spacing and installation pattern. Closer spacing reduces the drainage distance, while a triangular arrangement provides a relatively uniform distribution of drains within the treated area [16][18][20]. Appropriate selection of drain spacing, depth and installation method is therefore important to achieve the required degree of consolidation within the available construction period.

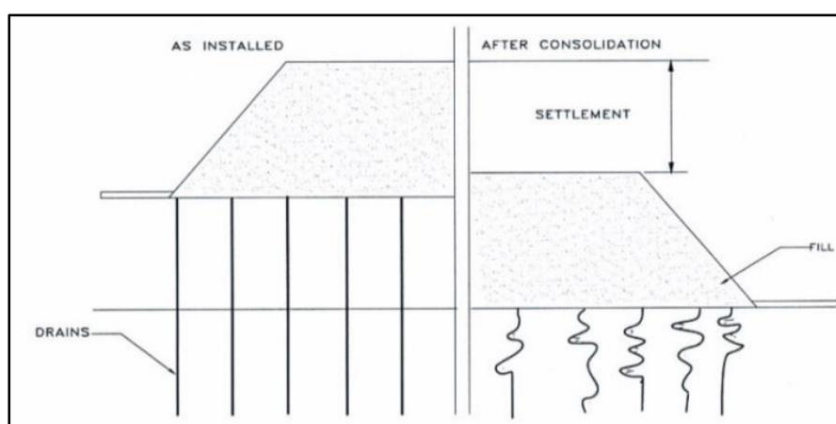


Figure 4 Drain Deformation During Consolidation [33]

## Advantages and Limitations of PVD In Soft Clay

The application of PVDs provides an effective means of accelerating consolidation in soft and highly compressible clay deposits. By shortening the drainage path, PVDs facilitate faster dissipation of excess pore-water pressure and allow the required consolidation to be achieved within a shorter construction period [16][18][24]. This is particularly beneficial for large embankment projects where excessive post-construction settlement and low initial soil strength may affect construction performance.

Another advantage of PVDs is their relatively simple installation and adaptability to large treatment areas. The drains can be installed to considerable depths using a mandrel system, allowing improvement of thick deposits of soft soil without requiring extensive excavation or replacement [11][18]. The use of appropriate drain spacing and installation patterns also provides flexibility in controlling the expected consolidation rate according to project requirements [16][20].

Despite these advantages, the performance of PVDs can be affected by several factors. Installation using a mandrel may disturb the surrounding soil and create a smear zone, resulting in a reduction in the horizontal permeability around the drain [15][21][25]. The resulting decrease in drainage efficiency may increase the time required to achieve the target degree of consolidation.

PVD performance may also be influenced by drain spacing, drain length, soil permeability and the discharge capacity of the drain [18][21][24]. Therefore, these parameters need to be appropriately considered when estimating the consolidation response. In addition, PVDs primarily accelerate the rate of consolidation and do not eliminate the magnitude of settlement caused by the applied embankment and surcharge loads. Proper design of the PVD system is therefore necessary to achieve the required consolidation within the intended construction period.

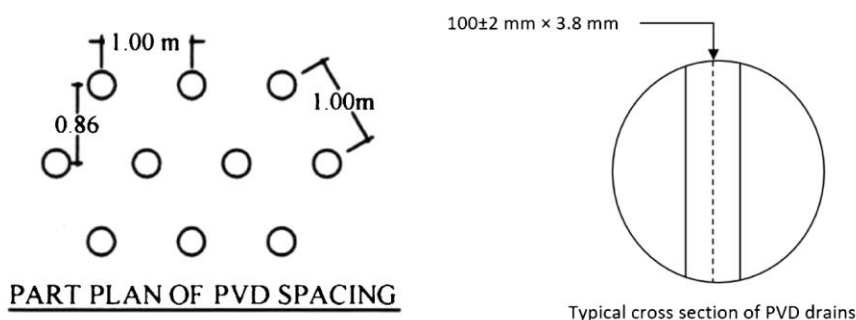


Figure 5 PVD Spacing and Typical Cross-Section of PVD Drains [21]

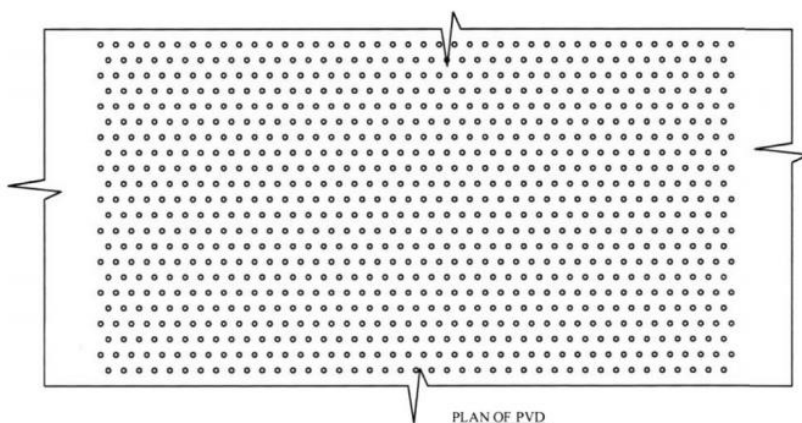


Figure 6 PVD Layout Plan [21]



(a)



(b)

**Figure 7 (a)PVD Installation [20] (b) Completed PVD Installation According to The Spacing, Pattern and Depth [20]**

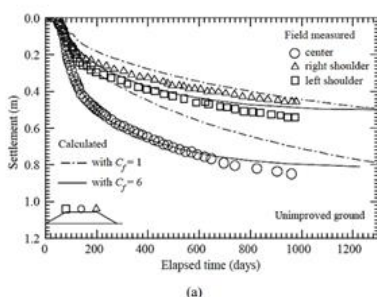
### Effectiveness and Cost Compared with Other Ground Improvement Methods

Several ground improvement techniques are available for improving soft and compressible soils, including stone columns, sand drains, vacuum consolidation and prefabricated vertical drains. The suitability of each method depends on the soil conditions, required improvement, construction sequence and project constraints [18][21][24]. PVDs are particularly suitable for thick deposits of soft clay because they provide an additional drainage pathway without requiring removal and replacement of the existing soil. Compared with conventional sand drains, PVDs generally require less material and can be installed at relatively close spacing, making them suitable for treatment over extensive areas [18][20]. Their use together with surcharge loading allows consolidation to occur before the supported structure is completed, thereby reducing the potential for significant post-construction settlement.

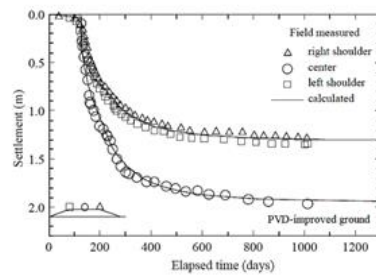
The effectiveness of PVD treatment is strongly dependent on the selected spacing and installation depth. A smaller spacing reduces the distance that pore water must travel to reach a drain and consequently increases the rate of consolidation [16][18]. However, closer spacing also increases the quantity of drains required. Therefore, the PVD arrangement should be selected by considering the required consolidation period together with construction and material requirements. For embankment construction over soft marine clay, the combination of surcharge loading and PVDs provides a practical approach for accelerating consolidation while retaining the existing soil. In this study, the assessment therefore focuses on the predicted settlement and consolidation response associated with the proposed PVD and surcharge arrangement.

**Table 1. Approximate Cost and Consolidation Time for Three Options of Soil Improvement [21]**

| Option                                                            | Consolidation time | Material cost (USD/m <sup>2</sup> ) | Construction cost (USD/m) |
|-------------------------------------------------------------------|--------------------|-------------------------------------|---------------------------|
| 200 mm diameter sand drain @ 1.0 m c/c in a triangular pattern    | 80–145             | 2.8                                 | 1.3                       |
| 200 mm diameter sand drain @ 1.5 m c/c in a triangular pattern    | 90–170             | 2.0                                 | 1.0                       |
| 250 mm diameter sand drain @ 1.0 m c/c in a triangular pattern    | 75–140             | 3.0                                 | 1.5                       |
| 250 mm diameter sand drain @ 1.5 m c/c in a triangular pattern    | 80–150             | 2.5                                 | 1.2                       |
| PVDs (width=100 mm, r=3.8 mm) @ 1.0 m c/c in a triangular pattern | 40–100             | 5.5                                 | 4.5                       |
| PVDs (width=100 mm, r=3.8 mm) @ 1.5 m c/c in a triangular pattern | 90–135             | 4.0                                 | 4.0                       |
| PVDs (width=100 mm, r=3.8 mm) @ 2.0 m c/c in a triangular pattern | 170–270            | 3.0                                 | 4.0                       |



(a)



(b)

**Figure 8 Measured and FE-Simulated Surface Settlement–Time Profiles of Embankment on: (a) Unimproved Ground and (b) PVD-Improved Ground [23]**

## Consolidation of Soft Soil

Consolidation is the gradual reduction in the volume of saturated soil resulting from the dissipation of excess pore-water pressure under an applied load. Soft clay is particularly susceptible to consolidation because of its low permeability and high compressibility. When an embankment or surcharge is placed on the soil surface, part of the applied load is initially carried by the pore water. With time, the excess pore-water pressure dissipates and the load is progressively transferred to the soil skeleton, resulting in an increase in effective stress and settlement [15][17][24].

The rate of consolidation depends primarily on the compressibility and permeability characteristics of the soil and the length of the drainage path. In conventional one-dimensional consolidation, drainage occurs mainly in the vertical direction and can therefore require a considerable period for thick deposits of low-permeability clay. The use of PVDs changes the drainage conditions by providing shorter horizontal drainage paths towards the installed drains [16][18][24].

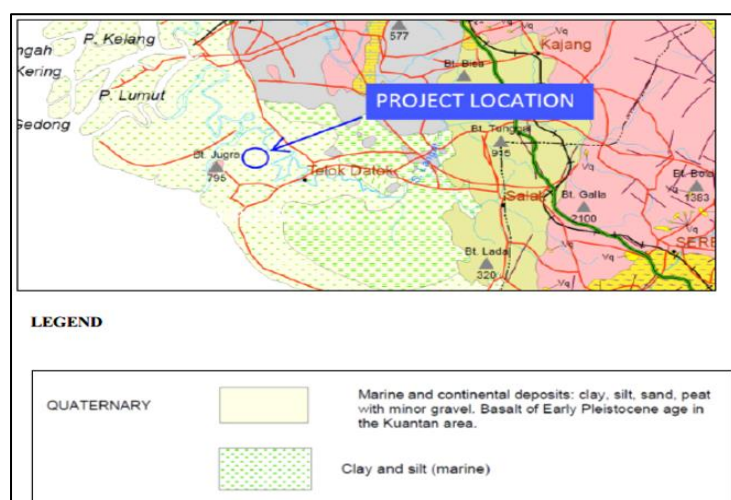
For an embankment constructed over soft clay, the magnitude of consolidation settlement is influenced by the thickness of the compressible soil, initial and final effective stresses, preconsolidation pressure and consolidation parameters such as the compression and recompression indices [17][24]. The time required to achieve a specified degree of consolidation is governed by the consolidation characteristics of the soil and, where PVDs are used, the drain spacing, equivalent drain diameter, horizontal coefficient of consolidation and effects associated with the smear zone and drain resistance [21][25][28].

In this study, one-dimensional consolidation theory is used to estimate the settlement resulting from the applied embankment and surcharge loading. The PVD analysis is subsequently used to evaluate the rate of consolidation by considering radial drainage towards the vertical drains. This approach provides an analytical basis for estimating the settlement magnitude and the time required to achieve the target degree of consolidation.

## Site Conditions and Methodology

The study site is situated in Mukim Bandar, Daerah Kuala Langat, Selangor, and proposed a development Phase 1 and Phase 2 which is comprises of 3 storey factories and infrastructural facilities such as roads, drains, water supply, sewage system, parks.

Based on the Geological Map of Selangor (Scale 1: 63,300) 1976, the proposed development site is located in Quaternary Formation. Figure 9 shows the site geology. Quaternary deposits consist of marine and continental deposits comprising of clay, silt, sand, with minor gravel. Figure 11 shows subsoil profile of five (5) deep boreholes.

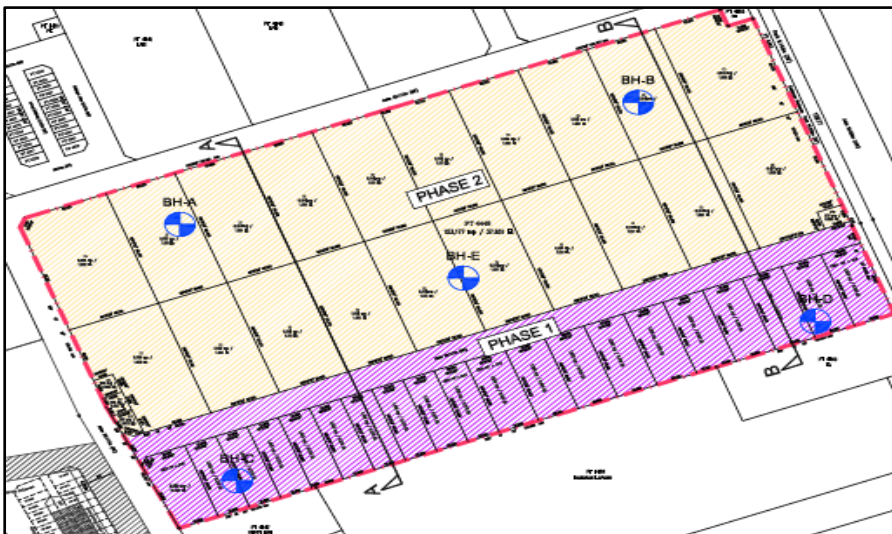


**Figure 9 Site Geology**

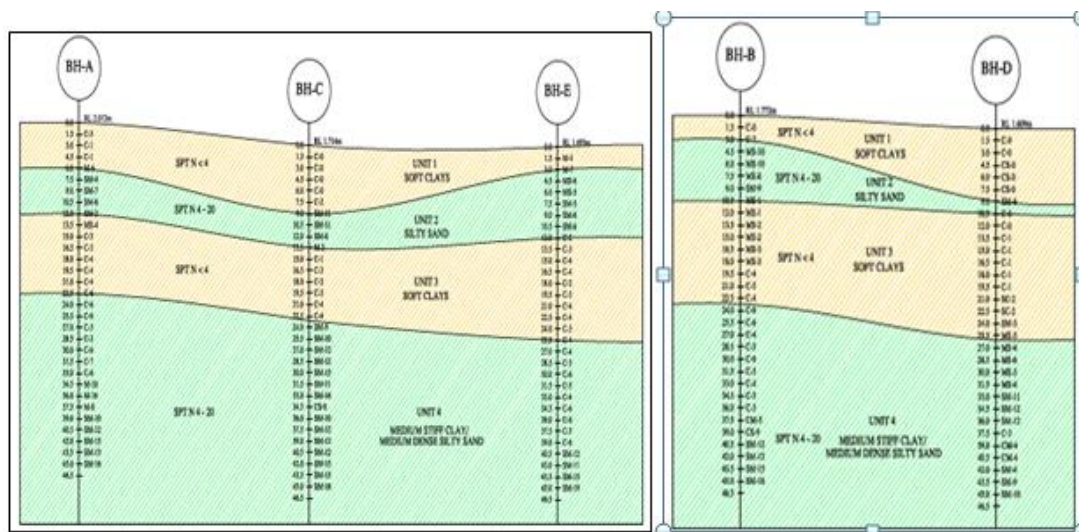
The fundamental properties, including, pre-consolidation pressure, compression ratio, recompression ratio, coefficient of vertical consolidation, coefficient of horizontal consolidation are collectively summarized in Table 3. The subsoil profile comprises as follows: 9 m of very soft clay, followed by 10 m of soft clay, and a 1.5 m sand blanket. Beneath this layer, a 1 m thick homogeneous soil is present, suitable for use as fill material.

**Marine Clay (Alluvium soils)** - These are surface deposits that mainly comprises of sediments of very soft to soft silts and clays. The SPT values are generally less than about 4 blows/300m. These soils are generally weak and are highly compressible. The depth of these soils varies from about 1.5m to 9m and 12m to 30m for Zone A and 1.5m to 9m and 10.5m to 37.5m for Zone B across the site.

**Residual soils** - This unit comprises of residual soils derived from weathered formation. The thickness of the layer varies from about 1.5m to 22.5m. The SPT N value of the layer is less than 20 blows/300mm.



**Figure 10 Soil Investigation**



**Figure 11. Subsoil profile Section A-A and Section B-B**

The data will be analysed and summarized based on the parameters necessary for settlement evaluation using empirical methods. Subsoil characteristics were derived from the site investigation. Table 2 outlines the soil parameters.

**Table 2. Summary of Soil Parameters Used for Settlement Assessment**

| Soil             | Depth (m) | Unit Weight (kN/m <sup>3</sup> ) | Undrained Shear Strength (kN/m <sup>2</sup> ) | Friction angle (°) |
|------------------|-----------|----------------------------------|-----------------------------------------------|--------------------|
| Sof Clay Layer 1 | 0 - 5     | 15                               | 14                                            | 0                  |
| Sof Clay Layer 2 | 5 - 10    | 15.2                             | 17                                            | 0                  |
| Sof Clay Layer 3 | 10 - 15   | 15.5                             | 20                                            | 0                  |
| Sof Clay Layer 4 | 15 - 20   | 16.0                             | 25                                            | 0                  |
| Sof Clay Layer 5 | 20 - 25   | 16.5                             | 30                                            | 0                  |

The consolidation parameters adopted for the settlement analysis were assigned according to the corresponding soil depth intervals presented in Table 3. The compressible clay layer was divided into five 5 m thick zones from 0 to 25 m depth, and the preconsolidation pressure, compression index ( $C_c$ ), recompression index ( $C_r$ ), vertical coefficient of consolidation ( $C_v$ ), and horizontal coefficient of consolidation ( $C_h$ ) were assigned separately to each zone. These depth-dependent parameters were used to represent the variation in soil compressibility and consolidation characteristics with depth rather than applying a single average value to the entire clay layer. The adopted parameters were subsequently used in the settlement and consolidation-time calculations.

**Table 3 Summary of Soft Ground Properties**

| Depth (m) | Preconsolidation Pressure (kPa) | Compression Ratio | Recompression Ratio | Coefficient of Vertical Consolidation ( $C_v$ ) m <sup>2</sup> /yr | Coefficient of Horizontal Consolidation ( $C_h$ ) m <sup>2</sup> /yr |
|-----------|---------------------------------|-------------------|---------------------|--------------------------------------------------------------------|----------------------------------------------------------------------|
| 0 - 5     | 35                              | 0.30              | 0.030               | 1.5                                                                | 3                                                                    |
| 5 - 10    | 70                              | 0.28              | 0.028               | 1.5                                                                | 3                                                                    |
| 10 - 15   | 80                              | 0.25              | 0.025               | 1.5                                                                | 3                                                                    |
| 15 - 20   | 100                             | 0.22              | 0.022               | 1.5                                                                | 3                                                                    |
| 20 - 25   | 140                             | 0.20              | 0.020               | 1.5                                                                | 3                                                                    |

### Settlement Analysis

Terzaghi's one-dimensional (1D) consolidation theory [12] was applied to estimate the settlements associated with 1D primary consolidation. Settlement analysis was conducted for anticipated settlements under backfilling to the design platform and compensation fill. Settlements due to a 1.5 m backfill and 2.0m

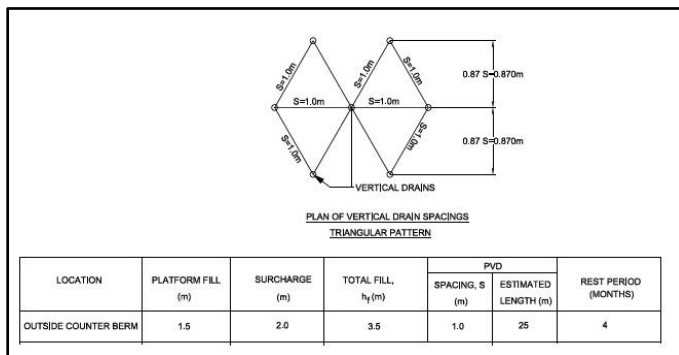
surcharge fill were analysed to assess the impact of pre-compression. Additionally, the role of vertical drains in expediting the consolidation process was evaluated.

The effectiveness of ground improvement was assessed based on meeting prescribed performance criteria and improvements in engineering properties.

Fill loading causes consolidation settlement in the underlying soft clay; therefore, ground improvement is required to accelerate consolidation and reduce post-construction settlement.

Ground treatment will minimize the post construction settlements of the platforms which supports the infrastructural facilities. The method of treatment will depend on the type of subsoil, their thickness and the time available for ground treatment works. The scope of work for the current ground treatment works is indicated as Phase 1 and Phase 2. Surcharge Preloading with Prefabricated Vertical Drains (PVD) method of soft ground treatment is proposed for Phase 1 considering the time available and the cost economics. This study is focused on Phase 1 which is the filling work with using geotextile reinforcement to ensure the stability of the embankment.

In this method, Prefabricated Vertical Drains are installed in the soft ground at design spacing and surcharge is applied on the ground subsequently to accelerate the consolidation settlements prior to construction of the infrastructural facilities and structures. This will reduce the amount of post construction settlements of the ground. Figure 12 shows the typical detail of PVD.



**Figure 12 Typical Detail of PVD**

### Prefabricated Vertical Drains (PVD) And Surcharge

The design of the surcharge and PVD scheme was carried out to achieve 90% of the total primary consolidation settlements that is predicted to occur under the weight of the platform fill.

Terzaghi's one-dimensional consolidation theory was used to assess the primary consolidation settlements. For over-consolidated clays, the primary settlement is given by:

$$S = \left( \frac{C_r}{1 + e_0} \right) \log_{10} \left( \frac{\sigma'_{v0} + \Delta\sigma'}{\sigma'_{v0}} \right) H \quad \text{for } \sigma'_{v0} + \Delta\sigma' \leq \sigma'_c$$

$$S = \left( \frac{C_r}{1 + e_0} \right) \log_{10} \left( \frac{\sigma'_c}{\sigma'_{v0}} \right) H + \left( \frac{C_c}{1 + e_0} \right) \log_{10} \left( \frac{\sigma'_{v0} + \Delta\sigma'}{\sigma'_c} \right) H \quad \text{for } \sigma'_{v0} < \sigma'_c < \sigma'_{v0} + \Delta\sigma'$$

where:

$S$  = primary consolidation settlement

$\sigma'_{v0}$  = initial effective overburden pressure

$\sigma'_c$  = preconsolidation pressure

$\Delta\sigma'$  = increase in vertical effective stress on soil layer

$C_c$  = compression index

$C_r$  = recompression index

$e_0$  = initial void ratio

$H$  = thickness of compressible soil layer

The consolidation settlement estimates and required compensating fill thickness were carried out for each zone.

### Prefabricated Vertical Drains (PVD)

Prefabricated vertical drains (PVD) are specified in conjunction with surcharge loading to accelerate radial pore-water dissipation across the full depth of the soft clay stratum. The spacing and arrangement of the PVD network are evaluated using Hansbo's (1979) modification of Barron's solution for radial consolidation.

The average degree of consolidation due to radial flow ( $U_h$ ) over a consolidation period ( $t$ ) is expressed as:

$$U_h = 1 - \exp\left(-\frac{8T_h}{F}\right)$$

where  $T_h$  represents the dimensionless time factor for horizontal drainage:

$$T_h = \frac{C_h \cdot t}{D_e^2}$$

The overall resistance factor ( $F$ ) accounts for the geometric spacing ratio  $F(n)$ , smear-zone disturbance  $F_s$ , and drain well-resistance  $F_r$ :

$$F = F(n) + F_s + F_r$$

$$F(n) = \ln\left(\frac{D_e}{d_w}\right) - 0.75$$

$$F_s = \left(\frac{k_h}{k_s} - 1\right) \ln\left(\frac{d_s}{d_w}\right)$$

$$F_r = \pi \cdot z \cdot (2L - z) \cdot \frac{k_h}{q_w}$$

The equivalent zone of influence ( $D_e$ ) for a triangular installation layout relates to the center-to-center drain spacing ( $S$ ) by:

$$D_e = 1.05 \cdot S$$

To ensure full transparency and reproducibility of the settlement timeline, the parameters adopted for the design of the PVD scheme are summarized in Table 3.1.

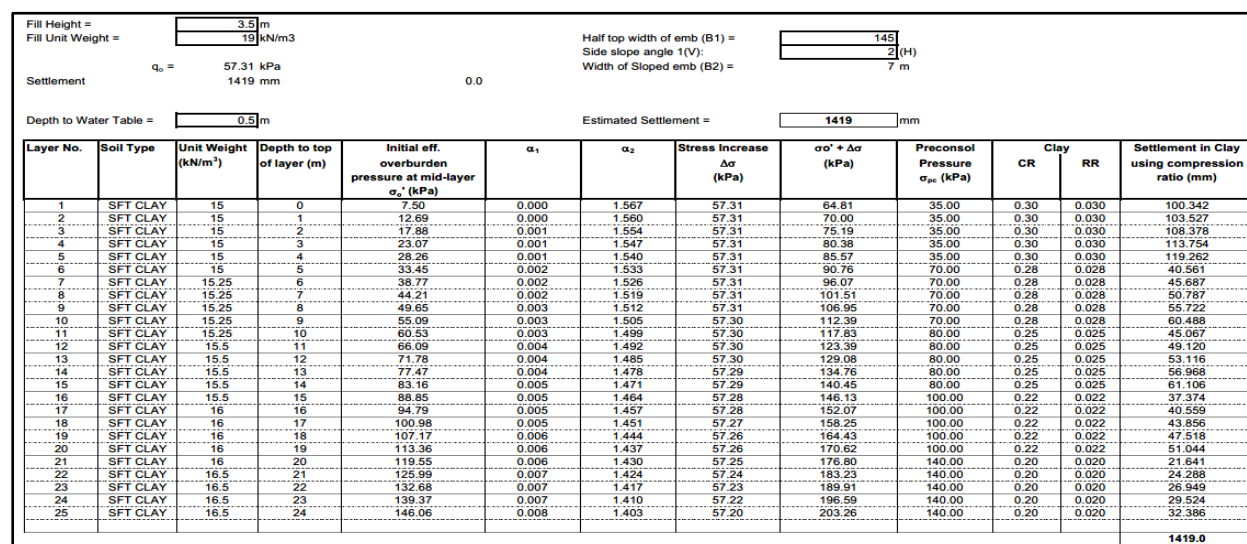
**Table 3** Design parameters adopted for PVD and radial consolidation analysis.

| Parameter                                              | Symbol    | Adopted Value | Unit              |
|--------------------------------------------------------|-----------|---------------|-------------------|
| Preloading rest period                                 | $t$       | 4 (0.333)     | months (year)     |
| Target degree of consolidation                         | $U_h$     | 85            | %                 |
| Coefficient of horizontal consolidation                | $C_h$     | 3             | $m^2/\text{year}$ |
| Ratio of drain discharge capacity to soil permeability | $q_w/k_h$ | 400           | $m^2$             |
| Drain length                                           | $L$       | 25            | m                 |
| Ratio of horizontal to smear zone permeability         | $k_h/k_s$ | 2             | —                 |
| Smear zone diameter ratio                              | $d_s/d_w$ | 4             | —                 |
| Proposed drain spacing                                 | $S$       | 1.00          | m                 |
| Installation layout                                    | —         | Triangular    | —                 |
| Spacing factor                                         | $F(n)$    | 2.29          | —                 |
| Smear factor                                           | $F_s$     | 1.39          | —                 |
| Well-resistance factor                                 | $F_r$     | 1.23          | —                 |
| Combined resistance factor                             | $F$       | 4.91          | —                 |
| Dimensionless time factor                              | $T_h$     | 1.16          | —                 |

Based on these governing parameters, a proposed PVD spacing of 1.00 m achieves the target degree of consolidation ( $U_h = 85\%$ ) within the required 4-month preloading period.

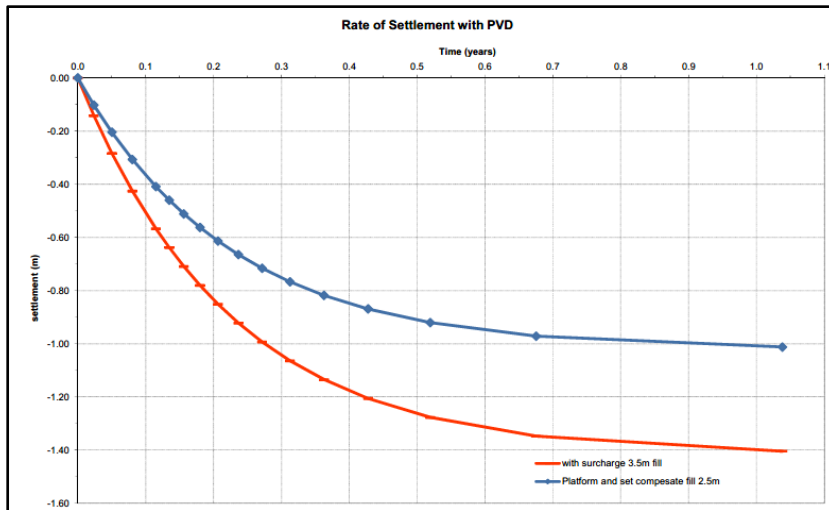
## RESULTS AND DISCUSSION

### Predicted Settlement



**Figure 13** Total Estimated Settlement

Based on Figure 13, the estimated total settlement for a fill height of 3.5m (comprising platform fill and surcharge fill) is 1419mm. To expedite drainage, prefabricated vertical drains (PVD) will be installed alongside the surcharge. The adopted PVD and surcharge arrangement is intended to accelerate consolidation and reduce the time required to achieve the target degree of consolidation.



**Figure 14 Predicted/Calculated settlement-time response**

### Engineering Implications of the PVD Scheme

The analysis shows that the PVD arrangement reduces the drainage distance within the soft clay and provides an additional pathway for excess pore water to dissipate during consolidation [12][40][41][42]. As the excess pore-water pressure decreases, the effective stress carried by the soil increases and settlement develops under the applied fill and surcharge loading.

The consolidation rate is affected by the spacing of the PVDs, the disturbance of the soil around the drains, the discharge capacity of the drains and the conditions during installation [10][13][14][43][44]. Among these parameters, drain spacing has a direct influence on the drainage distance. A smaller spacing provides a shorter path for water to reach the drains and can therefore increase the rate of consolidation. However, reducing the spacing also increases the number of drains required. The spacing should therefore be selected based on the required consolidation period and the characteristics of the soft soil.

For the site considered in this study, PVDs were adopted at 1.0 m triangular spacing and extended to approximately 25 m depth. The selected spacing and drain depth were based on the thickness and consolidation characteristics of the soft clay considered in the analysis. These values are specific to the conditions assessed in this study and should not be directly applied to other sites without considering their respective soil properties and consolidation requirements.

Overall, the analytical results indicate that the proposed PVD and surcharge arrangement can accelerate the consolidation process within the assessed period. The predicted response is based on the soil parameters and PVD design parameters adopted in the analysis. Therefore, the results represent an analytical assessment of the proposed ground improvement scheme rather than direct field verification of its performance.

### CONCLUSIONS

This study evaluated the performance of prefabricated vertical drains (PVDs) combined with surcharge preloading for improving a 25 m thick soft marine clay deposit in Kuala Langat, Selangor. For a total fill height of 3.5 m (1.5 m platform fill and 2.0 m surcharge), the total estimated primary consolidation settlement is 1419 mm, with a target 90% settlement of 1277 mm. Using Hansbo's radial drainage theory, the analysis confirms that installing PVDs at a 1.0 m triangular spacing to a depth of 25 m successfully achieves the target degree of consolidation ( $U_h \geq 85\%$ ) within a 4-month preloading window. Incorporating depth-dependent soil properties, smear-zone disturbance, and drain well-resistance provides a robust analytical framework for sizing PVD networks and predicting settlement timelines for soft ground infrastructure works.

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