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Characterization of Northwest Sinai Clay Based on Field Testing and Hydraulic Properties, A Case Study

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ABSTRACT

This paper presents a comprehensive case study focusing on a project located in northwest Sinai. The area under consideration is renowned for its deep soft clay deposits, posing significant challenges for construction and geotechnical engineering. The study draws attention to improving Northwest Sinai clay through the utilization of prefabricated vertical drains (PVD) associated with preloading, enabling successful construction, and mitigating potential geotechnical risks. In principle, the PVD accelerates the consolidation process of the clay layer. This consolidation process always relies mainly on the hydraulic properties of the soil; hence, a proper estimation of these properties should precede the design of the soil improvement system using PVD and preloading. This research aims to present the characterization of the natural soil layers in terms of soil types, strength, deformation parameters, and hydraulic characteristics obtained from field boreholes and CPTu. Numerical analysis was carried out to assess the estimation and refinement of the soil layers by comparing predictions with settlement measurements for a trial embankment. The findings of the case study are discussed drawing attention to the significance of the proper estimation of the hydraulic properties of the soil layers in the optimization and effectiveness of the design of PVD.

Keywords: *Soft clay, PVD, hydraulic properties, CPT, dissipation, numerical analysis.*

1. Introduction

The Egyptian government has recognized the strategic importance of developing logistic hubs in several areas across the country. This initiative aims to leverage Egypt's favorable geographic location, which serves as a vital trade gateway between Africa, Europe, and Asia. However, the successful establishment of these logistic hubs requires addressing the geotechnical challenges posed by the prevailing soft clay deposits in many regions of Egypt. Soft clay, a common geological deposit found in a majority of Egypt, presents significant engineering challenges due to its consolidation characteristics. Over time, soft clay undergoes excessive deformation because of the consolidation process, leading to post-construction settlements that can impact the stability of structures.

To mitigate the adverse effects of soft clay consolidation, one of the most widely used ground improvement techniques is the implementation of Prefabricated Vertical Drains (PVD) combined with preloading. This technique accelerates the consolidation process by shortening the drainage path of water and facilitating the dissipation of excess pore water pressure induced by preloading. However, the performance of PVD is influenced by various factors, including construction-related aspects and the inherent properties of the drains themselves. Therefore, a comprehensive understanding of these influencing factors is crucial for optimizing the design and effectiveness of PVD installations in soft clay.

This research paper presents a case study conducted in Egypt, where a field trial area was established to monitor settlements. The observed settlement data is utilized to validate a 2D numerical model developed using PLAXIS 2D software. Furthermore, the numerical model enables the investigation of the impact of various factors that are expected to influence the performance of PVD in soft clay.

By examining the case study and numerical modelling results, this research aims to provide valuable insights into the behaviour of PVD in soft clay deposits specific to Egypt. The findings will contribute to enhancing the understanding and application of PVD as a ground improvement technique, ultimately supporting the successful development of logistic hubs and infrastructure projects in Egypt's soft clay regions.

2. Background

PVDs are used as soil improvement for soft clay soils incorporating the concept of horizontal consolidation by shortening the drainage path of the water to be half the distance between two adjacent drains. Since the improvement relies mainly on the consolidation of the clay layers, it is crucial to understand the factors that may affect the drainage of water through the clay layer and the vertical drains such as the smear effect and the well resistance.

Smear Effect

The installation of the PVD is done by pushing a steel mandrel into the ground to install the PVD to the required depth. Installation can be either by static pushing of the mandrel, vibrating the mandrel, or hammering it to the ground. The smearing effect is the fact of remolding a specific area around the steel mandrel that is used to install the PVD which results in a drop in the permeability value for a certain thickness around the PVD. The smear effect and the corresponding reduction in permeability result in increasing the consolidation time which is dependent on the thickness and permeability of the smear zone.

Estimating the extent and the permeability of the smear zone is a difficult process that usually requires simulating the installation process using physical modeling. However, typical values for smear radius and permeability were suggested in several literature as presented in Table 1.

Table 1: Parameters of Smear Zone

Reference	Radius	Permeability
Barron (1948)	r_s=1.6r_m	k_h/k_s = 3
Hansbo (1981)	r_s=1.5r_m	k_h/k_s = 3
Bergado et al. (1991)	r_s=2r_m	k_h/k_s = 1
Onoue et al. (1991)	r_s=1.6r_m	k_h/k_s = 3
Almeida and Ferriera (1993)	r_s=1.5~2r_m	k_h/k_s = 3~6
Indraratna and Redana (1998)	r_s=4~5r_m	k_h/k_s = 1.15
Hird and Moseley (2000)	r_s=1.6r_m	k_h/k_s = 3
Xiao (2000)	r_s=4r_m	k_h/k_s = 1.3

Well Resistance

Well resistance refers to the finite permeability of the drain with respect to the soil (Indraratna et al. 2015). Well resistance depends on the discharge capacity of the drain, permeability of soil k_h, discharge length l_m, and the geometric deficiencies on the drain.

Generally, the discharge capacity does not have a great effect on the consolidation of PVD-Improved clay. Especially, when the drains are less than 30m in length. Accordingly, the well resistance can be ignored in many cases unless drains are very long and it is expected that bending will occur to the drains. Based on the previous insights, a comprehensive understanding of the effect of smear effect and well resistance will aid in better modeling of PVD using finite element modeling.

Numerical Modeling of PVD

The nature of a single PVD case is a drain centralized in the numerical 2D axisymmetric model. This can be applied as a unit cell analysis. However, it is not practical in cases where modeling multi-drains is required, which is the case in most applications. Modeling a PVD element in plane strain 2D model reflects a trench that extends in the out-of-plane direction with specified spacing in-plane direction which means that higher settlement values are expected from the 2D plane strain numerical analysis.

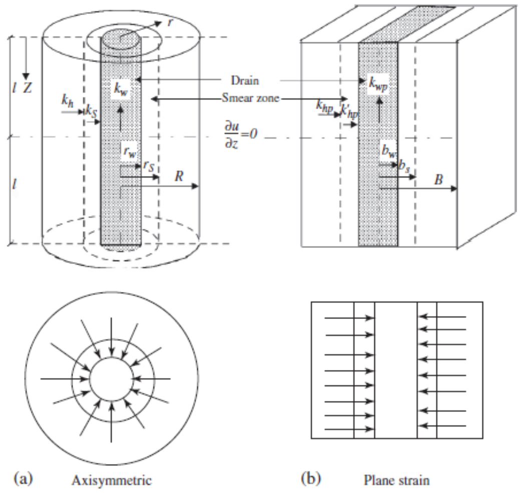

Figure 2.1. Axisymmetric-Plane Strain Transformation in Unit Cell Condition (Indraratna et al. 2015)

A proper transformation from axisymmetric to plane strain should be considered before starting the modeling of PVD problems. Different methods were presented in literature such as Hird et al. (1992) in which the plane strain theory by Hansbo (1991) was adopted and showed that the degree of consolidation at any depth and time is similar for axisymmetric and plane strain analyses if well resistance is ignored.

$$\frac{k_{pl}}{k_{ax}} = \frac{2B^2}{3R^2\left[\ln\left(\frac{R}{r_s}\right) + \left(\frac{k_{ax}}{k_s}\right)\ln\left(\frac{r_s}{r_w}\right) - \frac{3}{4}\right]} \quad \text{Eq. 1}$$

There is two possible methods to consider proper transformation from axisymmetric condition to plane strain condition, either by adjusting the geometry of the of the model or adjusting the horizontal permeability of the soil. To achieve geometric matching, the permeability values is assumed to be same for plane strain and axisymmetry conditions k_{pl}=k_{ax}=k_h and a corresponding drain distance is calculated, while permeability matching is achieved by assuming same drain distance for both conditions B=R and corresponding permeability for plane strain conditions is calculated. The numerical analysis in the current study was done considering the permeability matching to achieve the required transformation.

Where; k_{pl} is the horizontal permeability in plane strain condition

k_{ax} is the horizontal permeability in axisymmetric condition

k_s is the horizontal permeability of smear zone

Bergado & Long (1994) introduced a different approach based on the condition that equal discharge rate for axisymmetric and plane strain. The equivalent

$$\frac{k_{pl}}{k_{ax}} = \frac{\mu D(1 - a_s)}{2S\left[\ln\left(\frac{\alpha D}{d_s}\right) + \left(\frac{k_{ax}}{k_s}\right)\ln\left(\frac{d_s}{d_w}\right)\right]} \qquad \text{Eq. 2}$$

Where; $a_s = t/_D$, t is the thickness of the wall, D & S are row and pile spacing respectively

$\propto = {}^{D_e}/_D$

k_{ax} is the horizontal permeability in axisymmetric condition

k_s is the horizontal permeability of smear zone

Both approaches consider the effect of the reduced permeability of smear zone in estimating the equivalent horizontal permeability for plane strain condition. While the approach introduced by Bergado and Long (1994) consider both the reduced permeability of the smear zone as well as the well resistance.

1. Site Characterization

Numerous projects are being developed by the Egyptian government in Suez canal area. The specified location is well known of deep soft clay deposits which requires intensive geotechnical study to overcome the excessive deformation expected to occur through the lifetime of the projects. The project under study is constructed over a total area of about 16 km^2 comprising the construction of lightweight steel structures.

The geological nature of the project location indicated the presence of soft clay extending to depths of 35.0m to 50.0m. Since the proposed structures are lightweight structures, a soil improvement approach was proposed using PVDs associated with preloading in order to accelerate the consolidation process of soft clay and limit the post-construction settlement after removing the surcharge and applying structural loads. A preliminary soil investigation took place at the project site which concluded a representative soil profile given in Table 2.

Table (2): Soil Profile Based on Preliminary Site Investigation

Depth, m		Description	M, MPa	k_h, m/day	k_v, m/day	OCR
from	To					
0	10	Silty clay to clayey Silt with interlayers of Sand	5	2.7e-4	2.7e-5	2.25
10	15	Silty clay to clayey Silt with interlayers of Sand	2.75	2.7e-4	2.7e-5	1.1
15	50	silty Clay	5	2.05e-5	6.85e-6	1

The preliminary design was proposed where PVDs are distributed in a triangular pattern at a spacing of 1.5 m installed to a 25.0 m depth. The mock-up trial field was constructed on an area of 100m x 100m where PVDs were installed with the selected spacing, pattern, and depth. Then, the area was preloaded with the required surcharge height (6.5m). A monitoring program was planned to monitor the settlement using fixed Ground Measurement Points (GMP). The GMPs were installed on top of the working platform and the length of the steel pipes was adjusted during the surcharge preloading to always stay above the surcharge height and be monitored. A total number of 21 GMPs were installed within the trial area, and 7 of them were installed inside the preloaded embankment in addition to the field monitoring using GMPs, an additional soil investigation took place within the trial area. The soil investigation included drilling two boreholes of depth 70 m and 3 CPTu conducted to refusal depth and included 4 dissipation tests at each CPTu to evaluate the horizontal permeability value for the different layers.

Undisturbed samples were extracted during the drilling of boreholes from clay layers while disturbed samples were collected for sand layers. Oedometer test were performed to define the consolidation parameters of clay layers (C_c, C_r, C_α, k_v, p_c & e_o). Although the consolidation parameters of clay layers are the governing factors, the strength parameters should be calculated as well and used as input for the FE model later on for the calibration of soil parameters as well as the verification process. Three 1-dimensional consolidation tests were performed on the undisturbed clay samples. The samples were loaded with stress increments (100 kPa, 200 kPa, 400 kPa, 800 kPa and 1600 kPa).

Although the samples from boreholes can be an acceptable basis for the classification of soil profile in addition to evaluation of the soil parameters, CPTu can be of crucial part for classification of the soil and estimating more parameters that could not be evaluated by the boreholes and laboratory samples such as the horizontal permeability that can be evaluated from dissipation test. Four dissipation tests were performed in each CPTu to estimate the horizontal permeability values at different depths and used later for the verification of the preliminary design by numerical modelling.

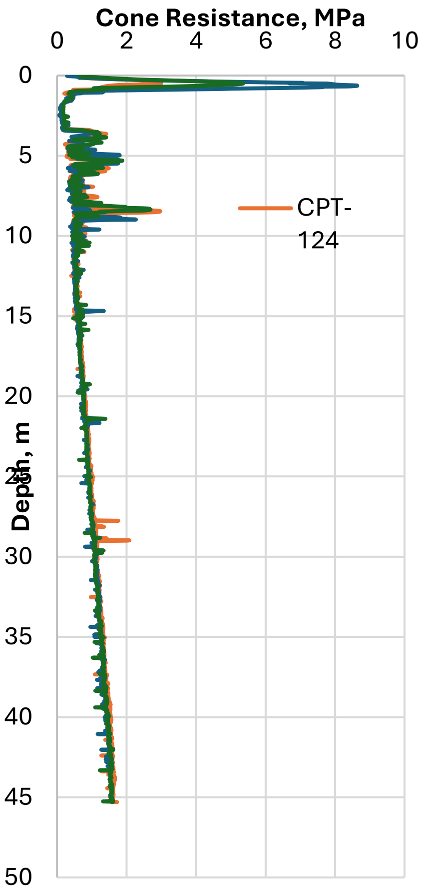

Figure 1: Cone Penetration (qc) from CPTu

Table 4: Horizontal Permeability Derived from Dissipation Tests

CPT	Depth, m	k_h, m/s
124	10	8.37e-10
	15	6.20e-10
	25	2.28e-10
	45	2.59e-10
224	10	7.57e-10
	15	8.36e-10
	25	4.19e-10
	45	2.97e-10
225	10	6.72e-10
	15	5.13e-10
	25	3.16e-10
	45	2.30e-10

Based on the available data from the soil investigation, a representative soil profile was selected as the basis for the verification process. The representative soil profile was based on the classification from boreholes and CPTu following the mechanical properties of the soil layer and averaging the hydraulic parameters over the proposed depths. The selected values for the consolidation parameters are in a good match with the values and interpretations presented by Abdel Rahman et al. (2004) on Sinai clay.

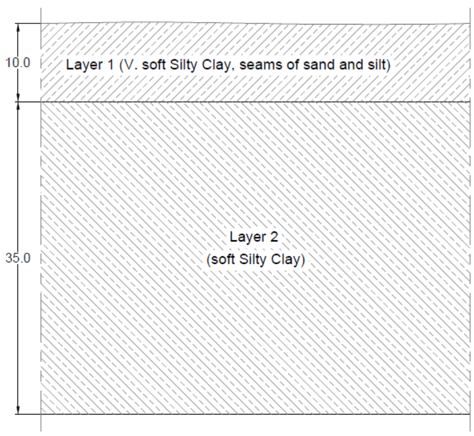

Figure 2: Layering of the Soil Profile Based on Soil Investigation in the Trial Area

Table 3.3: Soil Parameters after Trial Area Investigation

Layer	Thickness, m	C_c	C_r	C_α	k_v, m/d	k_h, m/d	e_o
V. soft Silty Clay seams of sand & silt	10	1.2	0.17	0.013	2.3e-5	6.89e-5	1.85
Soft silty Clay	35	1	0.17	0.015	1.39e-5	3.83e-5	2

Following the installation of the PVD as per the initial proposed configuration. The trial embankment was constructed fully loading an area of 100mx100m. The settlement of the trial embankment was monitored using settlement points starting from the construction of the trial embankment and for a period of 9 months.

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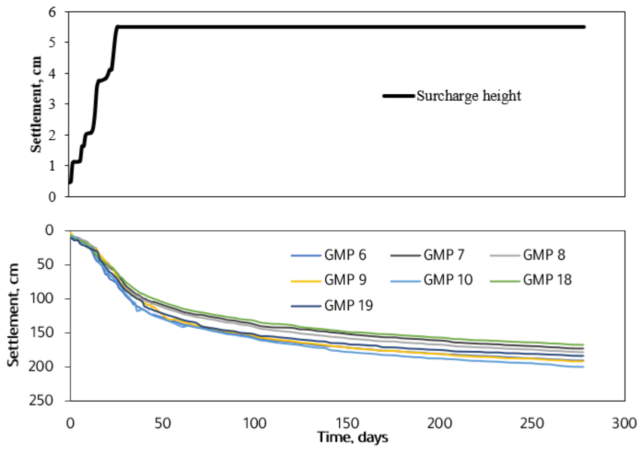

Figure 3.3: Field Measurement of Embankment Settlement

4. Numerical Analysis of Trial Embankment

To verify the feasibility of the proposed solution the preliminary design was modeled numerically. The process of verifying the design commences with the

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calibration of the soil parameters derived from the field and laboratory testing conducted on the preliminary investigation and the verification boreholes and CPT conducted in the trial mock-up area. The calibration of the soil parameters was done using PLAXIS V.20 soiltest module. Oedometer tests performed on the samples extracted from the boreholes were the basis of the calibration process. Oedometer tests were simulated in soiltest module in PLAXIS using the input parameters concluded from the preliminary soil investigation and compared to the results of laboratory testing on the samples extracted from boreholes.

The below figures show that the results of the calibration using the soil parameters given in table 4.2 have given acceptable accuracy presented in the matching between laboratory testing and numerical simulation of Sinai Clay.

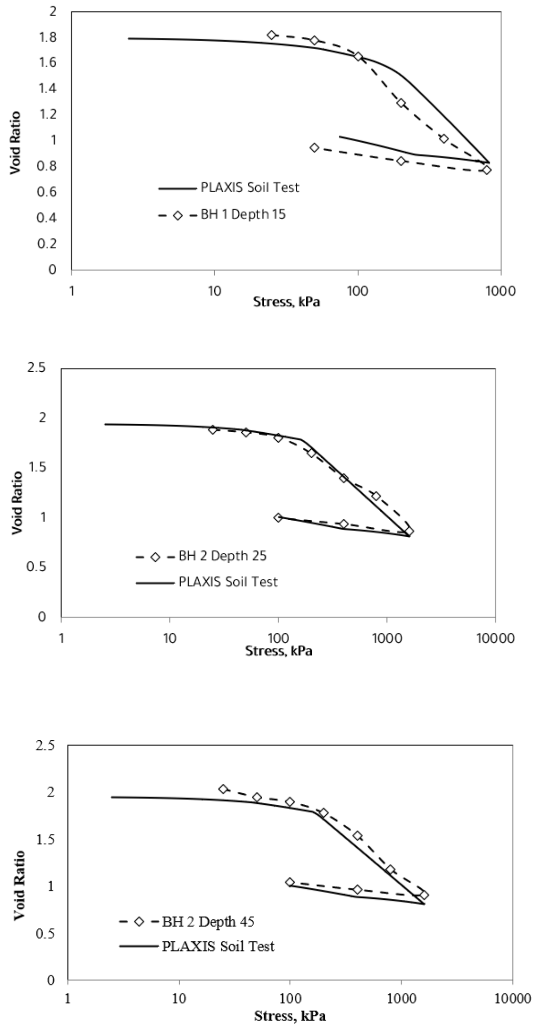

Figure 4.1: Oedometer test from Laboratory and Soiltest Module

The verification process of the preliminary design was done by preparing a multi-drain analysis in PLAXIS 2D numerical model considering the transformation from axisymmetry to plane strain conditions applying the approach proposed by Hird et al (1992) by which an equivalent horizontal permeability (k_{pl}) was calculated and introduced into the numerical model accounting for the smear effect following the installation of the PVD. Due to the difficulty of measuring the properties of the smear zone, smear diameter and permeability were assumed based on the values introduced in the literature. smear permeability "k_s " was assumed = $k_h/3$ while smear radius"r_s" was assumed 2.5 times the mandrel radius "r_m".

Table 4.2: Input Parameters for Plane Strain Multi-Drain Model

Layer	Depth, m	k_v, m/s	k_h, m/s	k_s, m/d	r_w, m	k_{pl} m/d
V. soft Silty Clay seams of sand & silt	10	2.3e-5	6.89e-5	2.3e-5	0.026	1.01e-5
Soft silty Clay	35	1.39e-5	3.83e-5	1.28e-5		5.59e-6

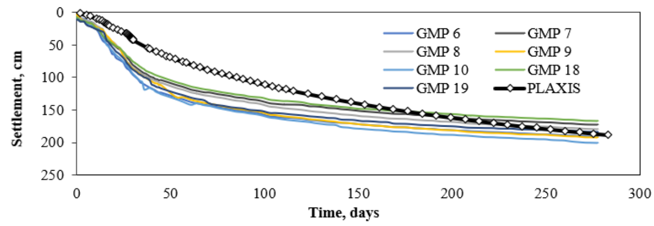

Figure 4.2: Field Measurement vs Numerical Prediction of Embankment Settlement

Although the calibration of the consolidation parameters conducted using soiltest module is in reasonable agreement with laboratory test results, the 2D Plane strain model results varied from the field measurements. In reference to the rate of consolidation presented in the numerically predicted results in Figure 4.2, the numerical model does not accurately predict the rate of consolidation of the clay layer. Hence, further improvement is required to be implemented in the numerical model.

5. Layer Characterization Refinement

The consolidation process of clay is governed by the hydraulic properties of the soil (permeability), a proper and accurate estimation of the permeability of the layers can have a crucial impact on the predicted deformations. As explained in the previous section, the layering of the soil profile was based on soil properties estimated from boreholes, laboratory tests, and dissipation tests from CPT. Although the dissipation test is considered a robust method to estimate the horizontal permeability, it only represents the exact depth at which it was conducted. The estimated permeability from CPT is based on the Soil Behaviour Type.

The estimated values of the permeability are presented in Figure x which shows that higher permeability values are estimated in the top 10m due to the presence of a higher percentage of sand and silt clearly observed from SBT Index from CPTu. Accordingly, the soil layers were further refined according to the hydraulic properties of the soil derived from the CPTu according to the Soil Behavior Type "SBT". Moreover, given the fact that extracting undisturbed samples from soft clay is a difficult process in addition to the stress relief that may impact the estimated OCR values of the extracted clay samples. OCR values estimated from CPT were considered as well in an improved soil profile presented in Table (5.1) which requires to re-do calibration the soil parameters using available Oedometer results in reference to the updated soil profile and refined soil layers.

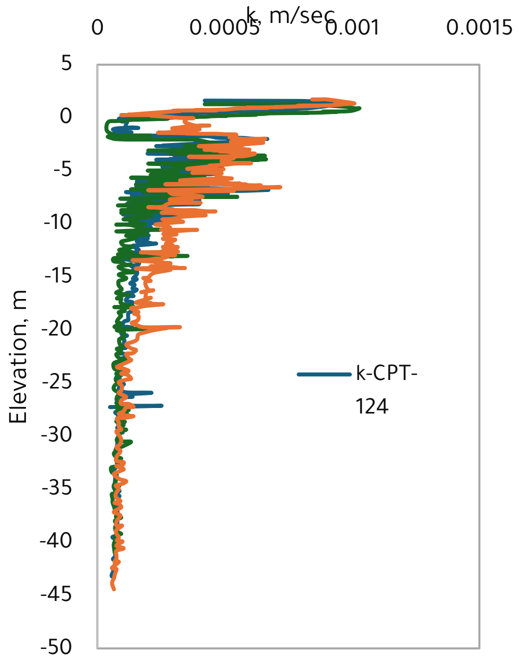

Figure 5.1: CPT interpreted Permeability

Table 5.1: Equivalent Horizontal Permeability Values After Hird et al. (1992)

Layer	Depth, m	C_c	C_r	C_α	k_v, m/d	k_h, m/d	K_{Hird}, m/d
V. soft Silty Clay seams of sand & silt	10	1.2	0.17	0.015	1.3e-5	1.62-3	1.68e-4
Soft silty Clay-1	5	1.2	0.17	0.015	1.39e-5	5.67e-5	5.86e-6
Soft silty Clay-2	10	0.95	0.13	0.0145	1.04e-5	2.42e-5	2.51e-6
Soft silty Clay-3	20	1	0.15	0.015	1.14e-5	2.26e-5	--

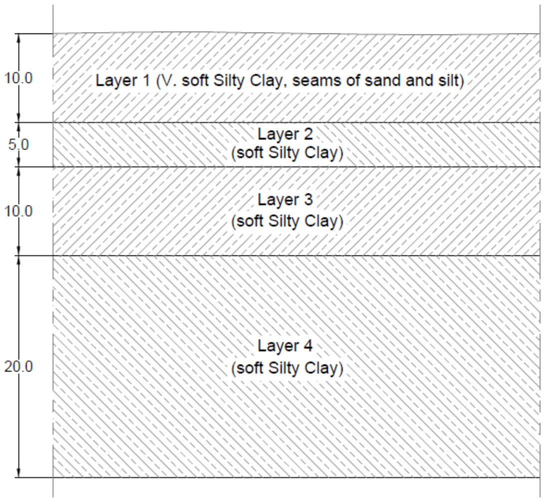

Figure 5.2: Refined Soil Layers Based on Hydraulic Parameters

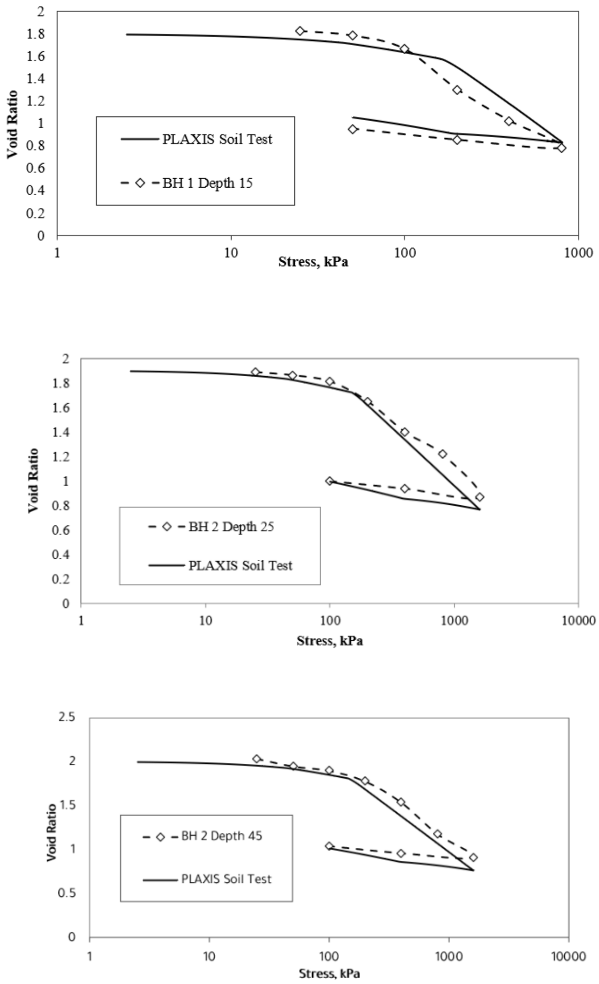

Figure 5.3: Oedometer test from Laboratory and Soiltest Module

In the first verification attempt, the permeability values were based on the dissipation tests over a wider depth which lead to the initial depths. The refinement of the soil profile in the second attempt considered an average value for each layer based on permeability derived from CPT. The refined soil layers were incorporated in the 2D plane strain model considering the equivalent horizontal permeability estimated as per Hird et al (1992) for each layer separately. The results of the amended model showed very good agreement with the field measurements of the embankment settlement. This results reflects the impact of the permeability values on the consolidation settlement of the clay soils.

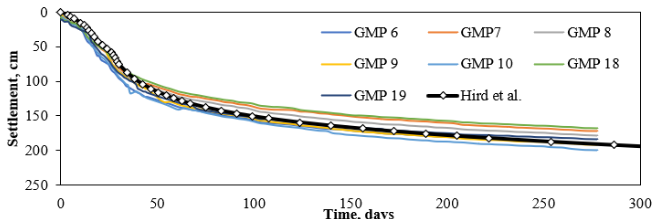

Figure 5.4: Field Measurement vs Numerical Prediction after Layers Refinement

Since the well resistance can be simulated as a finite permeability value for the PVD in the PLAXIS model, modelling the PVD as drain element in PLAXIS can not be done in case of considering the transformation proposed by Bergado and Long (1994) which includes the effect the well resistance. Accordingly, the PVD are modelled as volume elements with the thickness of the PVD material and a permeability value was incorporated as per the specifications of the supplied PVD material.

Table 5.2: Equivalent Horizontal Permeability Values After Bergado & Long (1994)

Layer	Depth, m	C_c	C_r	$C\alpha$	k_v, m/d	k_h, m/d	$k_{Bergado}$, m/d
V. soft Silty Clay seams of sand & silt	10	1.2	0.17	0.015	1.3e-5	1.62-3	3.62e-4
Soft silty Clay-1	5	1.2	0.17	0.015	1.39e-5	5.67e-5	1.27e-5
Soft silty Clay-2	10	0.95	0.13	0.0145	1.04e-5	2.42e-5	5.42e-6
Soft silty Clay-3	20	1	0.15	0.015	1.14e-5	2.26e-5	--

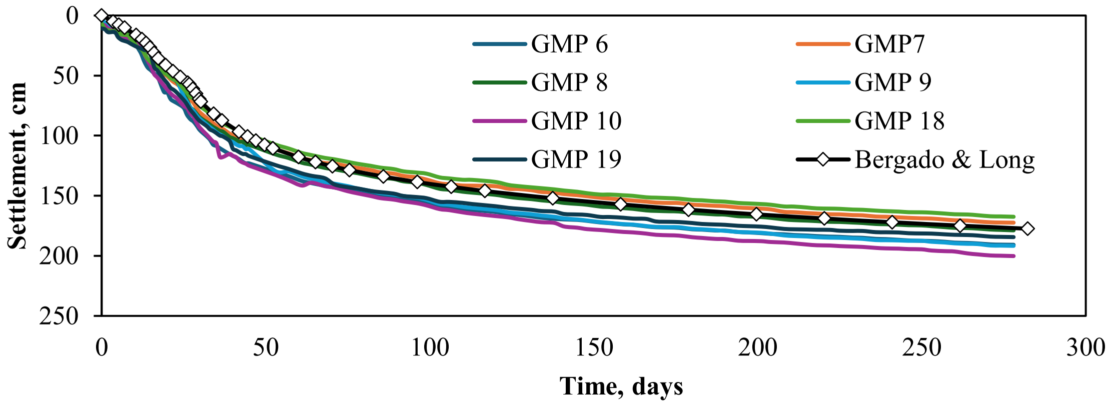

Figure 5.5: Field Measurement vs Numerical Prediction implementing Bergado & Long 1994

The results of the numerical model where Bergado and Long (2994) approach was applied does show a very good agreement with the field measurement same as the model prepared considering Hird et al. (1992) approach. However, the results of Hird et al. approach is closer to the lower bound of the field measurements which was recorded at the edges of the trial embankment where the measurements are not only due to the consolidation settlement, but also due to shear deformation of the slopes of the embankment which result in additional settlement measurement from the ground monitoring points locates at the edges.

6. Conclusion

The paper demonstrates the importance of characterization of the soft Sinai Clay with respect to various properties in addition to modelling the PVD problems in plane strain conditions considering necessary permeability consideration through a campaign of field measurements in a project in Egypt.

1. Creating a representative soil profile in case of consolidation-related problem should consider the hydraulic parameters of the soil layer as a key factor in layering the soil profile which highly impacts the estimated consolidation time and settlement.
2. Conducting CPT with horizontal permeability field testing is crucial to estimate appropriate hydraulic properties of the soil layers and incorporate them into the numerical model.
3. The 3D plane strain model can give accurate estimation of the embankment settlement over PVD-improved soft clay
4. Although neglecting the well resistance does not have a huge impact on the estimated settlement, including both, the smear zone and the well resistance effect in transformation from axisymmetric to plane strain gives more accurate results than that obtained only by considering the smear effect.

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