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Performance Prediction of Road Embankment on Soft Soil Stabilized with Prefabricated Vertical Drains Using Numerical Method

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ABSTRACT

The case history of a road embankment constructed over soft soil stabilized with prefabricated vertical drains (PVDs) is presented. Modelling very complicated subsoil and structural elements could be assisted by numerical methods. Finite element analysis (FEA) was conducted in this study to verify the effectiveness of PVD modelling in the subsoil utilizing Plaxis 2D. The field settlement data were collected and compared to FEM predicted with different smear effect permeability ratio. Thereafter, predicted settlement data relatively accurate was used in the back-calculated to determine the ultimate settlement with the Asaoka and hyperbolic methods. The ultimate settlement predicted with the smear effects permeability ratio is 6 similar to measured. Asaoka method was found to be reliable in estimating settlement of ground foundation.

Key words : Prefabricated vertical drains; Asaoka method; Hyperbolic method; Finite element method.

1. INTRODUCTION

In designing the road embankment on soft ground, the geotechnical engineers encountered several problems. These difficulties are related to the weak engineering properties of soft soil. The soft ground is low in bearing capacity and exhibit large settlement under load [1]. Preloading associated with PVDs is herein applied to the ground improvement of the embankment as one of the available techniques to overcome such difficulties. Due to the complexity of assessing the correct magnitude of the smear effect parameter of the improved ground, problems such as challenges accurately predict settlement during or after preloading arise. Determining the suitable smear effect parameters is not easy based on the engineer's experience. Reliable and computerized procedures for back-analysis, using the measured settlement in preloading practice, are appropriate to determine smear effect parameters based on case studies. Numerical prediction is expected to be accomplished with greater accuracy using the smear effect parameters identified for the behavior of the regulating road embankment over soft ground stabilized with PVDs.

A number of researchers have reported the performance of the numerical method in various fields [2]-[3]. Recent trends in analytical approaches, researchers and engineers prefer to performed the design of vertical drains using finite element method (FEM) compared with an empirical method because it saves time. However, the accuracy of laboratory test results and measured data are key parameters to reflect the actual site condition in design, which can then match back the field monitoring results. Thus, the back analysis is a useful tool to back-calculate the parameters during the construction sequence, based on the measured, to address the many sources of uncertainty [4].

The comparison between the results of field monitoring and FEA would assist designers gain a better understanding of actual soil behavior compared to modelling of finite elements. Therefore, appropriate tolerance could be permitted by using the FEM in future design work. In this study, the effectiveness of PVDs modelling in the soft soil using the FEM was evaluated. Furthermore, the back-analysis with Asaoka and hyperbolic methods were utilized to estimate the ultimate settlement.

2. PARAMETER OF SMEAR EFFECT

The installation of PVDs in soft soil using mandrel causes the soil structure around the drain to be disturbed. Regional disturbances will decrease the soil permeability called the smear zone. The presence of smear zone significantly affects the settlement rate [5]. The smear effect permeability ratio is the key parameter to characterize the smear zone. Due to the many uncertainties involved, however, determining this parameter is a challenging task [6]. Observations from past projects in similar ground conditions are often used to estimate this parameter, which is not always consistent [7]. A number of researchers have reported that the proposed range for this parameter is 1.3-10 [8]. The wide range proposed suggests that there is no comprehensive method for accurately predicting this parameter for practice engineers. Assuming smear zone characteristics can lead to inaccurate predictions of soil behavior.

3. METHODOLOGY

This study is based on a project involving the construction of a road embankment in Yan District, Kedah, Malaysia. The field monitoring was limited to the monitoring of settlements obtained from rod settlement gauges. FEA was performed using Plaxis 2D. The Soft Soil (SS) and Mohr-Coulomb (MC) models are used to model the properties of the soft ground constitutionally.

The equivalent permeability derivation by Hird et al. [9] was used in this study to obtain the matching between vertical drain axisymmetric behavior to plane strain conditions in numerical modelling. The Asaoka [10] and hyperbolic [11] methods were used to predict the ultimate settlement based on the data obtained from the measured and predicted.

3.1 Subsoil Condition

The road embankment is 11 m wide on top with a 1H: 1V side slope, as shown in Figure 1, consisting of following subsoil layers:

- Current fill: nonhomogenous soil with thickness of about 1.1 m.
- Sand cushion: Fine sand and is divided into two layers. Between these two layers is geotextiles. The thickness of the first and second sand layers are 0.3m and 0.2m, respectively.
- Layer 1: Clay silt of about 2m thick with some organic matters and average SPT-N values is 1.
- Layer 2: Underlying layer 1 with a thickness of about 4m, silty clay with some organic matters and average SPT-N values is 2.
- Layer 3: Underlying layer 2 with a thickness of about 3m, soft clay with some organic matters and average SPT-N values is 1.
- Layer 4: Underlying layer 3 with a thickness of about 9m, silty clay and average SPT-N values is 14.
- Layer 5: Underlying layer 4 with a thickness of about 9m, clayey silt and average SPT-N values is 39.

The basic properties of subsoil consisted of Unified Soil Classification System (USCS), average SPT-N values, initial void ratio (e_0), specific gravity (G_s), compression index (c_c), pre-consolidation pressure (p_c), and coefficient of permeability (k) are summarized together in Table 1. Based on the soil profile, the N-value of the subsoil at depths of 0 - 9m is approximately 1.5, which indicates that it is extremely soft soil. Moreover, this ground is generally of high plasticity, and the groundwater level is 2.3m from the surface. Overall, the subsoil for this case study is divided into five layers consisting of clay silt, silty clay, soft clay, and clayey silt.

Table 1: Summary of the soft ground properties

Soil strata	USCS	SPT N	e_0	G_s	C_c	p_c (kPa)
Clay silt	ML	1	2.17	2.54	0.983	21
Silty clay	CH	2	2.33	2.54	1.02	18
Soft clay	CH	1	2.67	2.52	0.952	21
Silty clay	CH	14	3.00	2.52	1.07	17
Clay silt	ML	39	3.09	2.51	0.944	22

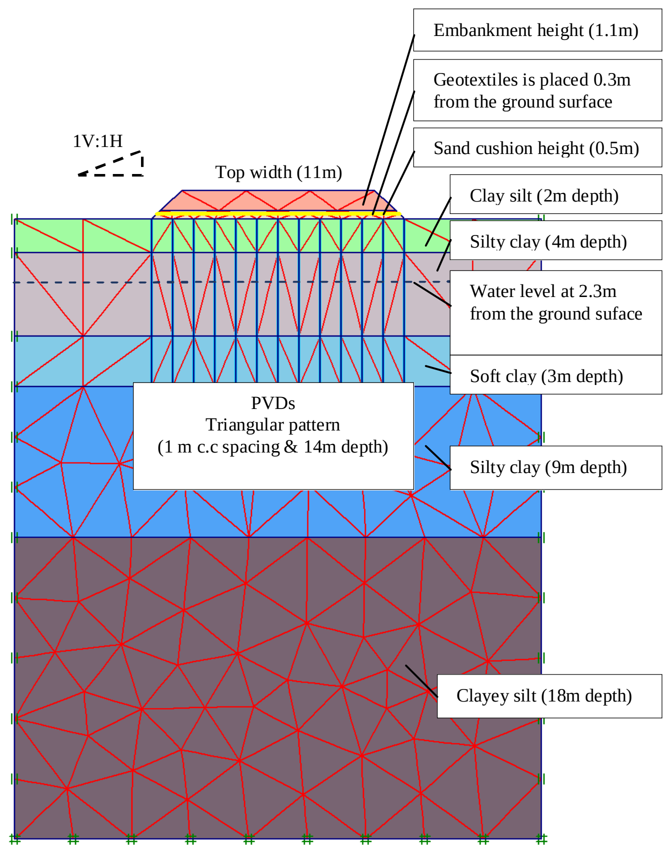


Figure 1: Numerical model with mesh structure.

3.2 Construction procedures

The layout of the monitoring instruments at the study site is presented in Figure 2. The PVDs were installed at a spacing of 1 m c/c arranged in a triangle along the road embankment. The PVDs have penetrated a depth of about 14m into the subsoil. Preloading associated with PVDs was applied to RF1 and RF2 sections. The construction procedures at sections of RF1 and RF2 are summarized as follows:

- Removing topsoil and 0.3m thick backfilling of fine sand as a sand cushion for the working platform.

- Install geotextiles after 7 days.
- Fill 0.2m fine sand above the geotextiles and rest for 45 days.
- Placing embankment surcharge using nonhomogeneous soil with 1.1 m thickness and compacted.
- The embankment is allowed to be consolidated for a six month, and the settlement measurement is performed.

Once the data, as mentioned above, is provided, the data are summarized and interpreted in accordance with the parameters required for FEA settlement assessment. The properties of the subsoil are determined based on the site investigation report that will be modelled in the numerical method. The field settlement monitoring data were used to compare with predicted. Subsequently, the Asaoka and hyperbolic methods were used to estimate the ultimate settlement.

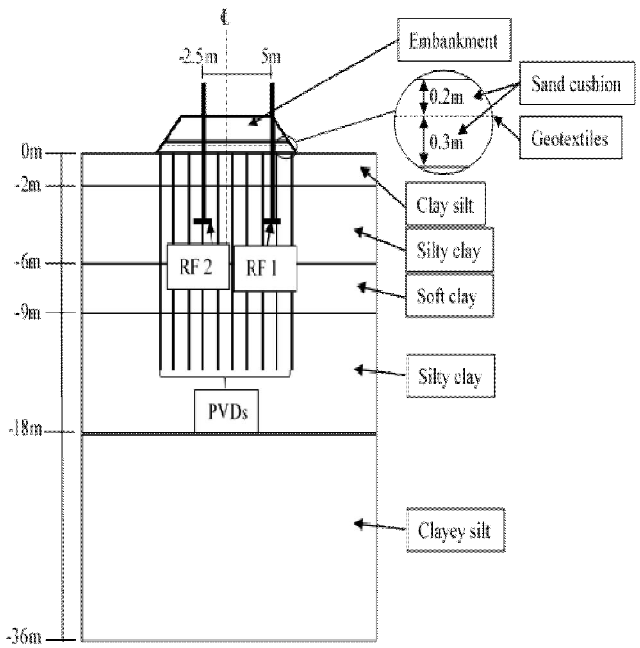


Figure 2: Layout of field instrumentation

3.3 Numerical modelling

In this study, FEM analyzes are performed using numerical software by Plaxis V8. The model of the plane strain was chosen with triangular components of 15 nodes. Using the MC model, modelling of granular materials such as sand cushion and embankment can be performed. The SS model is a model of Cam-Clay that simulates the normal primary compression condition of consolidated clay. Unlike the MC model constant stiffness, the SS model exhibits stress-dependent stiffness. The SS model stress-dependent stiffness is appropriate for predicting consolidation of normally consolidated soft clay.

The PVDs installed on the ground was modelled using the drains function. The PVDs are represented as drains that prescribe lines within the geometry model where the consolidation analysis sets (excess) pore water pressures to zero [12]. The drains function is activated in the calculation phase to account for the delayed PVDs installation. Table 2 shows the subsoil parameters used in this study modelling. The soil equivalent permeability is determined based on the smear effect permeability ratio. The smear effect permeability ratio of varying was used to determine the value that generates the most accurate prediction. Hird et al. [9] proposed using the following equation to determine the soil of equivalent permeability for analyzing the PVDs in 2D effect a plane strain condition:

$$k_{hpl} = \frac{2}{3}.\frac{B^2}{{D_e}^2}.\frac{1}{\mu}.k_h \tag{1}$$

where k_{hpl} = the plane strain condition of soil equivalent horizontal permeability; D_e = the diameter of the effective zone of drainage; B = the width of the plane-strain unit cell. The dimensionless factor μ is the smear effect that can be defined as:

$$\mu = \ln(n/s) + (k_h/k_s)\ln s - 0.75 \tag{2}$$

where n = the drain spacing ratio, (D_e/d_w); k_s = the horizontal permeability in the smeared zone; k_h/k_s = the smear effect permeability ratio. The diameter of the vertical drain (d_w), d_s/d_w and the factor of s is defined as the ratio of the diameter of the smeared zone (d_s). Rixner et al. [13] recommended the following equation to use the equivalent diameter to account for the shape effect of PVDs:

$$d_w = (w + t)/2 \tag{3}$$

where t = the thickness of the PVD; w = the width of a band-shaped PVD. Hird & Moseley [14] found that the diameter of the smear zone, d_s, is proportional to the diameter of the cross-sectional area of the mandrel (d_m):

$$d_s = 1.6d_w \tag{4}$$

For PVDs triangle pattern, unit cell diameter, D_e, is:

$$D_e = 1.05d \tag{5}$$

where d = spacing c/c of PVDs. The parameters of PVD are summarized in Table 3.

Table 2: Geotechnical properties of subsoil

Soil strata	USCS	SPT N	e_0	G_s	C_c	p_c (kPa)
Clay silt	ML	1	2.17	2.54	0.983	21
Silty clay	CH	2	2.33	2.54	1.02	18
Soft clay	CH	1	2.67	2.52	0.952	21
Silty clay	CH	14	3.00	2.52	1.07	17
Clay silt	ML	39	3.09	2.51	0.944	22

Table 3: PVD properties

Parameter	Symbol	Value
The width of the unit cell plane strain, m	B	0.75
The equivalent drainage diameter,m	d_w	0.052
Smear zone diameter	d_s	0.176
Horizontal permeability ratio of undisturbed soil and smear, (k_h/k_s)	k_r	3
The ratio of the diameter of the smear zone and drainage, (d_s/d_w)	s	3.38
Unit cell diameter, m	D_e	1.26
The ratio of the diameter of the unit cell and drainage, (D_e/d_w)	n	24.23

3.4 Asaoka method

The graphical of Asaoka method is probably the most widely utilized technique of estimating the ultimate settlement (s_{ult}) induced by the preloading process. The ultimate settlement is determined in a graphically from a special diagram plotted using each settlement read out at the time interval (Δt) on the *s-t* curve.

$$s_{ult} = \frac{\beta_0}{1-\beta_1} \tag{6}$$

where β_0 = the intercept line; β_1 = slope of of a straight line in the special diagram. The settlement at any point of time, s_t, can be calculated as a fraction of the final settlement s_{ult} is based on the equation proposed by Arulrajah et al. [15] as follows:

$$\frac{s_t}{s_{ult}} = 1 - \frac{8}{\pi^2}\exp\left[-\left(\frac{8c_h{'}}{{D_e}^2\alpha} + \frac{\pi c_{vi}}{4{H_{Ti}}^2}\right)t\right] \tag{7}$$

where c_{vi} = the intial coefficient of consolidation due to vertical flow. In this study, c_{vi} is assumed to be equal to the average coefficient of consolidation in vertical direction (c_v). H_{Ti} is the total equivalent thickness of all layers. The H_{Ti} can be calculated as follows:

$$H_{Ti} = H_1\left(\frac{c_{vi}}{c_{v1}}\right)^{0.5} + H_2\left(\frac{c_{vi}}{c_{v2}}\right)^{0.5} + \ldots H_n\left(\frac{c_{vi}}{c_{vn}}\right)^{0.5} \tag{8}$$

The coefficient of consolidation in horizontal direction c_h can be determined:

$$\frac{-\ln\beta_1}{\Delta t} = \frac{8c_h}{{D_e}^2\alpha} + \frac{\pi^2 c_v}{4{H_{Ti}}^2} \tag{9}$$

where Δt = time interval and the drain factor, α, can be determined as follows:

$$\alpha = \frac{n^2\ln n}{n^2-1} - \frac{3n^2-1}{4n^2} \tag{10}$$

3.5 Hyperbolic method

The hyperbolic method has become one of the most convenient and commonly used techniques for predicting the ultimate ground settlement based on available field data [16]. It provides a reliable prediction of ultimate settlement only when a large number of consolidation process (generally more than 60%) have occurred; on the contrary, this approach leads to an overestimation of the ultimate settlement if applied using measurements performed at the early stages of the preloading period. The relation between consolidation settlement s_t and time t is postulated in the hyperbolic method to approach a hyperbolic curve, and the straight-line part of the curve (t/s) versus t can be represented by the following equation [17]

$$\frac{t}{s_t} = \alpha^* + \beta^* t \tag{11}$$

where α^* = the intercept line; β^* = the slope of the straight-line segment of the curve of (t/s) versus t. Once sufficient field data are available, these two constants can be easily obtained through regression analysis. Finally, the ultimate settlement can be calculated as follows:

$$s_{ult} = s_0 + \frac{1}{\beta^*} \tag{12}$$

where s_0 = the settlement at the end of surcharging at t_0.

4. NUMERICAL ANALYSIS

The consolidation analysis of fill embankment over soft soil stabilized with PVDs was performed using the back-calculated c_h at RF1 and RF2. This was done by applying the equivalent horizontal plane strain permeability conversion as proposed by Hird et al. [9] with varying permeability ratio of smear effect. In this study, the permeability ratio of the smear effect were 1, 3 and 6.

The predicted time rate of consolidation settlement has performed a comparison with measured are shown in Figure 3 and Figure 4. From the data in these figures, it is apparent that the consolidation settlement process is faster during the initial stage of embankment filling, which shows a significant difference in magnitude of settlement. The differences in cumulative settlement term, however, are decreasing and attempting to converge for a long-term consolidated period. A possible explanation for these results may be due to the compaction energy that during the first stage of sand cushion filling imposed on the upper layer of soft clay resulting in a higher settlement rate that can not be modelled.

Moreover, the final of settlement measured at RF1 and RF2 were 0.023 and 0.029m, respectively. It clearly shows that the point near to the embankment centre is the higher the settlement magnitude. This finding is in agreement with Krishnamoorthy's [18] results that the total settlement in the embankment centre decreases gradually toward the embankment toe.

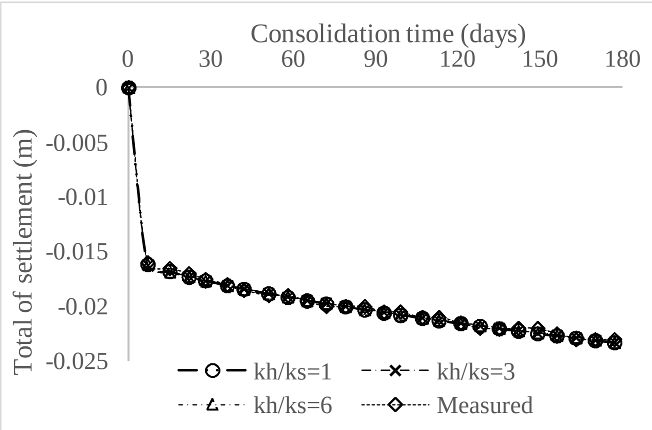


Figure 3: Comparison of ground settlement between predicted and measured at RF1

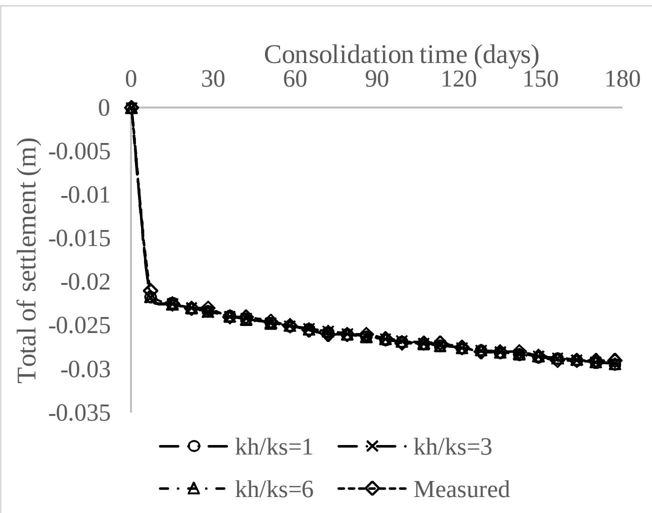
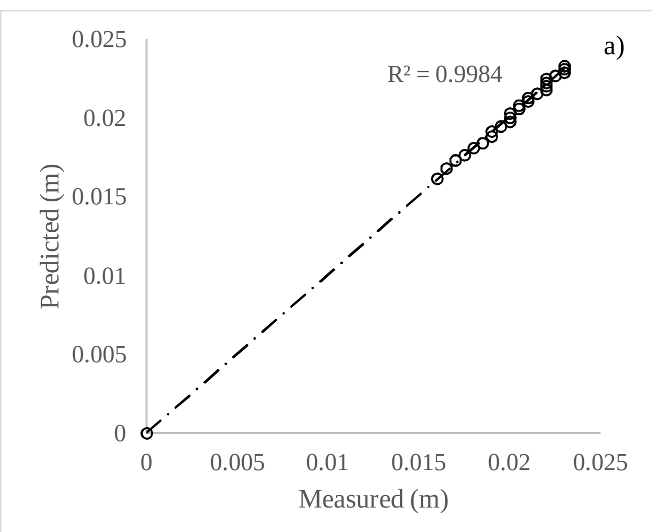
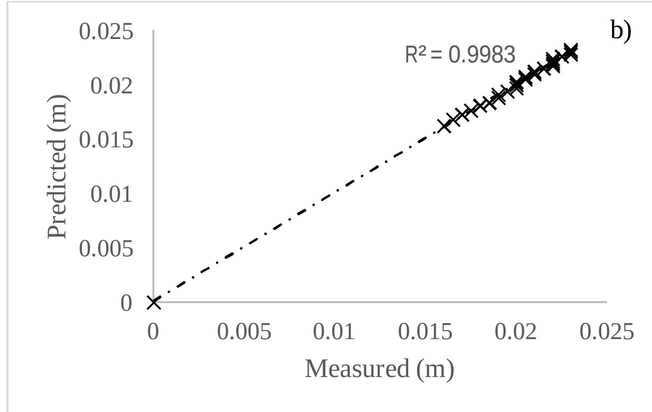


Figure 4: Comparison of ground settlement between predicted and measured at RF2





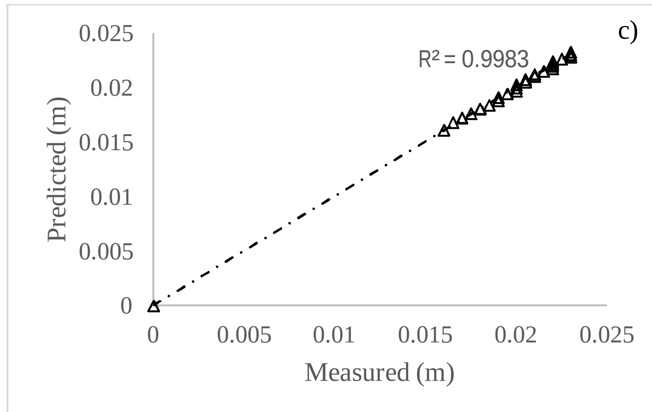
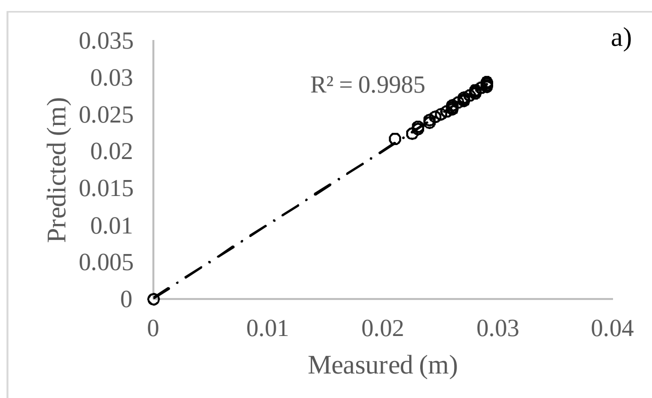


Figure 5: The R^2 values of the predicted settlement in RF1 a) k_h/k_s=1; b) k_h/k_s=3; c) k_h/k_s=6

In order to evaluate the FEM simulation model, the correlation coefficient (R^2) was adopted. Figure 5 shows the accuracy of the FEM simulation model against the settlement at RF 1. The permeability ratio of smear effect with 1 and 6 was found to have a similar R^2 values, and the highest was 0.9984 (refer Figures 5a and c). As shown in Figure 6, the R^2 value of the smear effect permeability ratio with 1 was found to be highest of 0.9985. Despite the values of R^2 on FEM models developed exhibit relatively good accuracy, the smear effect permeability ratio with 6 was found to have the highest reliability. The reason for this finding is that k_h/k_s = 6 on RF1 and RF2 is found R^2 is 0.9983.



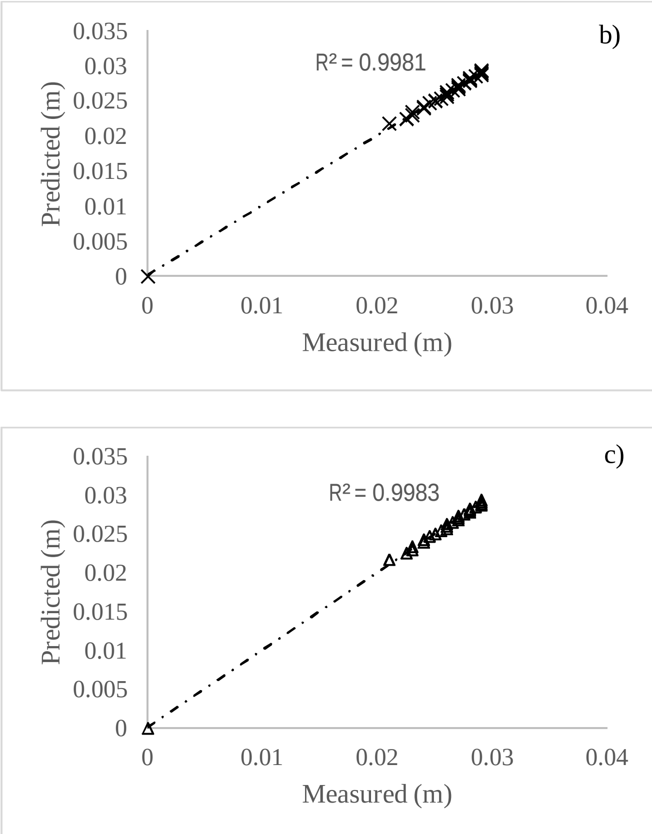


Figure 6: The R^2 values of the predicted settlement in RF2 a) k_h/k_s=1; b) k_h/k_s=3; c) k_h/k_s=6

5. ESTIMATION OF ULTIMATE SETTLEMENT

Asaoka and hyperbolic methods were used to estimate ultimate settlement. In order to evaluate the performance of settlement prediction methods, the estimated ultimate settlement was compared with measured. The ultimate settlement predicted with k_h/k_s = 6 and measured at RF1 were presented in Figures 7 and 8, respectively using Asaoka method.

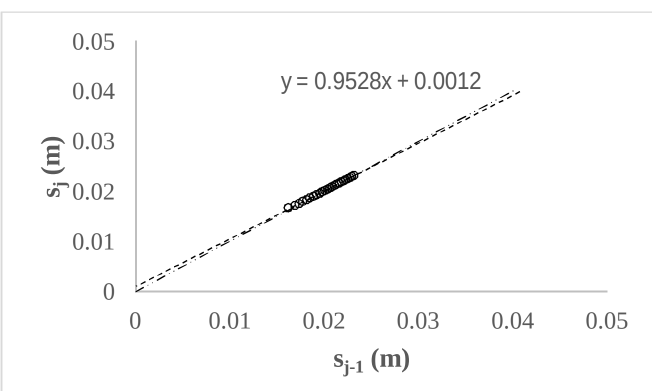


Figure 7: Asaoka plot of RF1 by FEM predicted consolidation settlement

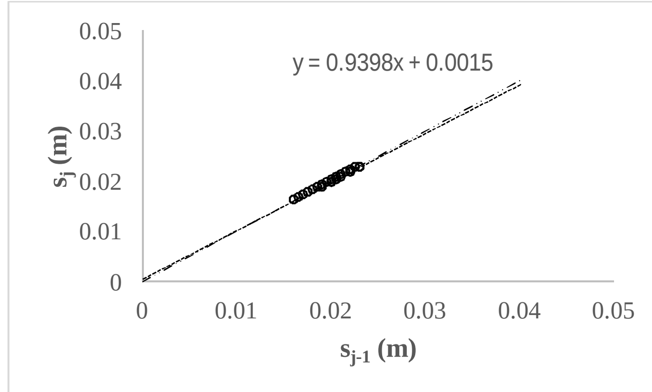


Figure 8: Asaoka plot of RF1 by measured consolidation settlement

What is interesting in these figures is that the magnitudes of ultimate settlement predicted are slightly lower than measured. This phenomenon was noted in a study on Changi East reclamation project where the ultimate settlement was significantly lower predicted [15]. Figures 9 and 10 show the ultimate settlement using the hyperbolic method predicted and measured, respectively. It can be seen; all the curves include a straight line for 60%≤U≤90%. Also, the time of predicted and measured for the consolidated 90% is similar to the 0:04 year.

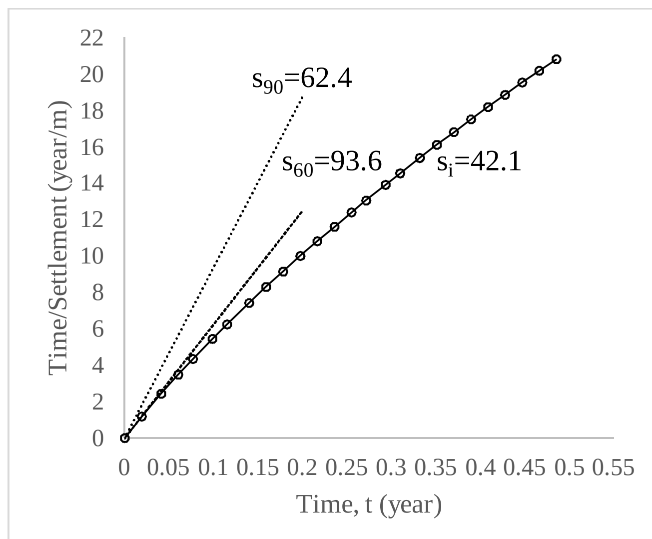


Figure 9: Hyperbolic plot of predicted settlement with k_h/k_s=6 at RF1.

Table 4 presents the ultimate settlement and settlement at 90% consolidated estimated by Asaoka and hyperbolic methods. It is apparent that the settlement estimated by the Asaoka method is similar between FEM and measured. On the other hand, the hyperbolic method has a slight difference between predicted and measured, which is about 6%.

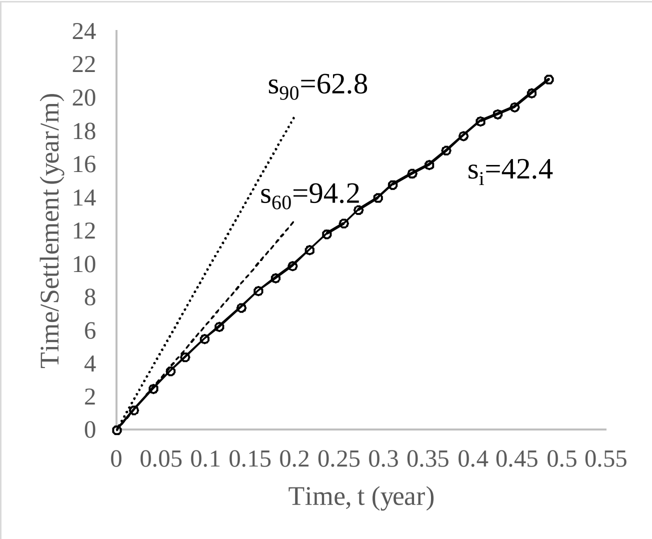


Figure 10: Hyperbolic plot of measured settlement at RF1

Comparing the two methods, it can be seen that the estimated ultimate settlement produced are not significant with a difference of about 28%. Together these results provide important insights that Asaoka method can provide reliable estimates of settlement.

Table 4: Comparison of settlement assessed by Asaoka and hyperbolic methods

	Asaoka		Hyperbolic	
Methods	FEM	Field	FEM	Field
Ultimate settlement, s_f (m)	0.025	0.025	0.018	0.018
Settlement to date, s_t (m)	0.023	0.023	0.016	0.017
Difference between s_f predicted and measured (%)	0		0	
Difference between s_t predicted and measured (%)	0		6	

6. CONCLUSION

A comparative evaluation of the performances of settlement estimation methods was performed for a site on a soft soil deposit stabilized with PVDs. Settlement data from the 2 settlement plates at the site during embankment preloading were used to evaluate the accuracy FEM prediction. The specific findings can be summarized as follow:

1) Smear effect parameters influence settlement analysis of embankment stabilized with PVDs. In FEM analysis, equivalent horizontal permeability with k_h/k_s=6 was found to produce the most accurate predictions. Also, increasing k_h/k_s values were found to tend to decrease the magnitude of settlements predicted.
2) The ultimate settlement was estimated using Asaoka and hyperbolic methods. It was found that the ultimate settlement estimated by Asaoka method shows reasonable agreement with measured. The estimated settlement are similar to predicted and measured.
3) The estimated settlement of the hyperbolic method at 90% consolidation was different, about 6% between the predicted and measured. However, the ultimate settlement was similar for both data types.

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