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Numerical studies on the behaviour of soft subsoil improved by prefabricated vertical drains based on trial field data

Etude numérique du comportement de sols mous améliorés par des drains verticaux sur la base d'essais sur site

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ABSTRACT: The paper presents a simple numerical model for complicated preconsolidation case studies, where a very soft soil up to 50 m was partially improved using prefabricated vertical drains (PVD) in combination with surcharge loading. The soft soil sediments are formed in three layers with different permeability and stiffness. A numerical model was built to simulate the current behaviour and to predict the long term settlements. The model considered the variation in the soil layers, the effect of PVDs in the upper improved layers, the drain design (spacing, discharge, length, smear effect) and the preloading pressure. Different constitutive models were used to define the soil behaviour (Hardening Soil Model, Soft Soil, Soft Soil Creep, Mohr-Coulomb) and the construction stages were modelled in detail to simulate the loading sequences (starting from executing the platform, drain installation and surcharge layers). The parameters in the study are derived on the one hand from an intensive soil investigation program including CPTu, boreholes and field measurements. And on the other hand from a monitored trial field as well as previous studies in the same area. The numerical model was calibrated and verified with measurements obtained at different locations of the construction site. Finally the model was used to predict the long term behaviour. These results are also in a good agreement with conventional analyses and data from literature.

RÉSUMÉ: L'article présente un modèle numérique simple pour l'études de cas complexes de preconsolidation, ou un sol très mou, atteignant une profondeur de 50m, a été partiellement amélioré par l'installation de drain verticaux préfabriqués (PVD, Prefabricated Vertical Drain) et une surcharge. Les dépôts de sols mous se sont formés en trois couches de perméabilités et rigidités différentes. Un modèle numérique a été développé pour simuler le comportement actuel du sol ainsi que pour estimer les déformations à long terme. Le modèle considère les variations dans les couches de sol, les effets des drains verticaux et leur paramètres de conception (espacement, décharge, longueur, effet « smear ») et la pression de prechargement. Plusieurs modèles de sol ont été utilisés (Hardening Soil, Soft Soil, Soft Soil Creep, Mohr-Coulomb) dans cette étude et les différentes étapes de construction ont été simulées (exécution de la plateforme de travail, installation des drains puis de la surcharge). Les paramètres utilisés dans l'études sont dérivés d'une importante campagne d'investigation comprenant CPTu, trous de sondages, mesures sur site, mesures réalisées lors de planches d'essais ou encore de précédentes études dans la même zone. Le modèle a été calibré, ses résultats ont été comparés avec les mesures prises a différentes location du chantier et se sont révélés être en adéquations avec celles-ci. Le modèle a ensuite été utilisé pour prédire le comportement à long terme et s'est également révélé être en accord avec les calculs manuels et les informations disponibles dans la littérature. Enfin, les mesures post-amélioration sont également présentées et comparées aux prédictions du modèle numérique.

Keywords: Soft clay, Consolidation, Preloading, Numerical analysis, Vertical drains

1 INTRODUCTION

Many coastal regions all over the world contain very soft soils, which have undesirable geotechnical properties such as low strength and high compressibility. Without using a proper soil improvement, excessive settlements and lateral movements can dramatically affect the stability of structures built on such soft ground. Several ground improvement techniques can be used to improve the behaviour of soft soil (Ayeldeen & Kitazume, 2017), however vertical drains and surcharge are considered the most economical and ecofriendly technique for such soils.

Generally, the idea behind the pre-fabricated vertical drains (PVD) is to shorten the drainage path of the water from clay layers by installing vertical drains. These drains allow the groundwater to migrate inside the clay layer (to drain horizontally) towards the vertical drains instead of taking a longer drainage path equal to half the thickness of the clay layer or the whole clay thickness if the drainage is allowed from one side only (Indraratna et al. 2012 and 2015). In other words, it accelerates the consolidation process during the preloading which leads to an increase of the soil stiffness and a reduction of the final settlements for the final / long term stage. The behaviour of soft soil improved by means of vertical drains can be simulated and modelled numerically and analytically. However, a proper evaluation and verification of the soil parameters used in the model is essential.

2 GENERAL PROJECT DESCRIPTION AND SOIL CONDITIONS

The mega poject discussed in the following is located at the east side of Port Said, Egypt. The paper investigates the improvement of soft clay layers using a combination of pre-fabricated vertical drains and a surcharge. The entire project comprises a total area of 64 km^2.

The soil profile of the investigated area consists of 10 to 15 m of soft silty sand to silty clay (defined in the study as "Clay 1") over a layer of soft clay extended below to level up to -50 m (defined in this study as "Clay 2"). The total 50 m of soft soil is laying above a dense sand layer. The location of the groundwater table is roughly 1.0 m below the surface.

Based on intensive lab investigations, and performed in-situ tests the parameter determination was performed. In the following only some key soil parameters are explained in detail more information can be found in Ayeldeen (2018).

2.1 Stiffness and over consolidation: C_c, C_r and OCR

For the determination of the compression index C_c and the recompression index C_r oedometer tests were performed on the extracted samples from two different boreholes. Additionally the correlations according to Skempton & Jones

(1944) were used to estimate compression indices (see Fig. 1).

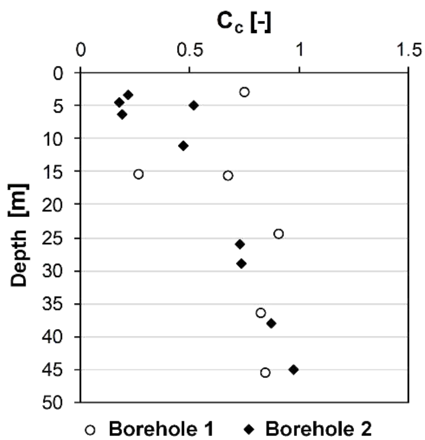

Figure 1. Compression index with depth after Skempton & Jones (1944)

The over consolidation ratio (OCR) was evaluated based on CPTu results, where the upper 10 m show a high OCR value of 3 to 5 comparing to the below layers with lower OCR value of 1 to 1.2.

2.2 *Coefficient of consolidation: c_v and c_h*

The coefficient of consolidation in vertical direction c_v is determined based on performed oedometer tests, as the water during this test is allowed to dissipate only towards the top and bottom of the soil sample. While the coefficient of consolidation in the horizontal direction c_h is determined from the dissipation tests performed during the cone penetration tests at different depths. The majority of the pre-consolidation deformation during preloading is coming from the horizontal dissipation of the excess pore water pressure due to the effect of the surcharge (in combination with the PVDs). Therefore, the horizontal coefficient of consolidation c_h is one of the key parameters to model the realistic preconsolidation process. The results of the dissipation tests performed during the cone penetration testing are presented in Figure 2. Additionally c_h values have been back calculated using piezometers and settlement point measurements (according to Bergado et al. 2002). The obtained coefficients of permeability have been verified finally using the Asaoka method (1978).

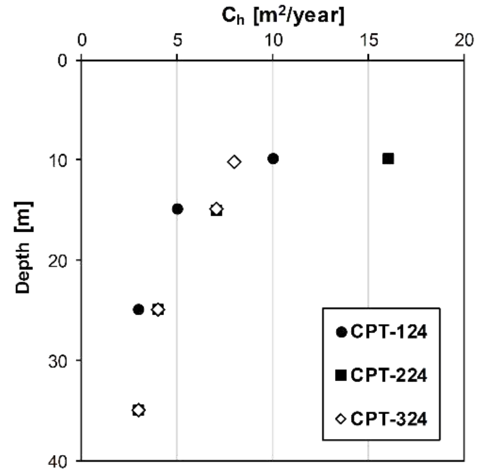

Figure 2. Variation of c_h with depth from field dissipation test

2.3 *Creep index: C_α*

Since one of the key issues of the design concept is related to the reduction of predicted long term settlements it is required to include creep settlements in all the analyses. Similar to the other consolidation parameters, the secondary compression index C_α was obtained from conducted oedometer tests. Table 1 shows the obtained C_α values and the used stiffness parameters until a depth of -50.0 m.

Table 1. Sample (use 10 pt both in heading and table)

Layer	Depth [m]		Creep index C_α [-]			C_c	C_r
	from	to	sampling - depth [m]	appl. stress [kPa]	C_α [-]		
Clay 1 A	0	-10				1,22	0,17
Clay 1 B	-10	-15				0,88	0,13
Clay 2 A	-15	-25	-15,5	100	0,013	0,94	0,12
Clay 2 B	-25	35-50	-26,0 / -36,5	200 / 400	0,014 / 0,017	1,18	0,15

3 TRIAL FIELD

The trial zone with a dimension of 150 m times 150 m was built and intensively monitored to evaluate and verify the soil parameters used in the following design.

Vertical drains with a length of 25 m were installed in combination with a 6.5 m high surcharge. The preloading duration was 9 months. The surcharge was placed in stages: stage 1 loading was up to 20 kPa, stage 2 up to 35 kPa, stage 3 up to 60 kPa, stage 4 up to 68 kPa and stage 5 up to 91.60 kPa (6.50 m fill height). Piezometers, extensometers, inclinometers and ground measurement points (GMP) were installed in the trial zone and continuously monitored for more than 9 months. Additional soil investigation was performed during the trial field construction as well. These investigations included boreholes, lab tests and CPTu's. Figure 3 shows a top view of the test field including the installed measurement devices.

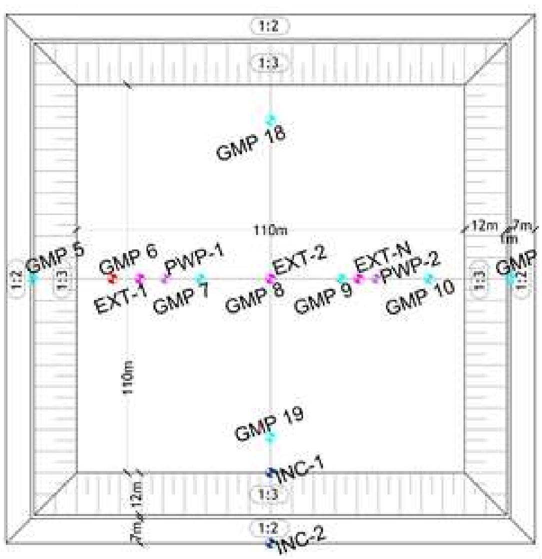

Figure 3. Layout - Trial field

The settlements were measured through 18 ground measurement points all over the trial zone. The average settlement after 6 months of preloading was about 180 cm. The measurements showed that almost all the settlements are coming from the improved layer (upper 25 m), while the degree of consolidation after 6 months for the lower 25 m does not exceed ~4%.

4 DESIGN CONCEPT

The preconsolidation of soft soil layers due to the effect of the surcharge is a complicated consolidation process, where the excess pore water pressure dissipates in both, horizontal and vertical direction (towards the drains and the upper and lower drainages respectively). As a consequence of the anisotropy of permeability (in vertical and horizontal direction) the consolidation process is relatively complex and the decrease of excess pore water pressure in vertical and horizontal direction is not equal. Besides the difference between vertical and horizontal permeability, the effect of PVD installation in the zone arround the drains (smear zone) has to be considered in the design. It is well known that a remarkable reduction of permeability occurs arround drains due to the effect of the mandral installation (Bergado et. al 2002). Therefore, it is important to have a design concept and a calculation model which is capable to represent a realistic consolidation process considering all factors mentioned above. And additionally it should have the ability to include actual conditions of loading/unloading during and after removing the surcharge.

5 ANALYTICAL ANALYSES

The analytical analysis in this study is based on the radial consolidation theory after Bergado et. al (2002) which also takes the smear effect into account. The long term creep behaviour was considered according to Mesri (2003) using the coefficient of secondary compression (C_α) and its well known time dependant correlation. Additionally the reduction of creep strains due to the effect of preloading (as disscussed by Mesri 2003) is taken into account.

6 NUMERICAL MODELLING

The numerical predictions using PLAXIS 2D Version 2017 (Brinkgreve et al. 2017) were executed as small deformation analyses. The calculations were performed by taking into account consolidation (time) effects during the individual construction phases. The objective of the numerical modelling is to assess the performance of the PVDs and to evaluate the long term behaviour of the project. Different constitutive models have been used to model the different soil layers, including the Soft Soil Creep model for the soft clay layers, the Mohr Coulomb model for the working platform and surcharge and the Hardening Soil Small (HSS) model (Benz, 2007) for the deep sand layer. The advantage of the HSS model is, that the high stiffness at very low strains is taken into account, thus the obtained soil displacements at deeper depths are automatically reduced and a more realistic settlement profile with depth can be computed (Tschuchnigg 2012). Since the majority of the primary and secondary displacements are caused by the soft clay layers only the Soft Soil Creep (SSC) model is briefly described in the following.

6.1 *Soft Soil Creep model*

The SSC model is a 3D-model, which was developed as an extension of conventional 1D-creep models (e.g. Bjerrum 1967, Garlanger 1972). To obtain the SSC model, a differential equation for 1D conditions was derived (Vermeer & Neher 1999). This differential equation is based on the assumption that all inelastic strains are time dependent. Furthermore, an increasing pre-consolidation stress with accumulated creep strains is assumed (Vermeer & Neher 1999). To extend the 1D-formulation to a three dimensional stress space, the equivalent isotropic stress p'_{eq} is introduced on the basis of the effective mean stress p' and the deviatoric stress q. The current stress state is situated on the ellipsoid associated to the equivalent isotropic stress p'_{eq}. However, the normally consolidated state is characterized by an ellipsoid associated to the pre-consolidation stress p'_p. The definition of the ellipsoids representing the current stress state (CSS – p'_{eq}) and the normal consolidation state (NCS - p'_p) is according to the Soft Soil model (Brinkgreve et al. 2017). The ellipsoids are shown in Figure 4.

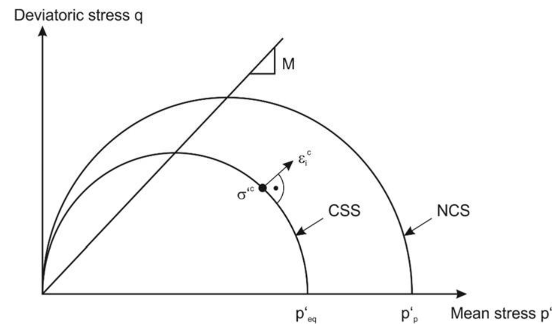

Figure 4. State surfaces in the SSC model (after Vermeer & Leoni 2005, Brinkgreve et al. 2017)

The volumetric creep strain rate depends on the ratio between the equivalent isotropic stress p'_{eq} and the pre-consolidation stress p'_p, in other words, the distance between the two ellipsoids (CSS and NCS) determines the magnitude of the creep rate (Vermeer & Leoni 2005). For the definition of the entire strain rate vector, reference is made to Vermeer & Neher (1999). The stiffness of the SSC model is defined by the modified compression index λ^* and the modified swelling index κ^*. These parameters can be obtained from isotropic compression tests with isotropic unloading. Failure is formulated according to Mohr-Coulomb. Generally, an associated flow rule is applied. However, the flow rule for stress states on the Mohr-Coulomb failure surface is non-associated.

6.2 *FE model*

Figure 5 illustrates a typical 2D axisymmetric finite element model used and the geometrical conditions investigated. The finite element models consist of around 6500 to 7000 15-noded elements with a shape function of 4th order. The

FE model has a width of 0.788 m (x-direction) and a depth of 81 m (y-direction). Boundary conditions are horizontally fixed on both sides and fully fixed at the bottom of the model.

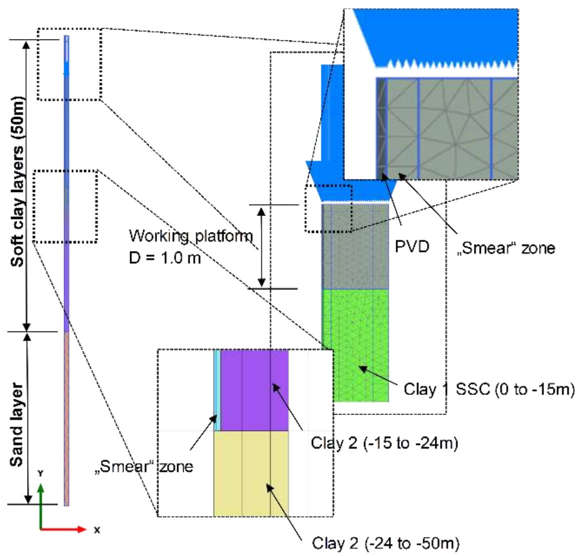

Figure 5. Finite element model

Different methods to model the PVDs have been investigated and in the final FE model the PVDs are modelled explicitly by means of drain elements. The soil disturbance, due to the installation process is taken into account in a way, that the horizontal permeability is reduced within the affected regions (smear zone) of the PVDs. Additionally some clusters are defined to enable the required discretisation of the boundary value problem. A number of preliminary studies have been performed in order to come up with a robust FE model which is capable to predict both, the effect of PVDs on the consolidation settlements and the effect of creep on the secondary settlements.

6.3 Calculation procedure

In order to obtain realistic deformations and a reliable excess pore water pressure (ExPP) distribution in the clay layers, it is necessary to model an accurate initial stress field and the relevant construction phases. For the generation of the initial stress state it is important to take the overconsolidation of the soil into account. This is done with the over consolidation ratio (OCR). The earth pressure coefficient K_0 is defined based on the OCR value of the individual soil layers. As a consequence of the overconsolidation the volumetric and deviatoric yield functions are shifted and the elastic region of the constitutive models is increased.

The modelled calculation phases including the related construction times for the trial field are as follows:

1. Initial stresses
2. Construction of working platform (7 days)
3. Consolidation of 83 days
4. PVD installation (28 days)
5. Consolidation (9 days)
6. 1st layer of surcharge (7 days)
7. 2nd layer of surcharge (7 days)
8. 3rd layer of surcharge (5 days)
9. 4th layer of surcharge (9 days)
10. 5th layer of surcharge (4 days)
11. Consolidation (150 days)
12. Consolidation (6 / 9 / 12 months)
13. Removal of surcharge to level 2.25 m,
14. Loading at level 2.25 m (Construction time 3 / 6 months)
15. Consolidation – Long term consideration (20 / 50 years)

6.4 Model adjustments

After building the first numerical model and the definition of the calculation phases, it was necessary to calibrate the model and to adjust the soil parameters. The flowchart presented in Figure 6 summarizes the used methodology to come up with the final FE model.

6.5 Sensitivity studies and model improvements

To investigate the effect of model uncertainties a number of studies have been performed. These investigations involved not only sensitivity studies related to the soil behaviour but also geometrical and numerical modifications. For the improvement of the final FE model the following studies have been performed:

- Different approaches to model PVDs
- Influence of smear zone
- Influence of const. model on settlements
- Influence of const. model on ExPP
- Sensitivity studies related to OCR
- Modification of construction sequence
- Change of permeability due to settlements
- Effect of large deformations (updated mesh)
- Influence of consolidation boundary conditions
- Variation of surcharge and pre-loading
- Effect of creep on ExPP mobilisation
- Sensitivity studies related to C_c, C_r, C_α, c_h, c_v

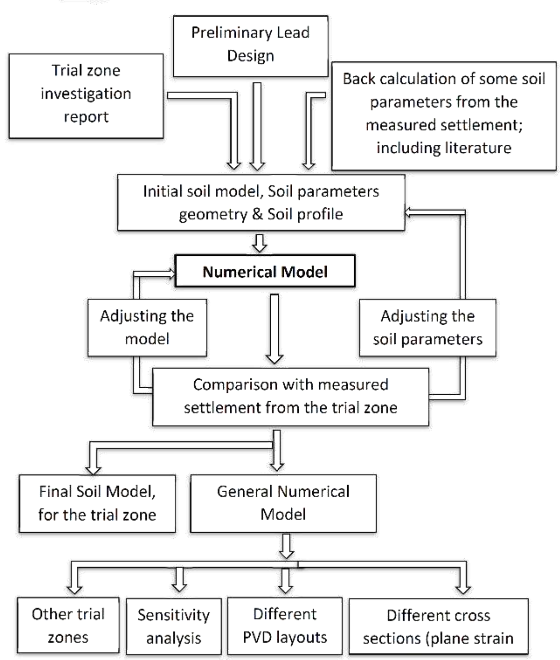

Figure 6. Model verification methodology

6.6 Validation of the FE model

In the next step the improved FE model was used to compute the time settlement behaviour and the obtained results were compared to performed measurements. Three test fields were used to validate the FE model and the locations were chosen in three different regions (with slightly different soil conditions) of the 64 km^2 large project. Figure 7 compares the measured time-settlement curves with the computed settlements using the improved FE model. The comparison shows a good agreement for all three test fields, which clearly confirms that the FE model in combination with the used constitutive models is capable to predict the time-settlement behaviour.

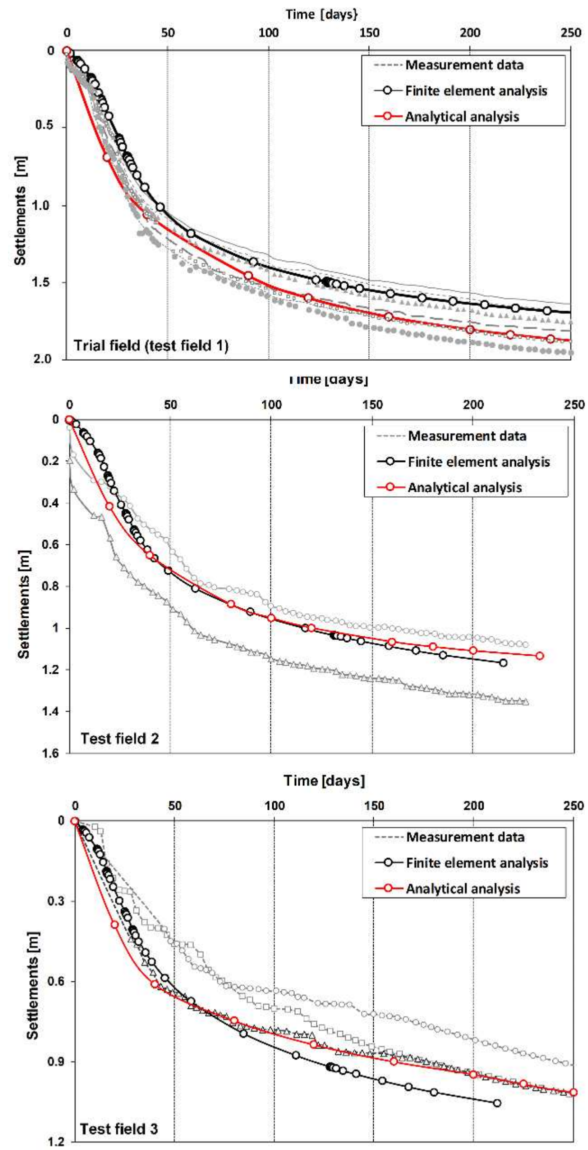

Figure 7. Time-settlement curves for all test fields

Additionally results of analytical predictions are illustrated, which show also a nice match with both, measurements and FEA. However, it has to be mentioned that the analytical model is based on the findings of the performed FE analyses.

6.7 Detailed plane strain investigations

During the execution of the project it was decided to install additional PVDs in some parts of the trial field. These PVDs were installed until a depth of -18 m and the aim of these PVDs was to verify some of the assumptions related to their behaviour and consequently related to some of the assumptions of the numerical analyses.

The effect of the additional PVDs was as expected: Within the first weeks after the installation a slightly „steeper" time-settlement curve (increase of settlement rate) was observed. Two weeks after the installation this effect was almost zero and also the piezometer measurements confirmed that the influence of these additional PVDs is very limited.

2D FEA have also been performed to investigate the effect of the additional PVDs. Therefore, 2D plane strain models were used, where the permeability in horizontal direction was adjusted in order to take into account the real drainage path length. Different approaches to define this equivalent permeability have been investigated, namly Hird et al. (1992), Indraratna & Redana (1997) and CUR 191 (1997). Figure 8 shows exemplary one of the investstigated plane strain models. The FE analyses confirmed that the effect of the shorter PVDs in between the existing prefabricated vertical drains on the time settlement behaviour is very limited.

Finally this validated 2D plane strain model was used to investigate a number of sensitive zones within the entire project.

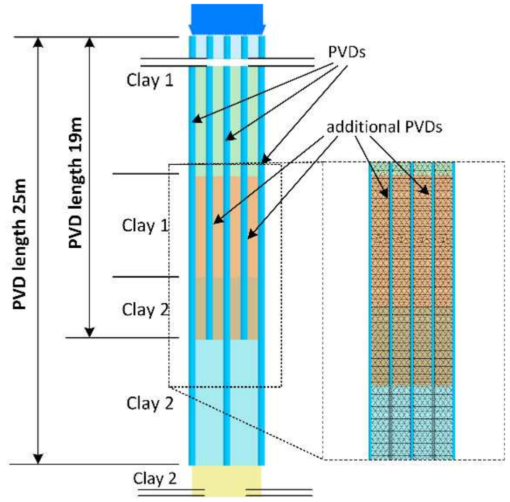

Figure 8. Plane strain FE model

7 CONCLUSIONS AND GAINED INSIGHTS

From the investigations the following conclusions can be drawn:

1- A good performance of the numerical model was presented and its general applicability to other similar cases can be confirmed.

2- The analytical model can give reasonable results for simple conditions. However, for complex boundary conditions, the numerical model is preferable.

3- Although PVDs are a cheap technology, it is important to spend some money to carefully investigate the soil properties and to have a trustable model (numerical or analytical) to predict their behaviour.

4- The available literature is sufficient to build and calibrate a numerical model. However, the big challenge is the evaluation and verification of the soil parameters and the smart choice of the numerical model elements.

5- In mega projects the construction of a trial zone in combination with a monitoring program is essential. Such a trial field (as constructed in the discussed project) provides important information related to the entire system behaviour.

6- The combination of an intensive soil investigation program with data obtained from the monitored trial zone can be used in a a very efficient way to build a trustable numerical model which can simulate the behaviour with high accuracy.

7- The improvement of the soil parameters (due to the effect of the PVDs) can be noticed by interpreting CPTu results. However, caution is required in analyzing the CPT data, which can be misleading due to the effect of preloading.

8- The combination of PVDs and surcharge can improve the soil behaviour and reduce the final settlements with high efficiency. And last but not least it is a very ecofriendly technique.

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