Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (43) No . (3) July . 2021

Preloading System with Partially Penetrating Vertical Drains in Marine Soft Clay deposits - Case study

Alaa El-Din A. El-Gendy[a], Mohamed H. Rabie[b], Mohamed A. Mostafa[c] and Ahmed M. Abouhashem[d]

[a] Professor of Soil Mechanics and Foundation Eng., Helwan University, Cairo, Egypt. [b] Professor of Soil Mechanics and Foundation Eng., Helwan University, Cairo, Egypt. [c] Associate Professor of Soil Mechanics and Foundation Eng., Helwan University, Cairo, Egypt. [d] Ph.D. candidate, Helwan University, Cairo, Egypt.

* (Corresponding author) 8609, Mokattam, Cairo, Egypt, 11571
Phone: +20 12 05-05-8650. Email: ahmed.abouhashem@yahoo.com

الملخص العربى

يستخدم نظام التحميل المسبق والمزود بمصارف رأسية مسبقة الصنع (PVD) كطريقة فعالة لتحسين التربة لتقليل انضغاط الطين البحري اللين. في عام 2018 تم عمل جسر تجريبي واسع النطاق مزود بتقنية مصارف PVD والممتدة في رواسب الطين البحرية اللين في مشروع المنطقة الصناعية بشرق بورسعيد في مصر. تم إنشاء الجسر التجريبي بمساحة علوية 110 × 110 م وارتفاع 5.5 م لتقييم النظام المختار لتحسين التربة والتحقق من معاملات التصميم .

وقد تم إجراء تحليل العناصر المحدودة ثنائية الأبعاد (FE) لدراسة تأثير نظام التحميل المسبق المزود بـ PVD في تدعيم رواسب الطين البحرية. تم التحقق من صحة نماذج FE وأظهرت توافقا جيدا مع الملاحظات الميدانية من حيث الإزاحة الرأسية لمركز الجسر, والازاحة الافقية لمقدمة ميل الجسر.

Abstract

Preloading system provided with prefabricated vertical drains (PVD) is commonly employed as an effective ground improvement technique to reduce the compressibility of soft consolidated marine clay. In 2018, full-scale trial embankment provided with PVD was installed in consolidated marine clay deposits at East-Port Said industrial zone project in Egypt. The trial embankment was constructed with the top plan area of 110x110m and height of 5.5m, to evaluate the selected system and verify the design parameters. The instrumentations included shallow settlement indicators, vibrating wire piezometers, extensometer, and inclinometers. Two-dimensional finite element analysis (FE) was performed to study the effect of preloading system provided with PVD in soft marine clay deposits. FE models were validated using finite element-based software PLAXIS 2D and showed good agreement with the field observations in terms of vertical displacement of embankment center, and lateral soil deformation beneath the embankment toes.

Keywords

2-D Finite element, Embankment Instrumentation, Marine soft clay, Prefabricated vertical drains (PVD).

Introduction

East-Port Said city at northern east of Egypt the is considered an important logistical area due to its location at the northern end of the Suez Canal with high volumes of trade traffic. East- Port Said area is widely known with soft soil deposits which are encountered along the Mediterranean coast. The foundation soil in these areas provide a geotechnical challenge due to the existence of soft soil deposits that have thicknesses in excess of 40.0m. These deposits are normally characterized by low shear strength and high compressibility which make them a difficult engineering exercise.

Many stabilization techniques used to mitigate unacceptable total and differential settlements of underlying soft soil (Indraratna et al. 2005) such as Vibro-replacement, electro-osmotic, explosion based, and deep mixing, but the associated cost may become excessive when the soft deposits layer extends to higher depths. Preloading system provided with prefabricated vertical drains (PVD) is one of the effective techniques used to mitigate the effects of differential settlement on structures and increase the shear strength of the soft soil deposits. In this method, a surcharge load, usually in the form of an embankment, that is equal to or greater than the anticipated foundation stress, is applied to the soft soil layer until most of the primary consolidation has been achieved. Vertical drains reduce the drainage path and accelerate the dissipation of excess pore water pressure generated from the application of surcharge loads. Figure 1 reveals the potential benefit of vertical drains to reduce the time required for a specific degree of consolidation as stated by Lau et al. (2000).

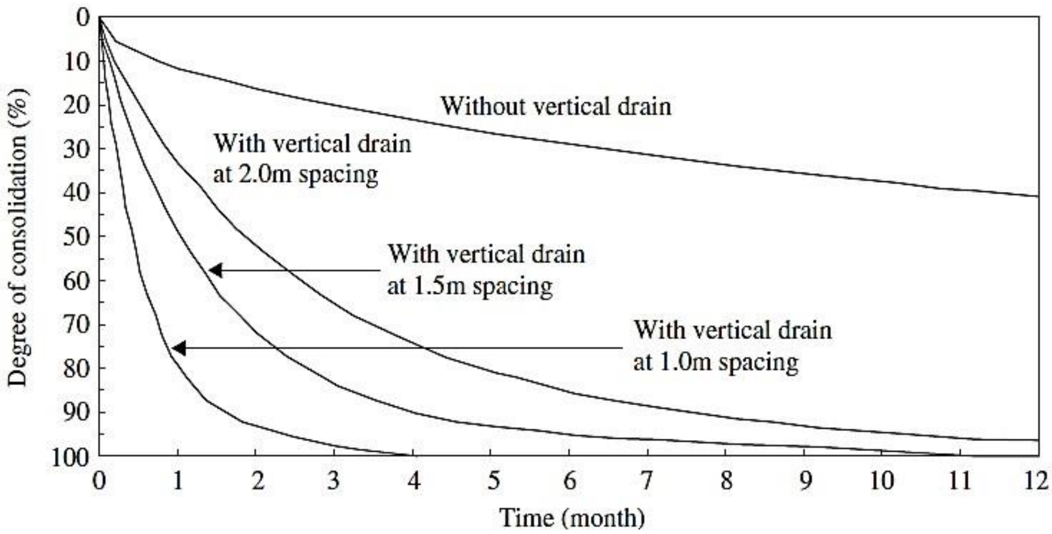


Figure 1: Potential benefit of vertical drains (after Lau et al. 2000)

The present paper uses measured vertical and lateral displacements from a trial field test embankment to compare the accuracy and appropriateness of predictions made using plane strain finite element analysis. The main objective is to calibrate and validate the numerical model in order to provide a reliable numerical prediction of the consolidated marine clay behavior under the subjected stress.

Case study

East Port Said Industrial Zone is an industrial park with a total area of 60 km square located in Egypt at the northern end of the Suez Canal Special Economic Zone (SC Zone) and South of East Port Said Port. It is about 20 km from Port Said City, 60 km to Ismailia City and 200 km to Cairo City. Figure 2 shows the location of East Port Said Industrial Zone.

Figure 2: Location of East of Port Said in Egypt

The topography of the site comprises a relatively flat and low-lying area with an average elevation of around +0.50 meters above mean sea level. In order to establish a stable working platform, the entire site area was reclaimed with sand blanket to reach a final elevation of +1.00 meters above mean sea level. Based on the site investigation program carried out by the contractor (Keller Holding GmbH), the subsurface condition in the site area can be classified mainly into four distinct soil layers, as shown in figure 3: on top is 1.0m fill layer (sand blanket) followed by 15m of soft silty clay with interlayers of silty sand followed by 30m layer of very soft clay to stiff clay layer, which is underlain by a dense to very dense sand layer followed by stiff to hard clay layer. The ground-water table is located close to the ground surface.

The contractor (Keller Holding GmbH) carried intensive field and laboratory tests to determine the different parameters for the clay deposits. The main Geotechnical parameters for upper clay layer required to be improved as resulted from one of the representative CPT is shown in figure 4 while figure 5 shows the selected idealized sub-Soil stratigraphy as well as design parameters presented by the contractor.

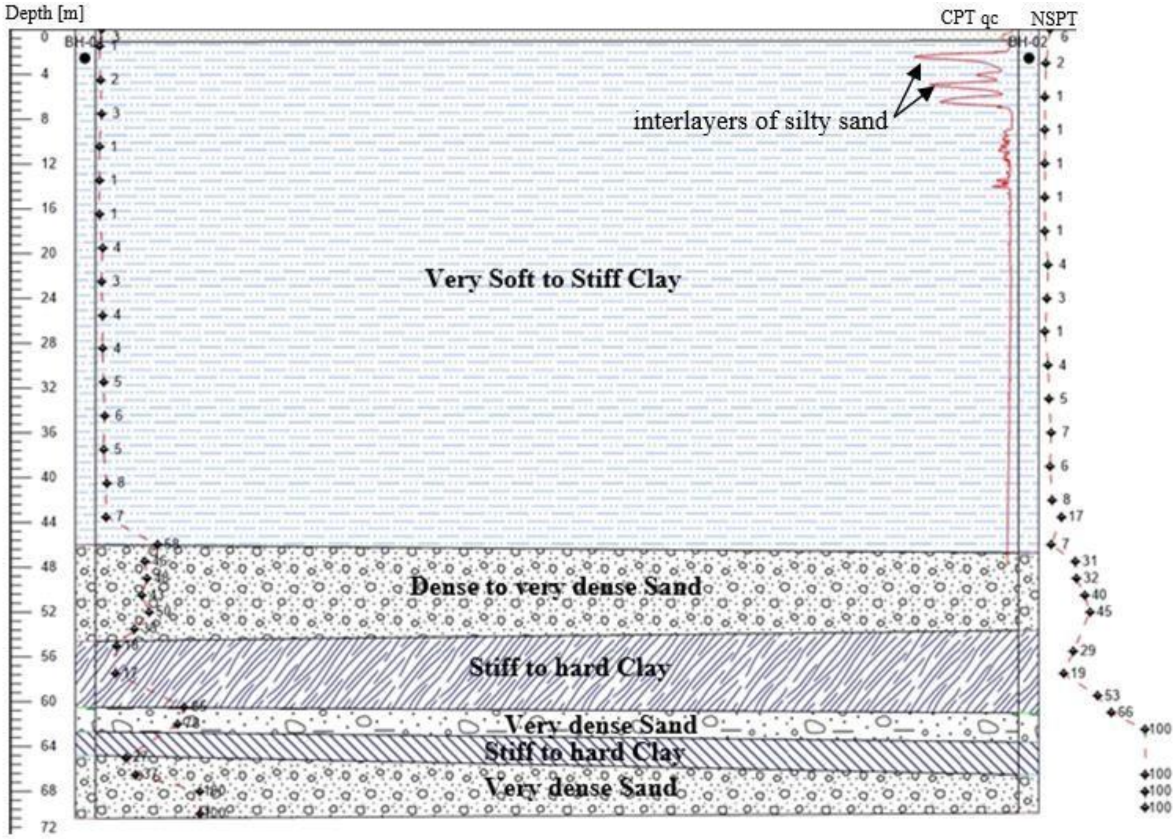


Figure 3: Soil Formation within East Port Said Industrial Zone

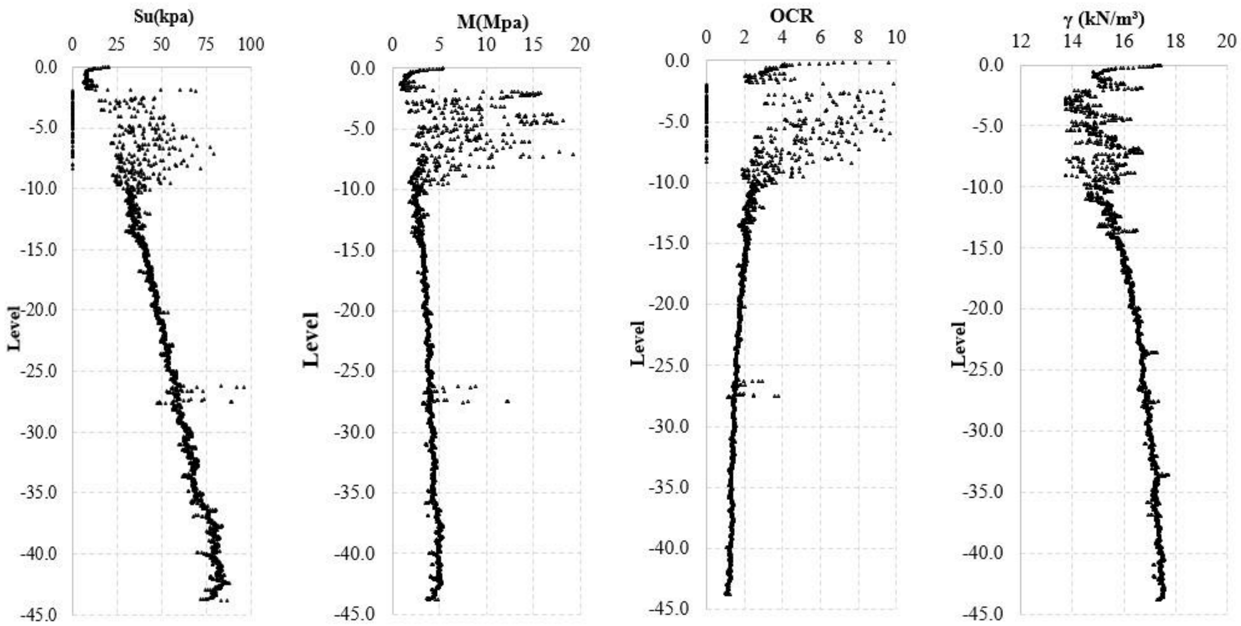


Figure 4: Main Geotechnical parameters evaluated from CPTu

Material	Layer	Level		Unit weight (kN/m^3)	Shear strength parameters			Deformation parameters			Time settelment parameters			
		Top	Bottom		Su (kPa)	Rate (kPa/m')	$\frac{Su}{\sigma v'}$	O.C.R	Constrained modulus M (MPa)	Rate (MPa/m')	Ch (m^2/year)	Cv (m^2/year)	Kh (m/year)	Kv (m/year)
silty Clay / clayey Silt with interlayers of sand	1-A	0.00	-10.00	16.0	22.5	----	0.5	2.25	5.0	----	>10	1.0	>1.0E-1	1.0E-2
	1-B	-10.00	-15.00	16.0	22.5 – 30.3	1.56	0.28	1.1-1.2	2.50 – 3.00	0.10	>10	1.0	>1.0E-1	1.0E-2
Silty Clay	2	-15.00	-50.00	17.0	30.3 – 85.0	1.56	0.28	1.1-1.2	3.00 – 6.50	0.10	3.0	1.0	7.5E-3	2.5E-3

Figure 5: Lithology and Design Geotechnical Parameters (Keller Holding GmbH 2016)

To speed up the consolidation process of the majority of soft clay layer, PVD together with 5.5 meters of filling material were installed, the drains were installed to a depth of 25 meters with a 1.5 meters centre-to-centre spacing in a triangular grid pattern.

For evaluating the selected improvement system and verifying the design parameters in order to prevent any problems in performance, a trial zone with instrumentation plan had been performed. The trial zone had was constructed with a top area of 110x110m and backfilled with height 5.5m after installation of vertical drains with the same material, installation methodology and configuration of the proposed system.

The embankment was constructed from a sand fill with average density 17 kN/m^3. The vertical drains were installed from the fill top layer. Then embankment fill process was carried out through 50 days. Settlement plates, inclinometers, extensometers were installed beneath the embankment to measure settlement, lateral displacement and pore water pressures. These instruments were installed immediately after installation of the vertical drains. The measurements from these instruments continued for 450 days. Figure 6 shows cross-section for the trial embankment and the instrumentation system used for measurement purpose while figures 7 and 8 show the surcharge history and the correspondent displacements for the trial embankment center and toe.

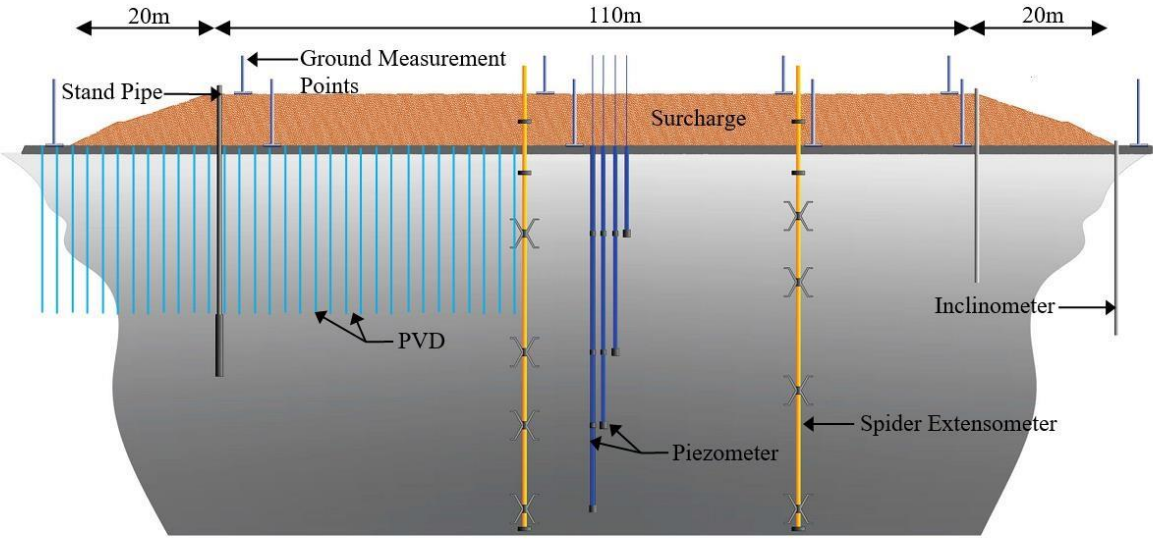


Figure 6: Cross-section for the trial embankment with the instrumentation system (Keller Holding GmbH)

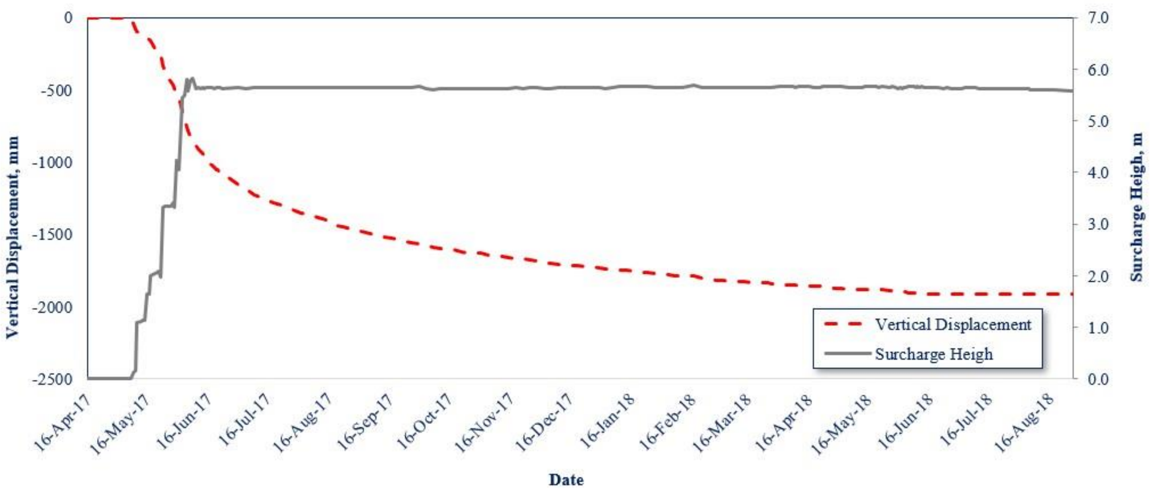


Figure 7: Embankment's center Settlement-Time relationship with respect to Surcharge height history (Keller Holding GmbH)

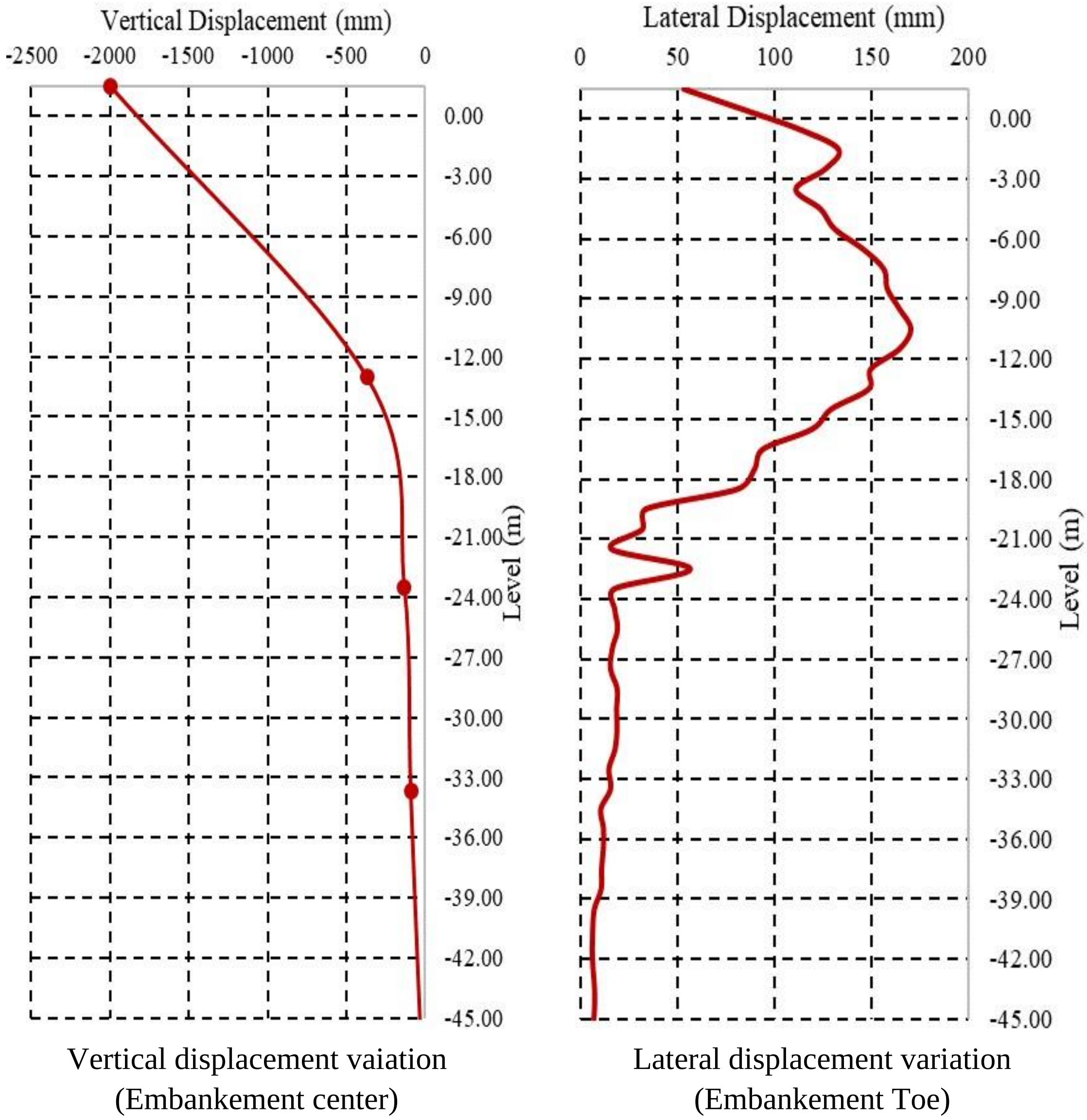


Figure 8: Variation of vertical and lateral displacement with level as measured from the trial embankment

Verification of consolidation parameters using lab test module in PLAXIS software

The main aims of this study are to verify the settlement values of the trial embankment using the parameters concluded from the odometer tests. The consolidation parameters (C_c, C_r, e_o, and OCR) concluded from the odometer tests had been verified using lab-test module included in PLAXIS 2D software. Soft soil model (SSM) uses an advanced model for the simulation of soil behavior. The soil parameter for soft soil model (SSM) includes the modified compression index λ* and the modified swelling index κ* which are defined in (PLAXIS 2D user's manual) as:

$$\lambda^* = \frac{C_c}{2.303(1+e_0)}$$

$$\kappa^* = \frac{2C_r}{2.303(1+e_0)}$$

The parameters of SSM used in calibration can be summarized as shown in Table 1.

Table 1: SSM Parameters used in consolidation parameters calibration

#	Layer Description	Layer Bottom level	Selected Consolidation parameters			modified compression and swelling index	
			C_c	C_r	e_0	□□□	□□□
1	Silty Clay/Clayey Silt with interlayers of Sand	-15.00	1.2	□□□□□	□□□□□	□□□□□□	□□□□□□
2	Silty Clay	-45.00	0.9	0.09	1.90	0.135	0.027

The Stress–void ratio relationship concluded from PLAXIS lab-test module had been compared to the actual laboratory results as showed good agreement as shown in figure 9.

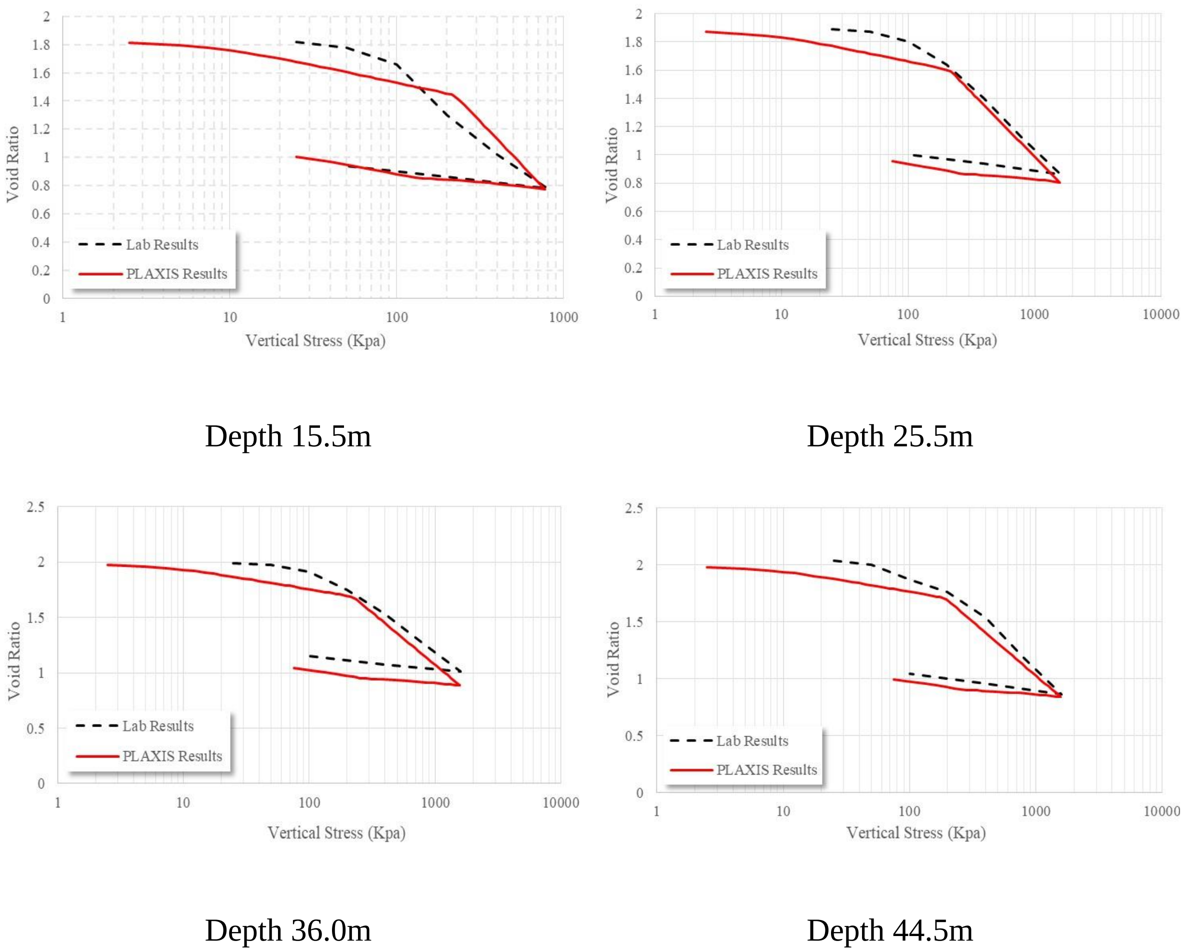


Figure 9: PLAXIS soil test results using SSM with respect to laboratory odometer test results

Numerical Modeling of the trial embankment

In this paper, a plain-strain 2D model was developed to simulate the present case study under investigation. The numerical model was based on the finite element method using the finite-element-based software PLAXIS 2D. The soil models used in the study are Mohr Coulomb Model (MCM) to simulate the fill surcharge layers and soft soil model (SSM) for clay layers. In addition, and in order to accurately compare the behavior of trial field embankment records with the finite element results, a sensitivity analysis had been performed to select the appropriate location for the model rigid boundary after the embankment slope toe. The sensitivity analysis had studied different locations of the model boundary as a function of the surcharge fill height (H). The study had been carried out considering a rigid boundary located at distance (X) varies between (1H to 20H). the results of analysis are presented in Figure 10and showed that the location of FE boundary has a minor effect on the final lateral displacement starting from a distance of 13 times the embankment height (>65m). accordingly, the rigid boundary limit had been selected at distance of 75m from the embankment toe. Figure 11 shows the geometry of the finite element model used in the analysis.

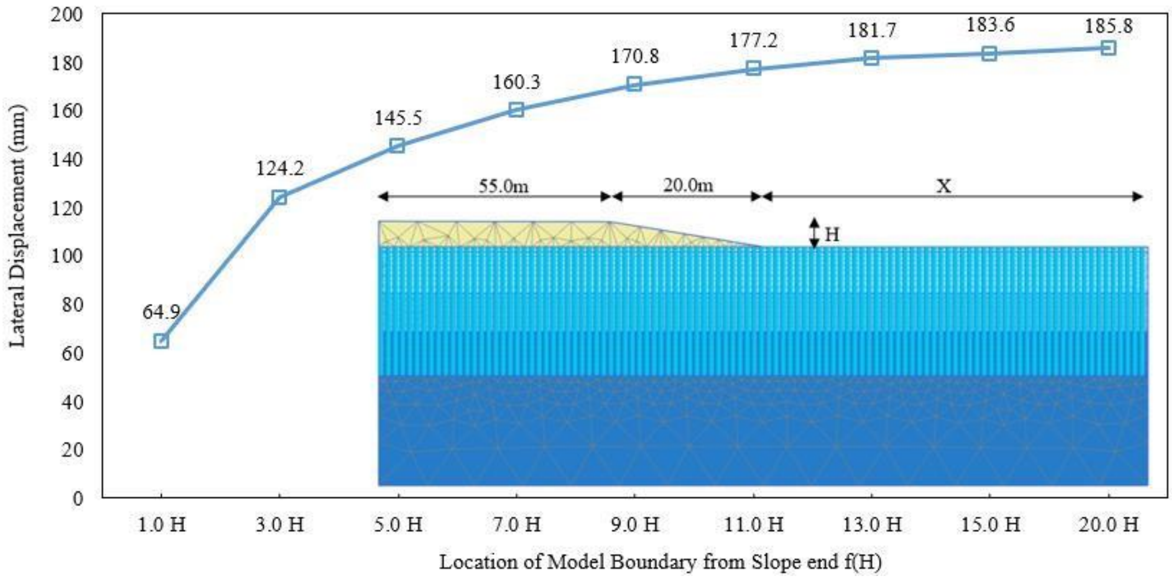


Figure 10: Effect of Location of Model Boundary from Slope end as function of the embankment height on the lateral displacement

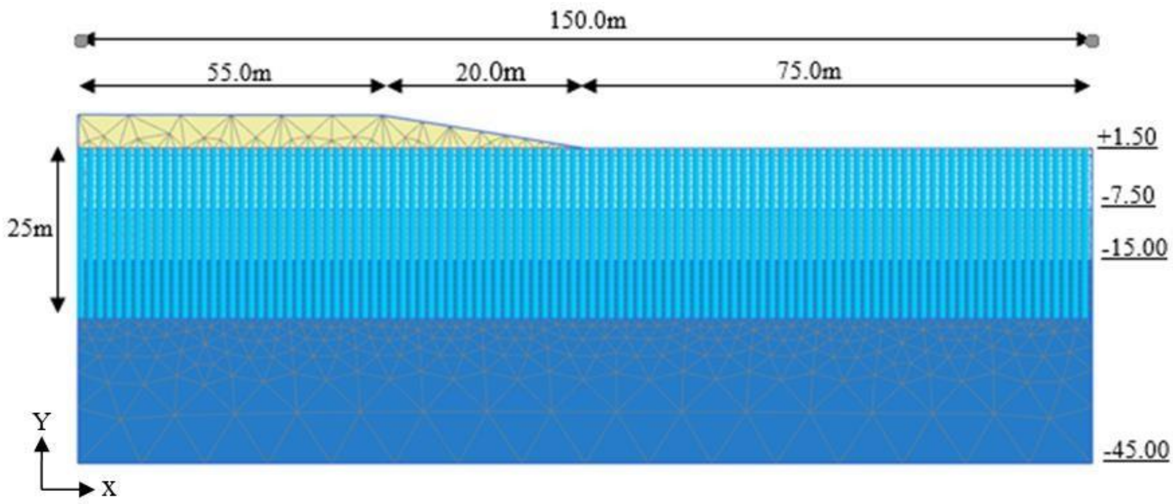


Figure 11: Configuration of the 2D finite element model

The deformation boundary had been considered as normally fixed for X_{min}, X_{max} and fully fixed for Y_{min} while Y_{max} had been considered as free. For ground flow boundary conditions, the X_{min} and X_{max} had been considered as closed since no dissipation of the excess pore pressures will take place there.

For the simulation of the vertical drains in the plain-strain analysis, the equivalence between axisymmetric and plane strain conditions prior to finite element modeling has been carried out based on the permeability equivalency procedure proposed by Hird et al. (1995) as expressed by the following equation:

$$\frac{k_{pl}}{k_{ax}} = \frac{2}{3\left[\ln(n) + \left(\frac{k_{ax}}{k_s}\right)\ln(s) - \frac{3}{4}\right]}$$

where, k_{pl} is the horizontal permeability of undisturbed zone in plane strain unit cell, k_{ax} is the horizontal permeability of undisturbed zone in axisymmetric unit cell, k_s is the horizontal permeability of smear zone in axisymmetric unit cell, n is the influence ratio r_e/r_W, s is the smear ratio r_s/r_W., r_e is the radius of influence zone, r_w is the equivalent radius of vertical drain, and r_s is the radius of smear zone (Onoue et al., 1991; Indraratna and Redana, 1998; Sathananthan, 2005).

For ideal drains, if both smear and well resistance effects are ignored, this equation simplifies to the following expression, as proposed earlier by Hird et al. (1992):

$$\frac{k_{hp}}{k_{ax}} = \frac{0.67}{[\ln(n) - 0.75]}$$

With respect to spacing of drains, an equivalent rectangular spacing had been considered which gives the same drain spacing ratio (n).

Results analysis

The results of PLAXIS 2D analysis show that the vertical displacement at embankment center after 450 days from end of backfill process at level +1.50 is about 1.83 m. Figure 12 shows Time-settlement relationship as concluded from PLAXIS 2D analysis compared to field measurements.

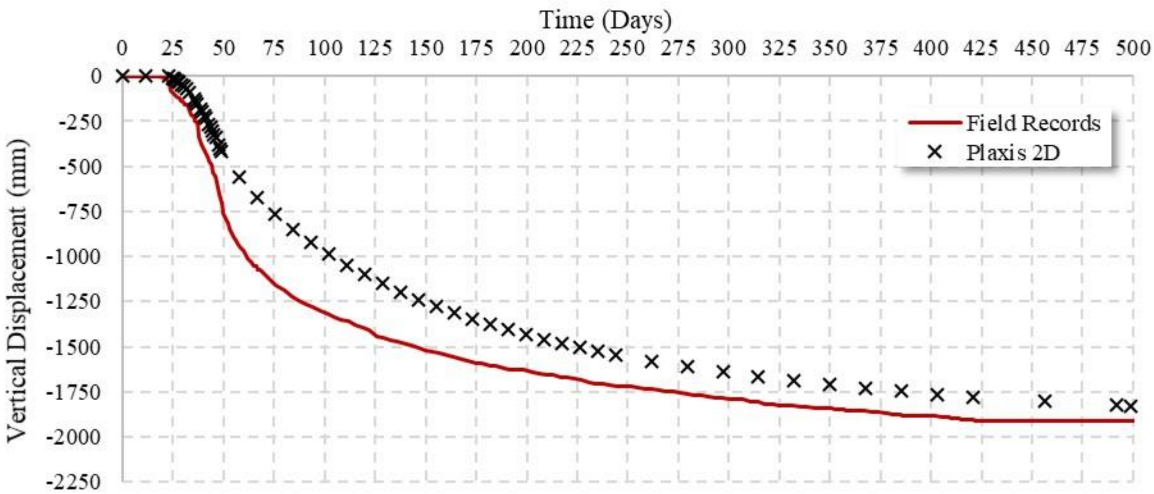
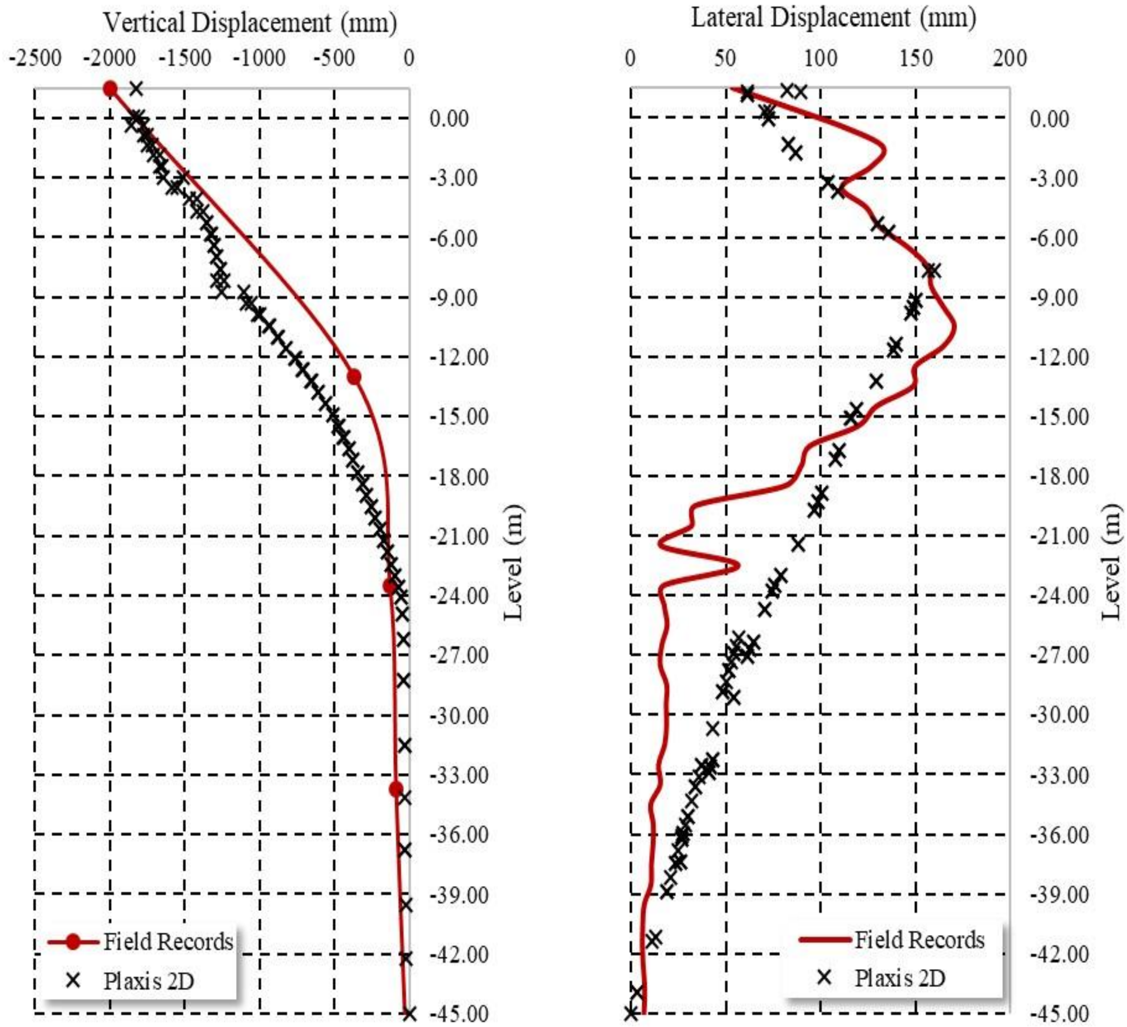


Figure 12: Field measurements for vertical displacement and the numerical results variation with time

From this figure, it is clear that PLAXIS 2D analysis generally underestimated the vertical displacement. However, it shows a good agreement with the filed records final settlement with a difference percentage of about 4%. For the first 200 days from the end of the backfill process, the difference percentage between PLAXIS 2D results and the field records reached about 25% probably due to the presence of Sand interlayers in the upper 15m that might affect significantly and accelerated the settlement.

With respect to the vertical displacement variation with depth, Figure 13a shows the vertical displacement variation with time resulted from PLAXIS 2D analysis with respect to field measurements. From this figure, 2D analysis shows good agreement with the filed records in all measured levels. Only for measuring station at level -13.00, PLAXIS 2D analysis overestimated the displacement value and showed higher value with a difference percentage of about 65%.

For lateral measurements, Figure 13b shows the vertical displacement variation with time for the finite element 2D analysis with respect to field measurements. From this figure, it’s clear that 2D analysis is close to the field measured value with a difference percentage of about 10%.



a) Vertical displacement at Embankement center

b) Lateral displacement at Embankement Toe

Figure 13: Field measurements for vertical and lateral displacements and the numerical results variation with level

Parametric Study

One of the main advantages of using PLAXIS 2D in long-term settlement calculations is considering the change of permeability during a consolidation analysis. The permeability will change according to the following relationship as stated by Taylor (1948):

$$\log\left(\frac{k}{k_0}\right)=\frac{\Delta e}{c_k}$$

In practice, C_c/C_k ranges between 0.5 and 2.0 (Berry and Wilkinson, 1969; Mesri and Rokhsar, 1974), with C_k taken from the empirical relation $C_k = 0.5e_0$. To investigate the effect of permeability change index C_k on the vertical displacement, a parametric study has been carried out with a different value of C_k as follows:

$$C_k \approx 0.5e_0$$

$$C_c/C_k = 0.5 \sim 10.0$$

Figure 15 shows Time-displacement relationship as concluded from PLAXIS 2D analysis compared to field measurements for all studied values of C_k while figure 16 shows the final concluded vertical displacement values.

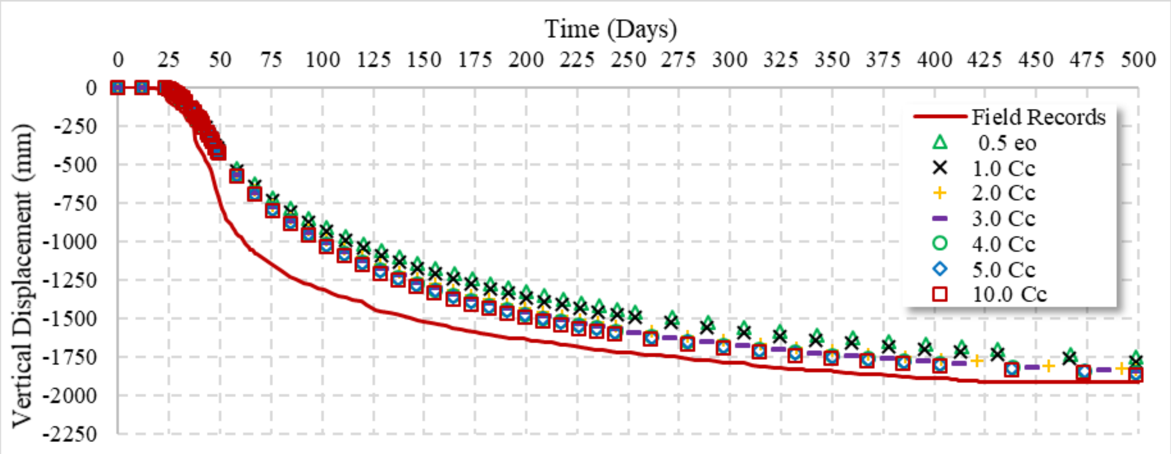


Figure 15: Field measurements for vertical displacement versus numerical results variation with time for all studied cases for C_k

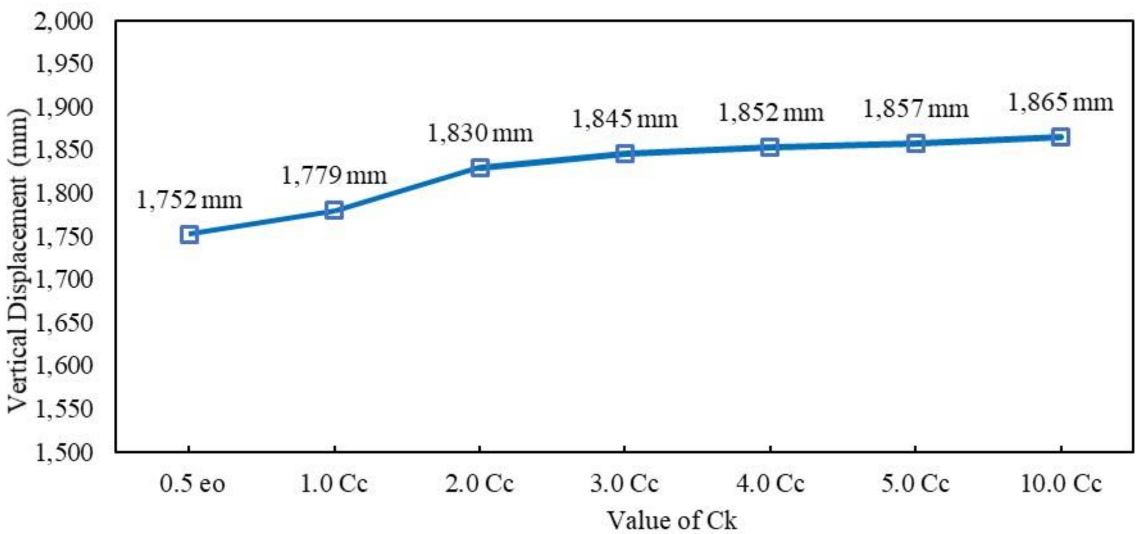


Figure 16: Total vertical displacement for all studied cases

From this figure, it is clear that C_k with value higher than C_k=3C_c has a minor effect on the final displacement value while it has a noticeable effect on the settlement increment with time.

Conclusions

The present study investigated 2D FE analysis and was compared to in-situ measurements for the performance of preloading system with partially penetrating vertical drains in consolidated marine clay deposits. The conclusions from the study can be summarized in the following points:

Although some variation of settlement prediction had resulted during the first 200 days from the end of the backfill process due to existence of silty sand interlayers in the upper 15m, FE analysis properly predicted the in-situ final measurements in terms of vertical and lateral displacements. The difference percentage between 2D FE to in-situ vertical displacement was about 4%. For lateral displacement, this percentage was about 10%.

Using soft soil model in the conducted study provided an adequate simulation for the behavior of marine soft clay under loading.

In 2D analysis, the plane-strain analysis was proper to model preloading system with partially penetrating vertical drains considering permeability equivalence between axisymmetric and plane-strain conditions using Hird et al. (1995) formula.

The triangular pattern in 2D plane-strain analysis was simulated with equivalent rectangular spacing considering the same drain Influence ratio (n) and provided a reasonable result.

Permeability change index C_k with value higher than C_k=3C_c has a minor effect on the final settlement value while it has a noticeable effect on the settlement increment with time.

Location of FE boundary has a noticeable effect on the lateral displacement of the embankment toe.

Location of FE boundary has a minor effect on the final lateral displacement with distance higher than 13 times the embankment height.

Notations

PVD Prefabricated vertical drains

FE Finite element

2D Two dimensional

MCM Mohr-Coulomb model

SSM Soft soil model

C_c Compression Index.

C_r Swelling Index

e_o Initial Void ratio

OCR Over consolidation ratio

C_k Permeability change index

K_h Coefficient of horizontal permeability

K_v Coefficient of vertical permeability

λ^* Modified compression index

κ^* Modified swelling index

References :

Berry, P. L. & Wilkinson, W. B. (1969). The radial consolidation of clay soils. Ge´otechnique 19, No. 2, 253–284.
Hird, C.C., Pyrah, I.C., Russell, D. Finite element modeling of vertical drains beneath embankments on soft ground. Géotechnique 42, No. 3, (1992), pp. 499-511.
Hird, C.C., Pyrah, I.C., Russell, D., and Cinicioglu, F. 1995. Modelling the Effects of Vertical Drains in Two Dimensional Finite Element Analyses of Embankments on Soft Ground, Can. Geotech. J. 32: 795-807.
Indraratna, B., & Redana, I. W. (1998). Laboratory determination of smear zone due to vertical drain installation. Journal of Geotechnical and Geoenvironmental Engineering, 124(2), 180–184.
Indraratna, B., Sathananthan, I., Bamunawita, C., & Balasubramaniam, A. S. (2005). Theoretical and numerical perspectives and field observations for the design and performance evaluation of embankments constructed on soft marine clay. In Elsevier geo-engineering book series (Vol. 3, pp. 51–89). Elsevier.
Lau, K.W.K. & Cowland, J.W. (2000). Geosyntheically enhanced embankments for the Shenzhen river. Advance in Transportation and Geoenvironmental Systems Using Geosynthetics, Geotechnical Special Publication.
Mesri, G. & Rokhsar, A. (1974). Theory of consolidation for clays. J. Geotech. Engng ASCE 100, No. 8, 889–904.
Onoue, A., Ting, N.-H., Germaine, J. T., and Whitman, R. V. (1991). “Permeability of disturbed zone around vertical drains.” Proc., Geotechnical Engineering Congress, Boulder, Vol. 2, 879–890.
PLAXIS 2D User’s Manuals (2020), Edited by Brinkgreve, R.B.J., Swolfs, W.M. and Engin, E., Plaxis BV, Delft, The Netherlands.
Sathananthan, I. (2005). Modelling of vertical drains with smear installed in soft clay. PhD, 305.
Tavenas, F., Jean, P., Leblond, P., & Leroueil, S. (1983). The permeability of natural soft clays. Part II: Permeability characteristics. Canadian Geotechnical Journal, 20(4), 645–660.
Taylor DW. Fundamentals of soil mechanics. New York, NY: John Wiley & Sons Inc.; 1948.