

Investigation of creep behavior of soft soil during and after vacuum preloading

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Abstract: Soft soil has been a major problem in the northern part of Java for the last decade, and several areas have been improved using the preloading method. In Indonesia, the improvement of soft soil using this method has already been regulated in several codes, such as SNI 8460:2017 and Geotechnical Manual series 4. However, these codes did not mention the effects of creep on post-settlement. In addition to creep, several factors influence the amount of post-settlement during the operational period, such as the thickness of the soft soil, load ratio, soil compression ratio, and the drain spacing and pattern. Larger spacing or pattern, higher compression ratio, greater secondary compression index (C_{α}), and increased soft soil thickness induce more post-settlement. In contrast, a higher load ratio resulted in less post-settlement. It was discovered that the load ratio of 1.20 stated in SNI 8460:2017 did not meet the requirement of a maximum yearly settlement of 20 mm as specified in Geotechnical Manual series 4. This research showed that with and without creep, the load ratio required should be in the range of 1.30 to 1.50, with an average value of 1.375. Furthermore, this study proposed a new coefficient, the load ratio coefficient (C_{LR}), that accounts for various factors influencing post-settlement. The proposed coefficient can be utilized along with a period of interest to estimate the post-settlement due to creep. It was also observed that the load ratio heavily affects the post-settlement.

Keywords: creep; load ratio; preloading; vacuum preloading

1 Introduction

Soft soil presents a major challenge in infrastructure design, and its creep behavior has been a difficult issue for engineers and researchers for many years^[1-2]. The northern region of Java, Indonesia, is characterized by soft alluvial soils that pose challenges to the construction and long-term performance of infrastructure such as roads, bridges, and other facilities^[3-4]. In particular, North Jakarta has been the subject of research on soft soil behavior for over a decade^[5-8]. Hence, ground improvement is necessary to conduct in this region, with vacuum preloading being the commonly employed technique.

Soft soil has a unique characteristic of exhibiting large strains during loading^[9-10] due to high compression index, void ratio, or compression ratio factors^[11]. These large strains can be mitigated using the preloading method. The fundamental concept of preloading involves applying a higher load during the improvement period compared to the operational period^[9]. This approach aims to mitigate potential post-settlement issues during the operational phase. The critical factor in this method is the ratio of the load used during improvement to that used during the operational phase^[12-13]. One of the preloading methods commonly used and renowned for its effectiveness, as highlighted in various studies, is vacuum preloading^[9, 14-16], and in Indonesia, vacuum

preloading is well-recognized for its efficacy in mitigating post-settlement issues during operational phases^[17-18].

However, in certain cases of preloading, significant settlement may persist, extending beyond 10 years into the operational phase. This enduring settlement was attributed to secondary consolidation or creep settlement^[19]. It is important to note that secondary compression will persist and never reach zero, but it can be reduced in tandem with a decrease in void ratio^[20]. The void ratio can be diminished by applying pre-compression pressure, such as preloading. Consequently, the application of preloading to creep soil can lead to a substantial reduction in post-settlement^[21-22].

International standards, such as the British Standard (BS EN 15237:2007)^[23], recognize that preloading can reduce post-settlement caused by secondary compression. However, the standard did not specify the extent of this reduction. In Indonesia, preloading is well-established through its national codes (i.e., SNI 8460:2017^[24] and Geotechnical Manual series 4^[25]), and is widely implemented in various projects. The Indonesian Geotechnics Requirement^[24] requires a preloading load 1.20 times greater than the operational load^[24], whereas the Geotechnical Manual series 4 limit the yearly post-settlement to 20 mm at 90% consolidation^[25]. However, neither code specified the minimum load ratio needed to address secondary compression, which this study aims to determine.

2 Soil preloading and its impact to secondary compression

2.1 Soil improvement method(preloading)

As mentioned in Chapter 1, preloading is a technique for improving soil that is aimed at mitigating post-settlement issues during its operational period. The post-construction settlement without preloading is represented by the dash-dot line in Fig.1, e_0 , e_1 are initial void ratio and the void ratio after preloading, e'_0 is the void ratio after the preloading is completed, Δe is the void ratio difference before and after preloading, $\Delta e'$ is the void ratio difference before and after unloading preload, $\Delta \sigma_z$ is the applied stress, σ'_{z0} is the initial overburden stress, τ_f , τ'_f are initial shear strength and post preloading shear strength, $\Delta \tau_f$ is shear strength difference before and

after preloading. Figure 1 indicating that structural settlement can become a significant issue. In contrast, when preloading is applied, the majority of settlement occurs during the preloading period, as shown by the solid line. This settlement is greater than the subsequent settlement that occurs during the operational period, demonstrating the effectiveness of preloading in reducing post- construction settlement.

The amount of preloading load is defined by the load ratio. The load ratio is the ratio of the improvement load compared to the operational load. The improvement load includes all loads applied above the original soil that induce excess pore pressure, such as a new backfill platform, soil surcharge, and other elements during the improvement stages. The operational load is the total load that has been applied during operations, including settlement compensation, leveling backfills, and others.

Mesri et al. [19] studied the impact of the amount of preloading on the post-settlement generated. In the study, the concept load ratio is represented by the parameter R_s (surcharging effort). The study concluded that the amount of preloading allowed additional time for the secondary settlement to rebound. It was also stated that preloading in soft soil reduces post-construction secondary settlement by decreasing the secondary compression index from C_α to C'_α . C_α is the secondary compression index after primary consolidation. In contrast, C'_α is the secondary compression index occurs after surcharge removal, representing creep along the flatter recompression curve, leading to slower and smaller post-surcharge settlement. Essentially, C'_α is smaller than C_α because surcharging pre-stiffens the soil.

2.2 Impact factors on preloading

Indraratna et al. [26] conducted research on the amount of post-settlement reduction due to the impact of preloading. Based on the conditions during the improvement process, the study summarized them using a factor called the β -factor. The β -factor is proposed to consider the drain and site loading conditions for a given depth of soil, regardless of the soil properties. β -factor is a dimensionless factor that considers aspects such as drain length, soft soil depth, improvement load, drain spacing, and diameter which could be determined as follows [26]:

$$\beta = (l_d \times H) / (\alpha \times s_d \times h_c) \quad (1)$$

where l_d is the vertical drain length; s_d is the spacing of the vertical drains; α is the pattern of the prefabricated vertical drains (1.05 for triangular and 1.13 for square spacing); H is the preloading height; and h_c is the compressible thickness of soft soil. A larger amount of β -factor means more impact has been given to the soft soil leading to lower post-settlement.

2.3 Impact of preloading to secondary compression

The impact of soil preloading on reducing the

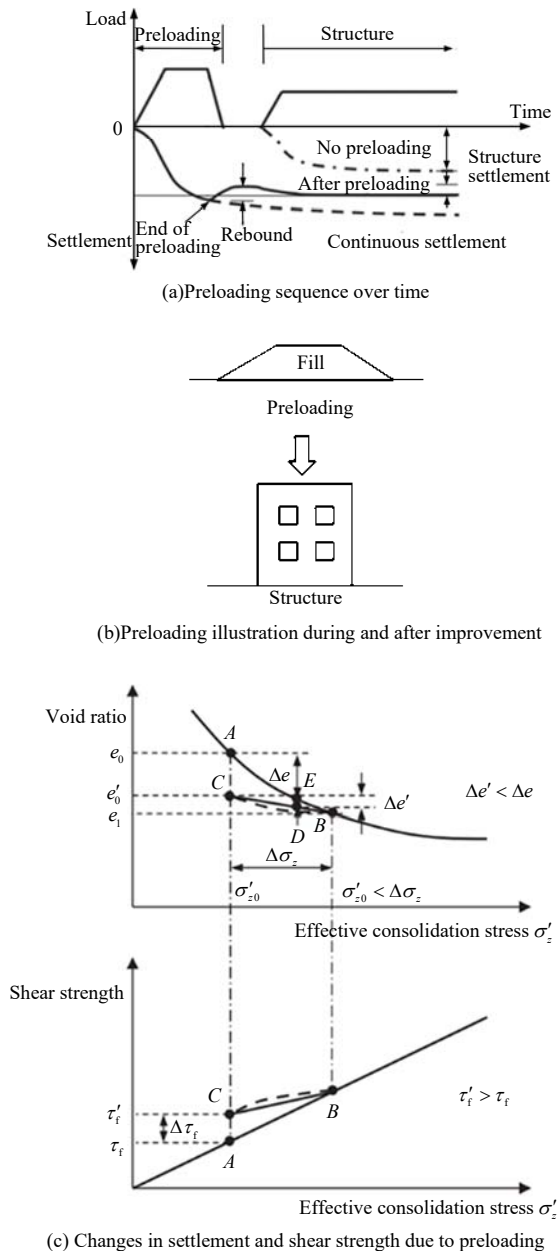


Fig. 1 Preloading sequence (Han [10])

secondary compression has been studied by Mesri et al.^[27]. The magnitude of the applied load on the soil significantly impacts the process of restoring secondary compression index (C_α) values to the consolidation curve. Instead of Load Ratio (LR), the study used R'_s which is the ratio between the vertical stress before and after unloading, denoted as σ_{vs} (total stress during preloading) and σ_{vf} (total stress after preloading complete), respectively. This ratio was found to be similar to the load ratio previously mentioned in the British Standard and Indonesian National Standard^[23-24].

Mesri et al.^[27] asserted that by applying a larger preloading load, the C_α value can transform into C''_α (normalized secondary settlement index), allowing for additional time for the secondary settlement to rebound. In Fig.2, the ratio between the effective vertical stress after completion of preloading, σ_{vf} , and the preconsolidation pressure σ'_p from St. Hilaire clay of different R'_s value is compared. It is evident that unloading at a low R'_s value resulted in no ground uplift (Change in void ratio, $\Delta e < 0$), and secondary subsidence recurred relatively quickly. In contrast, areas with larger R'_s experienced secondary rises and falls over an extended period.

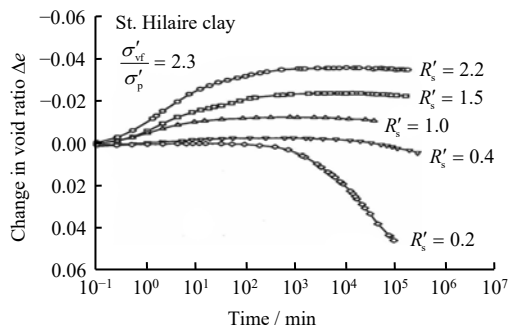


Fig. 2 Post-surge rebound and secondary compression of an inorganic soft clay as a function of effective surcharge ratio

In this study, R'_s is analogous to the load ratio during the ground improvement period, where a higher applied preloading stress leads to a greater degree of overconsolidation and reduced post-construction settlement. This supports the proposed use of a load ratio-based coefficient in estimating long-term creep settlement, as higher load ratios (larger R'_s) directly correlate with improved long-term performance.

3 Analytical method and soil model

3.1 D-settlement software

D-settlement is a geotechnical software program that is capable of simulating how soil behaves under different loading and unloading conditions. It outputs settlement curves that show how the soil responds to immediate, primary, and secondary consolidation.

D-settlement has been widely used and has shown to accurately predict settlement over time due to construction load. The key features of this software include predicting primary or secondary settlement, layered soil models, time-dependent analysis, several load type models, and ground improvement simulation. Tirta et al.^[28] analyzed the prediction for reclamation on the Holocene Marine Clay Deposit in Jakarta Bay. In the study, complex loading was modeled with well-defined soil parameters as well as accounting for various risk factors. This led to not only a well-predicted immediate settlement, but also the secondary settlement. Although, some parameters could not be calculated, such as quality of fill material and ground water fluctuation that may affect the consolidation process.

3.2 Soil models

There are 3 models that can be simulated using the D-Settlement program. This study shall use the NEN-Bjerrum soil model due to its suitability in capturing soil behavior under loading and unloading or reloading. This model simulates a linear strain model and supports linear strain parameters such as compression ratio, recompression ratio, and the secondary compression or secondary compression index (C_α). Other than simulating the settlement curve based on the input parameters, D-Settlement could also conduct back-analyses using settlement plate data and vacuum pressure data to back-calculate the soil parameters.

The NEN-Bjerrum model (Fig.3) simulates the idealized primary settlement loading and unloading behavior, which is also known as the typical void ratio plot with the vertical effective stress. In Fig.3, Δh_{prim} is a settlement during primary consolidation, Δh_{sec} is a settlement during secondary consolidation, Δh is total settlement, h_0 is the total thickness of the improvement layer, t is the total duration of consolidation, t_0 is time. Creep is a model based on viscoplastic behavior, meaning the strain induced by creep depends on Time Variable stress rate, the reached creep strain at a certain time, and the current overconsolidation ratio (OCR). Under different load ratios, the model is able to simulate the different settlement behaviors of

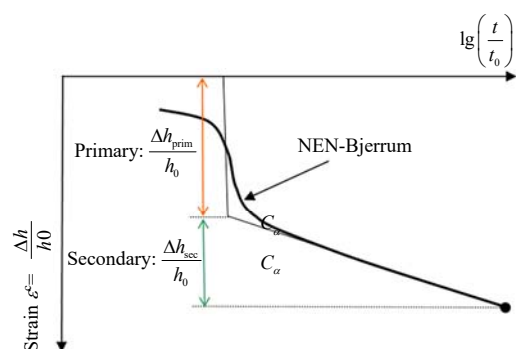


Fig. 3 NEN-Bjerrum

creep depending on the subjected improvement load, which aligns with the findings of Mesri et al.^[19]

The D-settlement program have been used in previous research by Chi et al.^[29], where D-settlement is used during construction to dealing with the high variability nature of the soft soils and also to achieve an optimum effectiveness of soil improvement. In the D-settlement which Chi et al.^[29] used, NEN-Bjerrum model and Darcy approach for consolidation model were combined to analyze the settlement behaviour which also used in this study. D-Settlement used a fit factors to multiply the main consolidation and compressibility parameters in a weight least squares procedure, which minimize not only the deviation between prediction and settlement, but also the deviation between the initial and modified parameters.

As a result, a satisfactory match is achieved for measurement from all settlement plates after 3,000 days which can be explained from the high similarity in the loading history and the evolution of settlement.

3.3 Model geometry and boundary

The model geometry was made in a 2D model with a total width of 100 m. The soil thickness, load, and parameters depend on the parametric study which shall be explained in Chapter 3.4. The model assumed that the bottom layer of the model and the platform were incompressible. Therefore, both layers will not induce any settlement.

In the soil model, the prefabricated vertical drain (PVD) depth follows the thickness of the model. During the improvement period, a typical vacuum preloading process applies a vacuum pressure of approximately 80 kPa, maintained consistently without significant loss over a period of 120 days^[30]. The PVDs were assumed to have a spacing of 1 m, a width and thickness of 100 mm and 3 mm, respectively. 2 types of grids were used in the parametric study, namely triangular and rectangular.

The operational load in this model was assumed to be a distributed load, referred to as a non-uniform load in the D-Settlement software. The operational load model refers to the pre-determined load ratio. For example, if the load ratio was 1.00, the non-uniform load was modeled to match the total improvement load, which is the vacuum pressure of 80 kPa. Therefore, the non-uniform load was set to 80 kPa. The non-uniform load shall be applied after the vacuum has already stopped for 30 days. As a result, the modeled settlement curve showed 30 days of rebound, followed by post-settlement behavior. An example of the D-Settlement soil model can be seen in Fig.4.

3.4 Parametric study

A parametric study was conducted to identify the key factors influencing post-settlement over time. Six main parameters are discussed in this paper, namely soil thickness, compression ratio, secondary compression

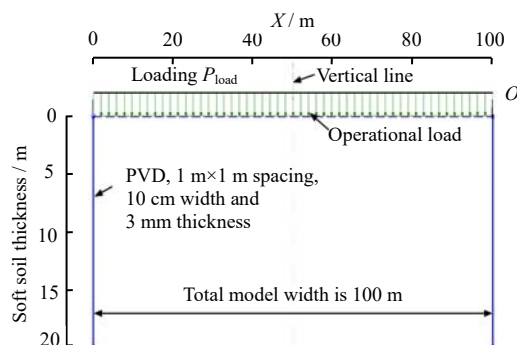


Fig. 4 Typical D-settlement soil model

index, drain spacing and pattern, and load ratio. Based on Setionegoro^[5], soft soil in North Jakarta typically has a thickness around 10 to 20 m. Hence, the study shall vary the thickness to 10, 15 m, and 20 m. The compression ratio (CR) was varied from 0.17 to 0.30 which encompassed moderately to highly compressible soil^[11]. These parameters were used to analyze the behavior of soft soils in generating post-settlement after the vacuum preloading period while also considering different soil stiffnesses. The secondary compression ratio or the secondary compression index (C_α) is an important parameter of secondary settlement, which is the main aim of this study. In this parametric study, the secondary compression index was taken from the correlation by Andersen^[31] between the compression ratio and the secondary compression index. The correlation was then plotted to the soil parameters in North Jakarta in Chapter 6. Varying the load ratio was conducted to examine the behavior under load ratios below 1.00, close to 1.00, and above 1.00 in inducing post-settlement. As mentioned in Chapter 2.2, drain spacing and pattern have an impact on the conditions of preloading. The spacing of the vertical drains can influence the degree of consolidation, as smaller drain spacings require a shorter distance for water to travel and dissipate compared to larger spacings. In this parametric study, the vertical drain spacing was in the range of 0.8–1.2 m. The 0.8 m drain spacing was chosen to minimize the effects of the smear zone, which becomes significant with closer spacing. If the drain spacing exceeded 1.2 m, the consolidation process takes longer, resulting in an extended preloading period. Whereas the pattern of the vertical drains affects the equivalent influence area. In design practice, two drain spacing patterns are commonly implemented: the triangular pattern and the rectangular pattern. Each pattern resulted in a different equivalent diameter of a unit cell. Approximately, the triangular pattern has an equivalent influence area of $1.06 s$, while the rectangular pattern has a larger equivalent area of $1.13 s$, where s refers to the spacing^[10]. All six parameters were analyzed by utilizing both creep and no creep behaviors to check the influence of creep parameters. The complete set of analyses is provided in Table 1.

Table 1 Parametric study

Set analysis	Soft soil thickness H / m	Function $f(C_\alpha)$	Compression ratio (CR)	Load ratio (LR)	Spacing (s) / m	Pattern	Description
1	10, 15, 20	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	0.50; 0.75; 1.00; 1.20; 1.50; 2.00	1.00	Rectangular	Investigate the effects of varying soil thickness
2	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$, $f(C_\alpha) = 0.005 \cdot CR^{1.58}$, $f(C_\alpha) = 0.016 \cdot CR^{1.58}$	0.20; 0.30	0.50; 0.75; 1.00; 1.20; 1.50; 2.00	1.00	Rectangular	Investigate the effects of varying secondary compression index (C_α)
3	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.17; 0.20; 0.22; 0.25; 0.27; 0.30	0.50; 0.75; 1.00; 1.20; 1.50; 2.00	1.00	Rectangular	Investigate the effects of varying CR
4	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	0.50; 0.70; 0.80; 0.85; 0.90	1.00	Rectangular	Investigate soft soil behavior under $LR < 1$
5	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	0.95; 1.00; 1.05	1.00	Rectangular	Investigate soft soil behavior under LR approaching 1
6	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	1.10; 1.15; 1.20; 1.30; 1.40; 1.50; 2.00; 3.00; 4.00; 5.00	1.00	Rectangular	Investigate soft soil behavior under $LR > 1$
7	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	0.50; 0.75; 1.00; 1.20; 1.50; 2.00	0.80; 1.00; 1.20	Rectangular	Investigate soft soil behavior under different drain spacings with a rectangular pattern
8	15	$f(C_\alpha) = 0.009 \cdot CR^{1.58}$	0.20; 0.30	0.50; 0.75; 1.00; 1.20; 1.50; 2.00	0.80; 1.00; 1.20	Triangular	Investigate soft soil behavior under different drain spacings with a triangular pattern

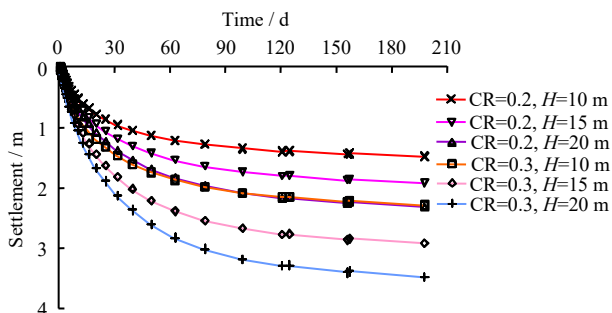
Note: *Secondary compression index (C_α) was input when the conducted analysis considered creep, $f(C_\alpha)$ can be seen in the formula below. Eq. (6) best fit regression: $f(C_\alpha) = 0.009 \cdot CR^{1.58}$; Eq.(7) quantile 5% or lower bound: $f(C_\alpha) = 0.005 \cdot CR^{1.58}$; Eq.(8) quantile 95% or upper bound: $f(C_\alpha) = 0.016 \cdot CR^{1.58}$. Mirrored analyses were conducted with and without considering creep.

4 Results analysis

4.1 Back-analysis of vertical coefficient of consolidation

The parametric study checks the post-settlement behavior due to different parameters and given conditions to the soil during the improvement period. The parameters in the study were maintained under vacuum preloading conditions, where vacuum preloading using PVDs with a 1 m × 1 m square pattern typically completed within 4 months, achieving a 90% degree of consolidation. Using this as the benchmark, the vertical coefficient of consolidation (c_v) was back-analyzed to determine the corresponding conditions.

With varying thicknesses and compression ratios, the average c_v value was determined to be $5 \times 10^{-8} \text{ m}^2/\text{s}$. It is worth noting that the 90% degree of consolidation was estimated by dividing the total settlement achieved within 120 days by the maximum possible settlement (100% consolidation). The 120-day settlement curve can be seen in Fig.5.

**Fig.5 120-day total settlement curves on different conditions**

4.2 Parametric study result

The parametric study identified trends in post-settlement under varying soil conditions improved by

vacuum preloading (see Table 1). Figure 6 compares first-year post-settlement across load ratios ranging from 0.50 to 2.00.

Figs. 6(a) and 6(b) depicted the results of varying soil thickness. It was observed that a thicker layer of soft soil experienced a higher post-settlement at lower load ratios (i.e., less than 1.00), but a lower post-settlement at higher load ratios (i.e., more than 1.00). This could be attributed to the generated effective vertical stress due to vacuum preloading being smaller compared to the middle part of the improvement layer. This contradicted the findings of Indraratna et al.^[13], in which it was indicated that the development of vacuum pressure near the ground surface was the highest, implying that the effective shear strength near the ground surface should be the highest.

Figs.6(c) and 6(d) depict results of varying drain spacing and patterns. The results indicated that, at identical spacing, the triangular pattern resulted in smaller post-settlement compared to the rectangular pattern. This was attributed to the shorter distance water must travel before dissipating. Over the same consolidation period (4 months in these analyses), if a rectangular pattern with 1 m spacing achieves approximately 90% consolidation, then the triangular pattern, having a more efficient drainage effect, attains an even higher degree of consolidation, leading to a reduced post-settlement. Similarly, the effect of spacing follows the same trend—wider drain spacing resulted in greater post-settlement due to the water requiring a longer travel distance to dissipate. However, it is important to note that the spacing of vertical drains is limited by the smear zone effect, which can cause soil disturbance and significantly reduce the vertical drain consolidation rate^[30].

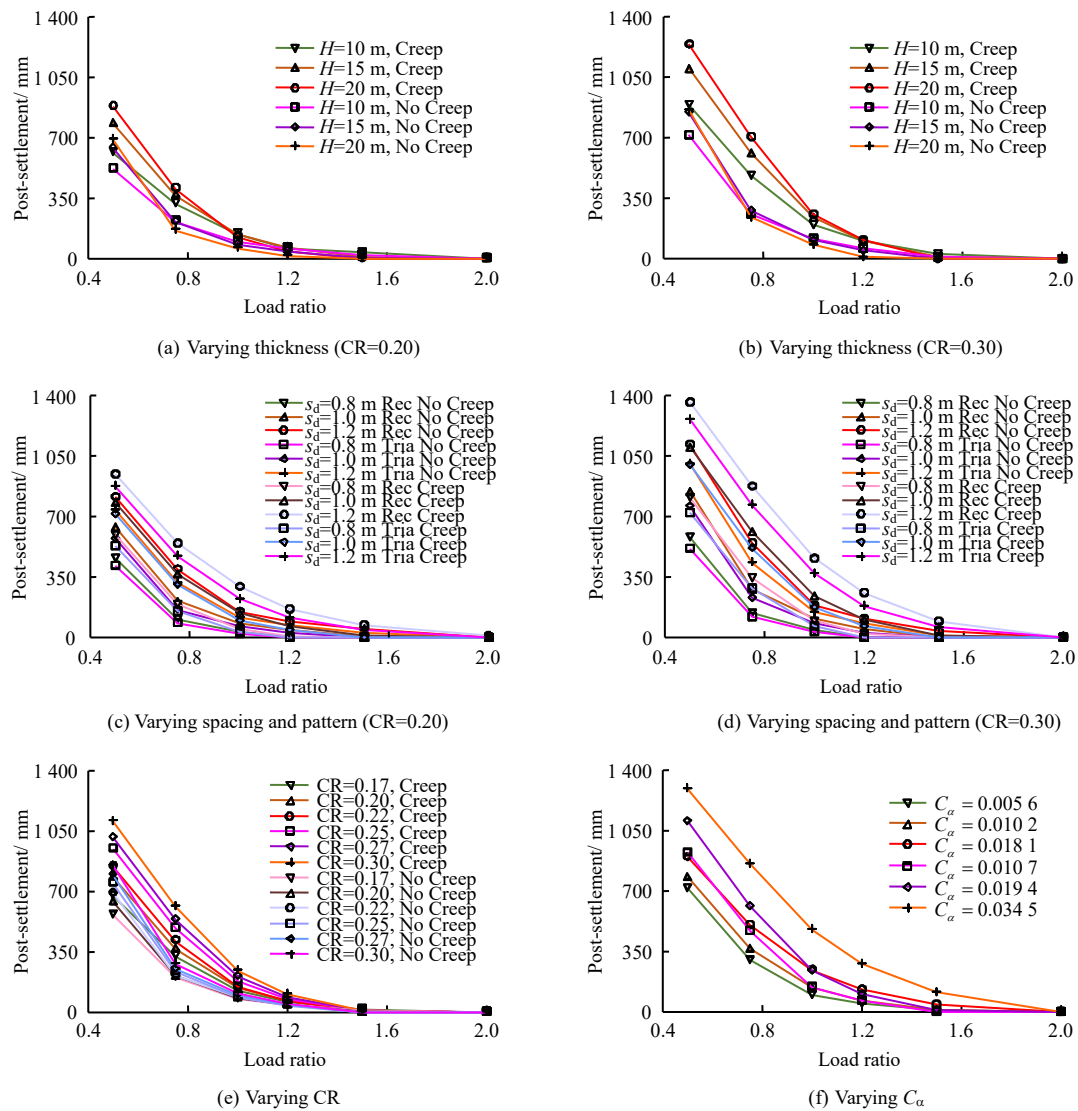


Fig. 6 Parametric study results

It was observed from Fig.6(e) that higher compression ratio resulted in a higher post-settlement. The presence of creep was also seen to influence the post-settlement outcome. Fig.6(e) showed that $CR=0.30$ with no creep induced less post-settlement than $CR=0.22$ with creep. Under the same CR, the post-settlement could go up to 4 times if creep was calculated. This was expected since the compression ratio parameter relates to the stiffness of the soft soil. Soft soil with lower stiffness (i.e., higher compression ratio) could lead to further post-settlement, whereas the higher stiffness could lead to smaller post-settlement.

Fig.6(f) showed that higher C_α led to higher post-settlement. Values of C_α were estimated using Andersen's correlation with CR (Andersen^[31]) where the formula can be seen in Table 1. Inputting 0.2 and 0.3 as CR, values for the lower bound (i.e., 0.0056 and 0.0107), best fit (i.e., 0.0102 and 0.0194), and upper bound (i.e., 0.0181 and 0.0345) were obtained. The results showed that at a load ratio of 1.50, 20 mm of post-settlement could be achieved using the lower

bound and the best fit. Whereas the upper bound resulted in more than 41 mm and 115 mm for C_α 0.0181 and 0.0345, respectively. It is worth noting that the upper bound is for highly organic soil or peat that has a very high void ratio and secondary compression index (C_α), which the North Jakarta soft soil is not. Therefore in Fig.7. can be seen that the post settlement below 20 mm can be seen in load ratio 1.3 with smaller secondary compression index.

However, the reduction in post-settlement at higher load ratios is primarily influenced by the thickness of the soft soil, given that the groundwater table is assumed to be at the ground surface. In areas with thicker soft soil, greater initial settlement occurs, causing a larger portion of the fill to become submerged. This condition increases buoyant support and reduces the effective stress within the soil mass. As a result, despite experiencing larger initial deformation, thicker soft soil layers exhibit smaller post-construction settlement. In areas with thicker soft soil, greater initial settlement occurred compared to areas

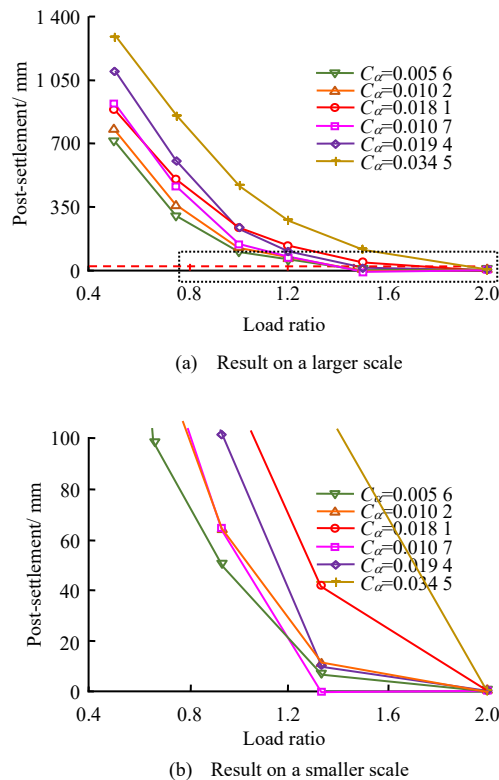


Fig. 7 Post settlement results on varying C_a (below 20 mm)

with thinner soft soil, causing a larger portion of the fill to become submerged. This increased the buoyant support and reduced the effective stress within the thicker soft soil, resulting in smaller post-construction settlement despite the larger initial deformation. The generation of effective vertical stress can be seen in Fig. 8. The final effective stress was greater in cases with higher settlement, such as when the soft soil was thicker or has a higher compression ratio. At the higher load ratio, the post-settlement decreased. Therefore, in the varying thicknesses of soft soil, since the strain of soft soil was mainly at the same level, a greater soft soil thickness resulted in higher settlement, which aligns with the result of settlement in thicker soft soil.

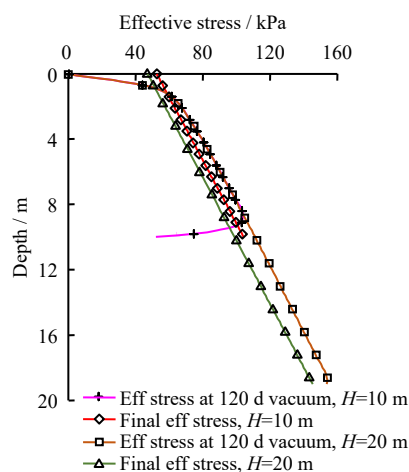


Fig. 8 Effective stress development from D-Settlement

4.3 Parametric study of load ratio

The parametric study also examined post-settlement behavior at a 1.20 load ratio for a rectangular pattern with 1.0 m drain spacing, 0.20 CR and 0.30 CR, and a soft soil thickness of 15 m. As seen in Fig. 9 in the absence of creep, the required load ratio was 1.250 or 1.375, depending on the compression ratio. A similar trend was observed in the creep analysis, where the minimum required load ratio was 1.30 or 1.50. Therefore, to limit post-settlement to a maximum of 20 mm, the load ratio is required to be at least 1.30, with an average of 1.40.

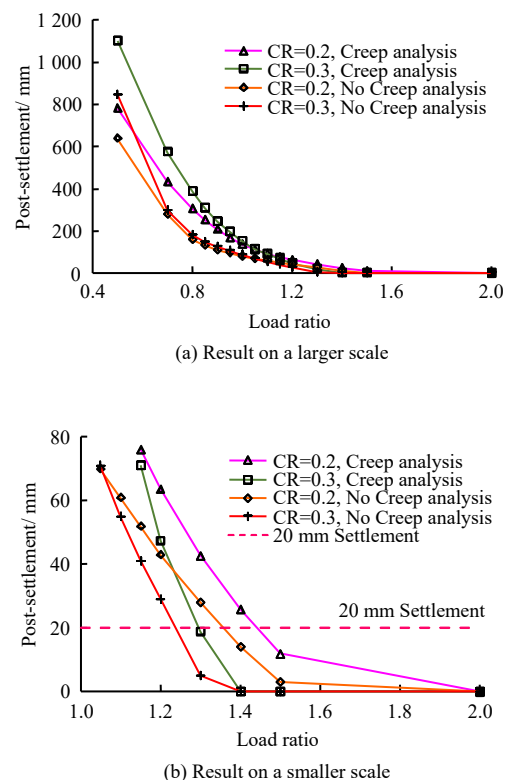


Fig. 9 LR to reach yearly settlement limit

The difference in settlement behavior was primarily due to the compression ratio (CR) of the soft soil. Soil with CR = 0.3 showed greater initial settlement than CR = 0.2, causing more of the fill to become submerged. This increased buoyant support and reduced effective stress. As a result, under non-uniform conditions, CR = 0.3 experienced lower active stress than CR = 0.2. This effect was more pronounced at higher load ratios, where greater submergence in the CR = 0.3 case led to smaller post-construction settlement despite its higher compressibility.

4.4 Summary of parametric study

In summary, several factors were shown to influence post-settlement which could be categorized into two—soil factors and external factors. The soil factors relate to the compression ratio and thickness of the compressible layer. These factors are intrinsic

mechanical properties of the soil and, therefore, cannot be modified, defined, or controlled. The external factors are parameters that influence post-settlement but can be modified by implementing different conditions. This includes drain spacing, drain pattern, and load ratio. However, those three parameters lead to a single parameter that controls the post-settlement, which is the degree of consolidation. Originally the 90% degree of consolidation which was stated in the Geotechnical Manual series 4^[25] was from the load ratio of 1.20 stated in SNI 8460:2017^[24]. In the absence of creep, achieving 90% consolidation under a load ratio of 1.20 is sufficient to control primary settlement, as the corresponding degree of consolidation exceeds that required for the final operational load by approximately 8%, providing a margin of preconsolidation. However, if the soft soil were to creep, an increase to the load ratio is necessary. Based on the parametric study, the load ratio should be increased to a value minimum 1.30.

5 Discussions

5.1 Comparison with previous study

Studies on soft soil post-settlement have been done for several decades; one of the comprehensive studies was done by Indraratna et al.^[26]. The study compared the influence factors of different preloading methods on post-settlement, which was similar to this research. However, in that study, the β -factor only considered the amount of impact given to the soil by changing the conditions of the improvement method and did not consider the soil properties, which was done in this study. Due to those conditions, β -factors may be favorable only if the soils shared similar properties. The results of the parametric study were plotted together with the literature^[26] results in Fig.10. It was observed that, from this study, as β -factor increased, the post-settlement decreased unlike the findings of Indraratna et al.^[26]. The discrepancy was caused by the limited influence of vacuum preloading, which applies additional pressure not accounted for by the β -factor. In contrast, cases with a high β -factor ($\beta > 16$) showed significantly reduced residual or post-construction settlement, primarily due to the combined effects of substantial fill surcharge and greater clay thickness, as reported in previous studies^[26]. Although a fill surcharge was not explicitly analyzed in the present study, the applied vacuum pressure was considered equivalent to a 5 m soil surcharge—assuming a unit weight of 16 kN/m³ (approximately equal to 80 kPa vacuum pressure)—to allow comparison with the findings of Indraratna et al.^[26].

5.2 Load ratio coefficient

An alternative coefficient was proposed to include the factors that have yet been considered in the β -factor called load ratio coefficient (C_{LR}). The

proposed coefficient can be determined as follows:

$$C_{LR} = \frac{CR \cdot H_{imp}}{\alpha s_d} \lg \frac{1}{LR} \quad (2)$$

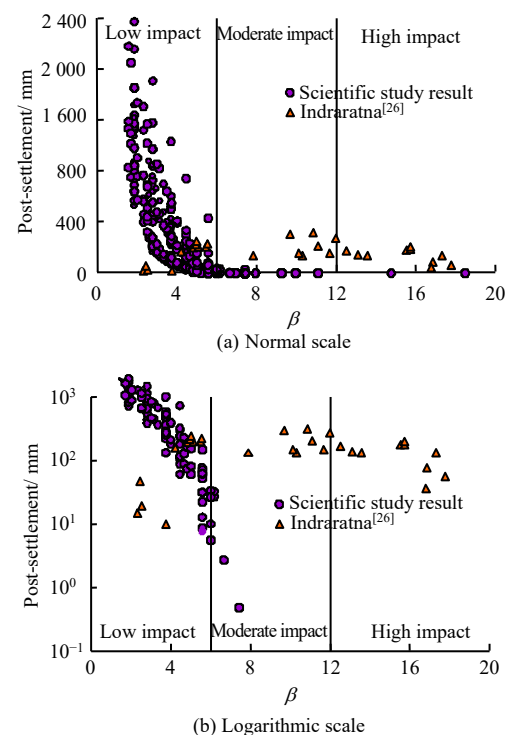


Fig. 10 β -factor results

where H_{imp} is the soft soil thickness. This equation is derived based on Indraratna et al.^[26]. β -factor. However, unlike Indraratna's equation, the current formulation varies the soil thickness with LR. Both the fill surcharge in Indraratna's equation and the load ratio in this study represent the magnitude of loading applied during the improvement period.

Several implications of C_{LR} are as follows: if the value is negative, it means that the load ratio is greater than 1, which induces less post-settlement. Conversely, a positive value indicates a load ratio of less than 1. As shown in Fig. 11, C_{LR} can be divided into three main boundaries: the lower boundary, which applies to soils with little to no creep effect; the middle boundary, which applies to soils with a moderate creep effect; and the upper boundary, where post-settlement is

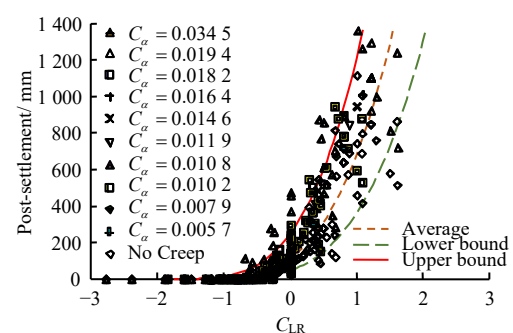


Fig. 11 C_{LR} vs post-settlement over a 1-year period

highly influenced by the creep effect.

The correlations between the load ratio coefficient and post-settlement can be seen in the equations below.

Lower bound:

$$S_{\text{post}} = (20 + n)(C_{\text{LR}} + 1.25)^{3.5} \quad (3)$$

where S_{post} is the post-settlement (mm), and n is the number of years.

Average:

$$S_{\text{post}} = (25 + 2.5n)(C_{\text{LR}} + 1.50)^{3.5} \quad (4)$$

Upper bound:

$$S_{\text{post}} = (30 + 5n)(C_{\text{LR}} + 1.75)^{3.5} \quad (5)$$

The inclusion of time was to accommodate the time-dependent characteristic of post-settlement occurrence as mentioned by Mesri et al^[19]. By the second year or later, primary consolidation may be complete, and secondary compression begins to affect post-settlement. This means that, at the lower boundary, the n multiplier is less than that of the upper boundary, since at the lower boundary, the secondary compression index (C_α) is minimal to negligible compared to the average influence at the upper boundary. Additionally, D-settlement can simulate post-settlement over a defined time period based on the user's input. As a result, post-settlement over a 10-year period (Fig.12) can be predicted with the equation.

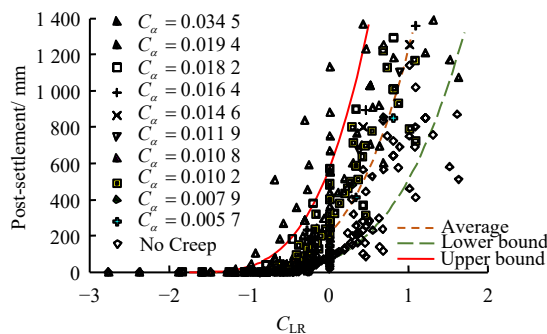


Fig. 12 C_{LR} vs post-settlement over a 10-year period

6 Case history

6.1 Project history and soil data

To verify the findings of this study, a project in North Jakarta that conducted vacuum preloading treatment with a total area of 1.38 hm² was selected. The project was originally a fishpond with a starting elevation of +0.00. Then, 2 months before the vacuum started, a stable working platform was constructed so that heavy equipment such as the vertical drain installation equipment could enter the project area. The working platform elevation during the handover to the ground improvement contractors was at +2.50. The vertical drains were installed with 1 m×1 m

drain spacing in a square pattern. Prefabricated horizontal drains (PHD) were also installed using a sand ditch system. The vacuum preloading used a membrane system; however, prior to covering the project area with geomembrane, a layer of geotextile was installed to cover the geomembrane layers. Afterwards, to mitigate pressure loss alongside the perimeter of the vacuum area, a sealing system was constructed. Once all the preparations were complete, various instruments were installed, including piezometers, settlement plates (SP), vacuum gauges (VG), extensometers, and inclinometers. For this study, only settlement plate and vacuum gauge data were used.

Before the project began, standard penetration tests (SPTs) were conducted within the project area. After backfill process was done, there were 9-point pre-electrical cone penetration tests (CPTe) conducted to determine the installation depth of the vertical drain. The CPTe layout followed a 50 m×50 m grid. However, to assess the vacuum boundary, six additional CPTe points were conducted along the project perimeter. The PVD installation depth was determined based on cone resistance (q_c) values, ensuring penetration into medium-stiff soil, which corresponds to a minimum cone resistance of 0.8 MPa. The layout and result of CPTe data can be seen in Fig.13 and Fig.14.

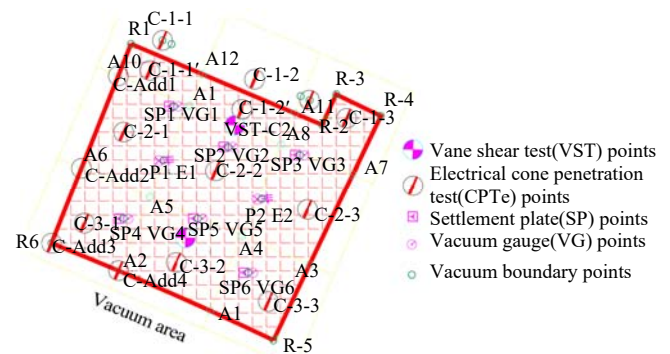


Fig. 13 CPTe and monitoring layout in vacuum preloading area

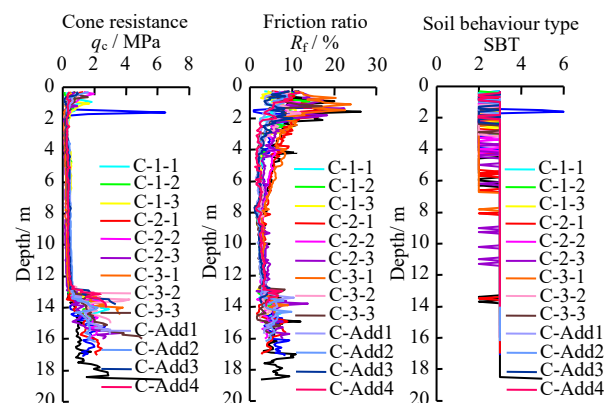


Fig. 14 CPTe results in vacuum preloading area

Based on CPT data, the improvement depth (PVD installation) ranges from 13.0 to 13.5 m. The soil profile consists of a 1.5–2.0 m backfill layer overlying normally consolidated very soft to soft soil extending

to 13.0–13.5 m, underlain by a stiff layer with cone resistance exceeding 0.8 MPa. SPT investigations included undisturbed sampling for laboratory testing, with results summarized in Table 2.

Table 2 Soil laboratory result form undisturbed sample

Depth / m	$\gamma / (\text{kN/m}^3)$	$w / \%$	LL	PL	PI	C_c	C_r	C_a	CR	$c_v / (\text{m}^2 \cdot \text{s}^{-1})$
4.0–5.0	13.0	124.6	—	—	—	—	—	—	—	—
8.0–8.5	12.1	146.2	151.0	39.5	111.5	1.51	0.11	0.016 7	0.319	4.16
12.0–13.0	13.0	117.1	142.0	39.2	102.8	—	—	—	—	—
16.0–17.0	13.5	103.4	—	—	—	—	—	—	—	—

Note: γ is unit weight, w is water content, LL is liquid limit, PL is plastic limit, PI is plasticity index, C_c is compression index, and C_r is recompression index.

Since the SPT data within the vacuum area was limited, additional nearby soil investigation data was incorporated to determine the average soil parameters. These data were used to verify the laboratory test results from within the project area and to ensure that the soft soil's behavior observed from the nearby locations aligns with that of the project site. As a result, an additional 15 secondary compression data points were obtained as supporting data. Fig.15 depicts the results of the soil parameter for different depths.

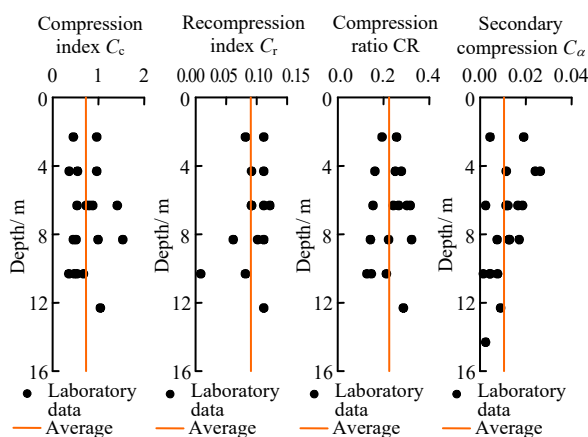


Fig. 15 Laboratory data results in vacuum preloading area

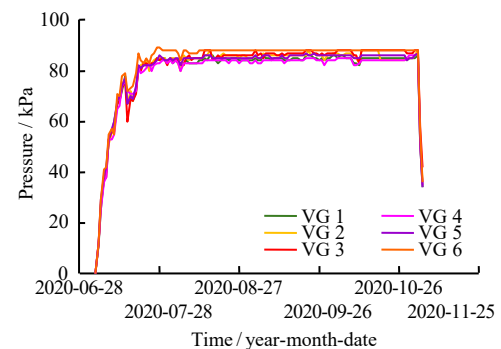
6.2 Soil improvement plan

The vacuum preloading process lasted for 121 d (approximately 4 months), resulting in an average settlement of 1.529 m. Six sets of vacuum gauges (VG) and settlement plates (SP) were monitored daily throughout the process. The vacuum pressure started smoothly; however, in the second week, a leakage caused a slight pressure drop for two days. Despite this, the pressure recovered and reached 80 kPa by the end of the second week. From that point onward, the vacuum pressure was maintained at a minimum of 80 kPa until the process was completed.

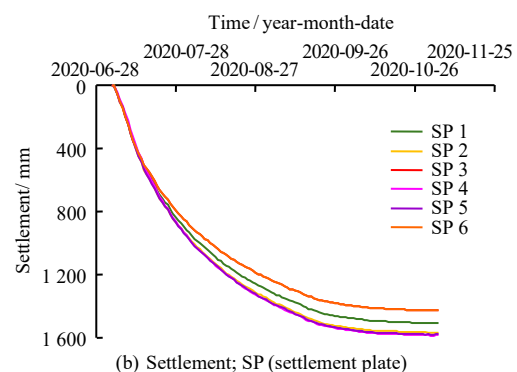
Before stopping the vacuum, an Asaoka analysis was conducted to assess the degree of consolidation, which was found to average 95% after four months of vacuum preloading. Fig.16(a) and Fig.16(b) presents

the monitoring graph.

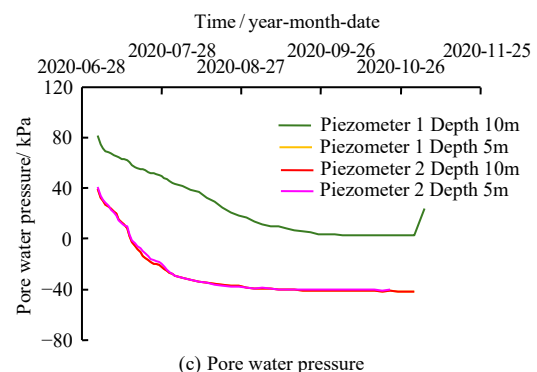
As illustrated in Fig.16(c), pore pressure measurements were obtained using two piezometers (P1 and P2), each instrumented at two depths: 5 m and 10 m below the ground surface. The reduction in excess pore pressure from the onset to the completion of the



(a) Vacuum pressure; VG (vacuum gauge)



(b) Settlement; SP (settlement plate)



(c) Pore water pressure

Fig. 16 Monitoring data of vacuum preloading zone

vacuum preloading phase averaged 81 kPa at the 5 m depth and 78 kPa at the 10 m depth. These results indicate that the vacuum preloading process successfully achieved a degree of consolidation exceeding 90%, based on the average pore pressure dissipation recorded by the piezometers.

6.3 Results

The verification process was done by doing back-analysis using the monitoring data from one of the vacuum preloading areas in North Jakarta. The back-analysis was conducted by inputting the vacuum pressure as a load, with the output being a settlement curve. The settlement curve was fitted to the settlement curve obtained from the settlement plate monitoring. The end product of the back-analysis process was the compression ratio. In the back-analysis process, the operational load was varied to 20, 30 kPa, and 40 kPa, corresponding to load ratios of 1.45, 1.30, and 1.17, respectively. The load ratio is defined as the ratio between the improvement load and the operational load. The improvement load comprises the platform load (32 kPa), vacuum pressure (80 kPa), and a minor water load (10 kPa). In contrast, the operational load consists of the platform load (32 kPa), settlement compensation and levelling backfill load (31 kPa), and the actual operational surcharge (ranging from 20 to 40 kPa). The back-analysis parameter results (Fig.17)

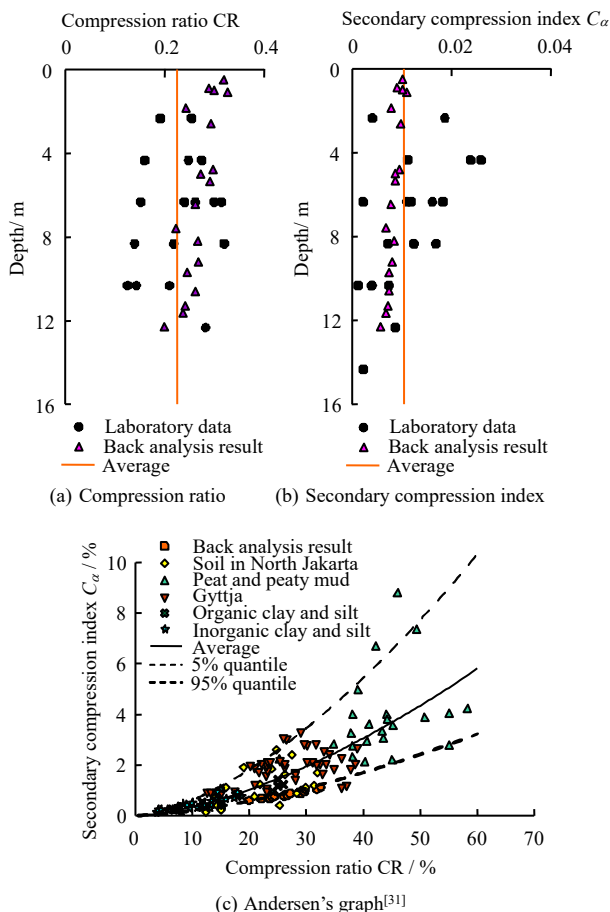


Fig. 17 Soil parameters from back-analysis

were also well-fitted with the parameters from the laboratory data and the graph by Andersen^[31].

Since there were two or more soil thicknesses on the back-analysis data, the parameters such as compression ratio, secondary compression, recompression ratio, and others need to be averaged using the thickness of each layer. The formula can be seen in the equations below:

$$CR_{avg} = \frac{\sum_i^n H_i CR_i}{H_T} \quad (6)$$

$$CR_{a,avg} = \frac{\sum_i^n H_i C_{ai}}{H_T} \quad (7)$$

where CR_{avg} is the average compression ratio value, $CR_{a,avg}$ is the average secondary compression value, H_i is the thickness of i -th layer, CR_i and C_{ai} are the compression ratio and secondary compression index for i -th layer respectively, and H_T is the total thickness of the compressible layer. Therefore, using Eqs. (6) and (7), the average compression ratio was calculated as the weighted average of the compression ratio for each layer, considering their respective thicknesses.

The results from the back-analysis process were plotted in a graph of the load ratio coefficient versus post-settlement (Fig.18). For a load ratio of 1.45 with a 20 kPa operational load, the induced post-settlement in the first year was minimal to negligible. At a load ratio of 1.30 with a 30 kPa operational load, the average post-settlement was approximately 21.3 mm, which was close to the 20 mm requirement. However, at a load ratio of 1.17, post-settlement increased significantly in the first year, ranging from 39 mm to 67 mm, with an average value of 56.8 mm. This indicated that LR plays a significant role in determining post-settlement.

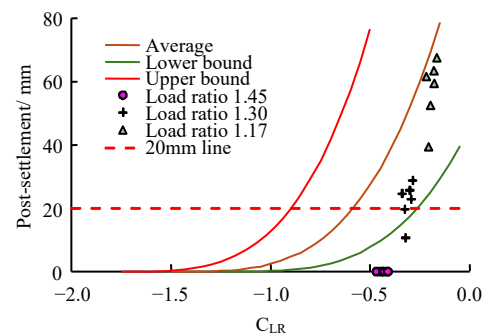


Fig. 18 Case study results

7 Conclusion

A load ratio of 1.20 required by the Indonesian National Standard (SNI 8460:2017)^[24] was found to not satisfy the 20 mm/a limit stated in the Geotechnical Manual series 4 regardless of creep

consideration. Instead, the required load ratio should be 1.30 or 1.40 depending on the soil's susceptibility to creep. Consideration of creep behavior is important, especially in more sensitive projects such as dam or bridge projects where a differential post-settlement may have significant effect as a potential failure factor to the structure.

The parametric study evaluated six parameters that influence creep behavior, which were soil thickness, compression ratio, secondary compression index, load ratio, drain spacing and drain pattern. A lower post-settlement could be attained through having a smaller soft soil thickness, lower compression ratio, lower secondary compression index, higher load ratio, lower spacing, and/or implementing a triangular pattern instead of a rectangular pattern. Several of these factors could ultimately be linked to the degree of consolidation, which relates to the load ratio.

Additionally, this study proposed a load ratio coefficient (C_{LR}) that considered both soil factors (i.e., soil thickness and compression ratio) and external factors (i.e., load ratio, drain spacing, and drain pattern). Eq.(2) were proposed to estimate the post-settlement based on this coefficient, factoring in the influence of time on creep behavior and secondary compression index C_α . The case study showed that among the parameters for the proposed coefficient, the load ratio plays a crucial role in the post-settlement calculation.

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