# Monitoring the behaviour of vertical drain improved soil by large scale trial field

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ABSTRACT: In this study a large scale trial zone was constructed and monitored in one of the largest soil improvement projects in Egypt where the soft soil layers are up to 50 m deep. An intensive monitoring system was built up including multi-level piezometers, extensometers and inclinometers to monitor the pore water pressure, vertical and lateral deformation along the profile depth during and after the surcharge construction. The ground settlement was measured using several settlement points distributed all over the trial zone. The monitoring program started two months before preloading and lasted for more than 7 months after the end of primary consolidation. Extra investigation was performed as well using CPTu`s and boreholes before and after preloading. Different soil parameters have been analysed and correlated based on back calculating the instrumentations data and the soil investigation report. End of primary consolidation, EOP was estimated and compared based on the lab test results, monitored pore pressure and measured settlement. A soil model was built considering selected parameters and used to simulate and predict both short- and long-term behaviour for the entire system, where the outcome was in a good matching with the measured date. The study shows that while having a sophisticated monitoring system to catch the actual soil behaviour is important, cautions should be taken during interpreting these data since some deviation can occur due to installation, mechanical function in the devices or during operation.

## 1 INTRODUCTION

Soft soil deposits can be found in many places all over the world generally and in Egypt specifically, especially coastal areas, which are recognized by a high compressibility and a low shear strength (Ayeldeen & Kitazume 2017). It became essential to find the appropriate method to improve the softy soil characterizations in order to meet the needed engineering requirements for construction. One of the most well-known method used to improve the soft soils is preloading over vertical drains. This approach can be used effectively to reduce the post-construction settlement and improve the soil shear strength as well. By considering the very low vertical permeability of the soft soils, the time required to achieve the required settlement will be too long compared to the available time for the construction. Moreover, the horizontal permeability of soft clay is much higher than the vertical permeability. Therefore, using vertical drains in soft soils will reduce the drainage path from the thickness of the soil layer (in case of vertical consolidation) to half of the drain spacing (in case of horizontal consolidation) (Indraratna et al. 2012 & 2015).

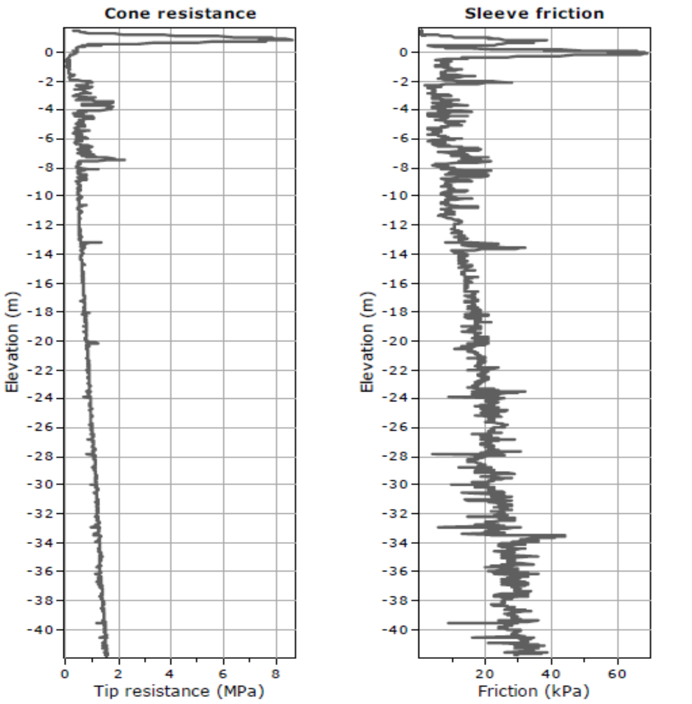
## 2 SOIL PARAMETERS AND TRAIL ZONE

The soil profile of the area under the study is consists of 10 to 15m of soft silty sand to silty clay (de-fined 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 are laying above a dense sand layer. A typical CPT results for the soil profile can be seen in Figure 1.

### 2.1 *Trial zone*

To define the exact required preloading duration and to confirm the achieved degree of consolidation after preloading; a trial zone (150 x 150 m) was executed and extensively monitored during the construction and preloading. Vertical drains with depth of 25m were installed in a combination with 6.50m surcharge height under preloading duration of 6 to 9 months. Piezometers, extensometers, inclinometers and ground measurement points were installed in the trial zone and continuously monitored during the whole preloading duration. Additional soil investigation was performed as well including boreholes, lab tests and CPTu’s.

Figure 1. Typical results for the CPT for the area under study




The settlement was measured for 18 ground measurement points, GMP all over the trial zone. The average settlement was about 180 cm after 6 months of preloading, where it was consider that almost all the settlement is coming from the improved layer (the upper 25m) while the degree of consolidation for the lower 25 m after 6 months will not exceed 4%. The settlement/ time curve corresponding to the surcharge construction can be seen in Figure 2.

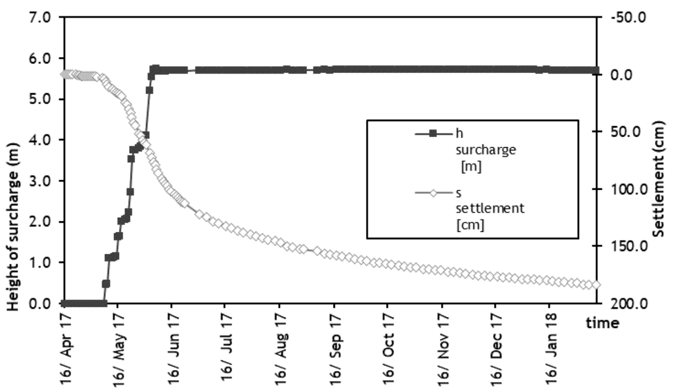



Figure 2. Measured settlement and surcharge height with time

It was noticed as well that the settlement all over the trial zone was not as expected to be smooth pot shape, whereas the observed scatter can be attributed to varying loading sequence and earthworks conducted. The actual settlement all over the trial zone after 6 months of pre-loading can be seen in Figure 3.

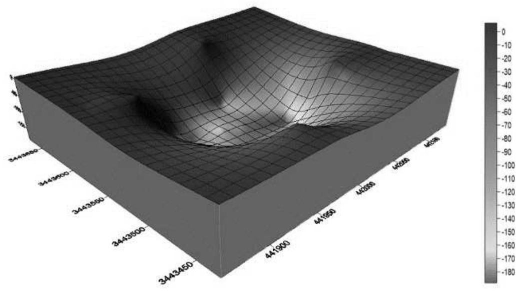


Figure 3. Measured settlement all over the trial zone after 6 months of preloading

## 3 INSTRUMENTATION MEASUREMENTS

### 3.1 *Pore-water pressure*

It was necessary to observe and analyse the total and excess pore pressure during the consolidation process to expect the required preloading duration. In the current trial zone, five multi-level piezometers were installed in different location trying to avoid the vertical drains locations. In all piezometers, four levels were chosen for the study (10, 20, 35 and 50 m). Some variation in the reading among the piezometers was observed which is a common observation (Holtz & Broms 1972, Hansbo 1997, Bo et al. 1999, and Bergado et al. 2002) and can be interpreted due to mechanical functions in the piezometers cells (Bo et al. 1999) or it could be a reason of some geotechnical behaviour such as the effect of creep on the pore pressure (Fatahi et al. 2013). The dissipation of water pressure was as expected and it was matching with the observed settlement as shown in Figure 4.

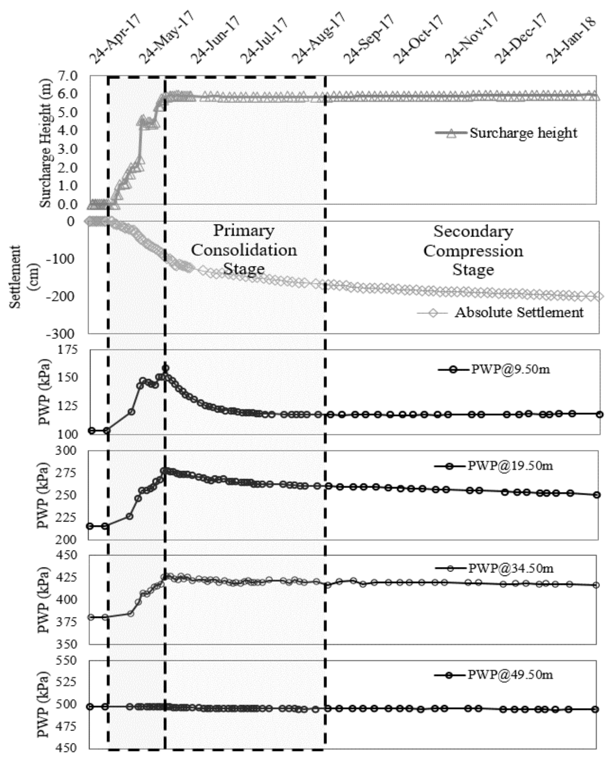



Figure 4. Variation in pore pressure with time

During the surcharge construction the pore pressure was increased due to the increasing in the total stress. This increasing was varied and reduced with depth and almost vanish at depth of 50m. After completing the surcharge, the dissipation process started to occur in parallel with the observed settlement and during the whole primary consolidation process for about 3 months. After completing the primary consolidation as proved by several calculations (such as Asaoka 1978), the secondary compression was started where the settlement can still be observed with not more reduction in the pore pressure.

### 3.2 *Pore-water pressure*

Beside the piezometers, two inclinometers were installed as well to measure the lateral deformation close to the slope edge. It can be seen from Figure 5 the noticeable increasing in the lateral deformation with time in the two months (April to June), while the increasing in lateral deformation decline later on (June to August), and it was almost stopped in the last month in the presented chart (September).

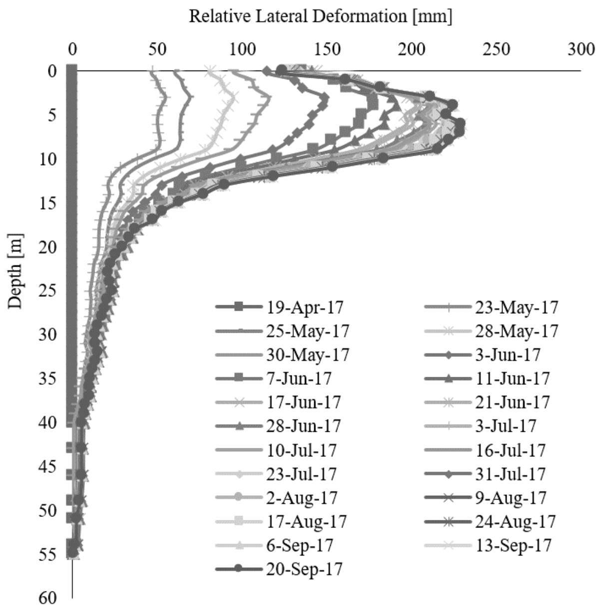



Figure 5. Lateral Deformation with depth

## 4 FINITE ELEMENT MODEL

### 4.1 *Building the model*

Manual calculations (Hansbo 1979) and numerical software (PLAXIS 2D) have been used in the analyses to cross check and ensure the accuracy of the results. The data collected from the instrumentation installed in the trial field were used to determine relevant soil parameters, conduct back analysis and verifications, and to estimate long term settlement. The finite element code PLAXIS has been used to model the whole problem including the PVD, smear zone and soil layers. The objective of using PLAXIS is to assess the performance of the prefabricated vertical drains (PVDs) after verification particularly to evaluate the long-term behaviour. Different soil modules were used to build up the model including Soft Soil Creep to model the improved soft layers, Soft Soil to model the unimproved soft soil layers, and Mohr Coulomb model for the working platform and surcharge. Hardening Soil Small model was used for the deep sand layer as it takes the high stiffness at very low strains into account. As a consequence, the obtained soil displacements at deeper depths are automatically reduced and a more realistic settlement profile with depth can be computed (Tschuchnigg 2010).

### 4.2 *Model elements and geometry*

Figure 6 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 4$^{th}$ 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.

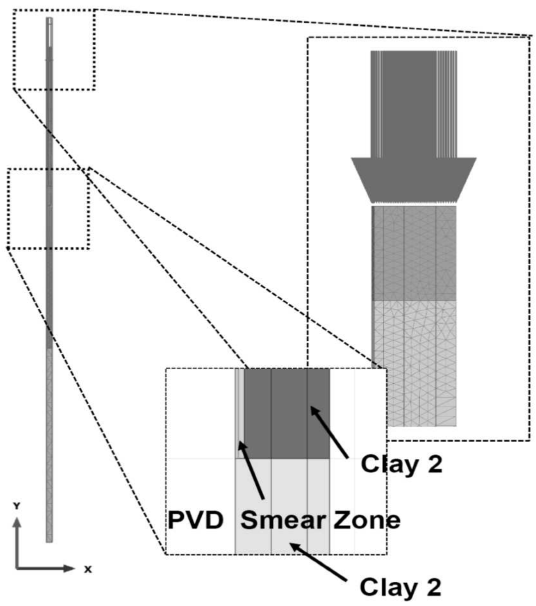



Figure 6. Illustration of finite element model

### 4.3 *Model verification*

The measured settlement from seven GMP`s were plotted against the estimated settlement from both the manual and numerical calculations as shown in Figure 7. By comparing both the measured and estimated behaviour it can be clearly seen the good matching between them both. This good matching was also observed by applying the same model on different areas in the same site. After verifying the numerical model, the model was used to estimate the long-term behaviour after 20, 50 years from removing the surcharge and applying the working loads. As expected from the manual calculations and confirmed from the model that the deformation from the improved layer is purely creep effect which was extremely reduced due to the effect of preloading (Mesri 2003).

## 5 POST INVESTIGATION

It was essential to investigate the occurred improvement during and after the improvement, therefore post CPTu`s were performed in different durations (1, 3 and 5 months) after completing the surcharge. However it should be clear that analysing the behaviour during preloading is not recommended as the CPT is extensively affect by the existing high pressure from surcharge and the occurred creep as well.

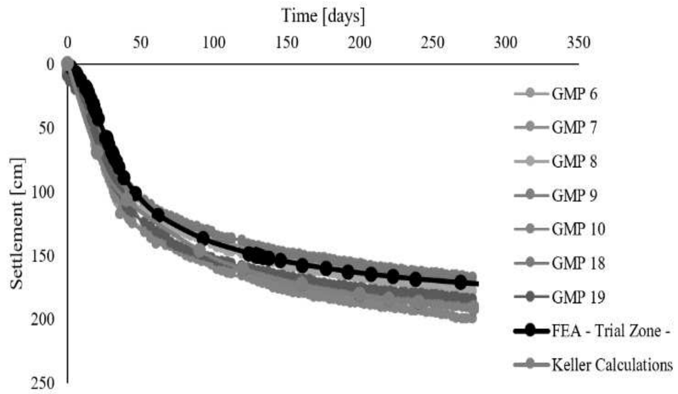



Figure 7. Time-settlement curve for both measured and estimated points

A simple comparison between the cone tip resistance and sleeve friction before and after preloading can be seen in Figure 8 for different depths.

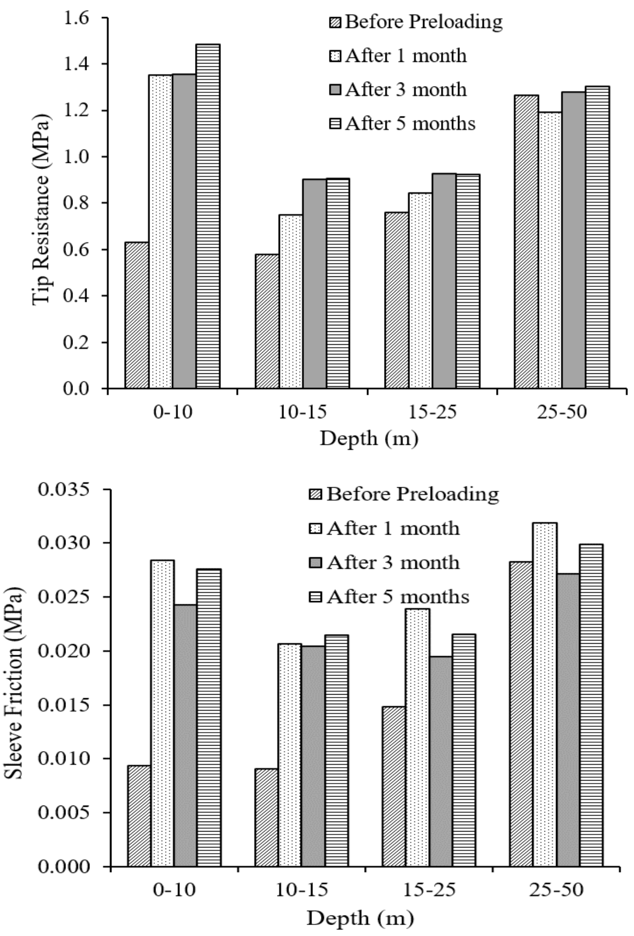



Figure 8. Improvement in Tip Resistance and Sleeve Friction

Both the tip resistance and sleeve friction increased for the upper 10 m layer after one month of preloading by more than 200 %, however the improvement was not that clear for the following months. The same increasing was observed in other deep improved layers (from 10 to 15 m and from 15 to 25 m), though the increasing percentage is much less than the upper layer and the time effect is much clear. For the deep unimproved layer (below 25 m) and as was expected that the effect of preloading will be limited. From this figure an indirect relationship between the degree of consolidation and the improvement in the soil parameters as for the upper layer (from 0 to 10 m) it was confirmed that more than 90 % degree of consolidation was achieved after the first month which is related to this high increasing in both tip resistance and sleeve friction, meanwhile in the following months (during the secondary compression) no remarkable improvement was recorded. As the degree of consolidation for the lower improved layer is less than the upper layer (due to the reduction in preloading stress and both drainage and boundary effect), the increasing percentage is less as well, and it increases with time in function of the increasing of degree of consolidation. It can also be noticed that the increasing in sleeve friction is higher than the tip resistance as a common effect of the clay.

One of the key parameters in PVD design and behaviour is the horizontal coefficient of consolidation, $C_h$ which is function in the horizontal permeability and the soil stiffness. Figure 9 display the reduction in Ch with time for different depths, which can also reflect the efficiency of improvement by reducing the permeability after and during consolidation and increasing the soil stiffness. However, and as mentioned before that caution should be taken during analysing the CPTu results during preloading as it could be misleading in some cases.

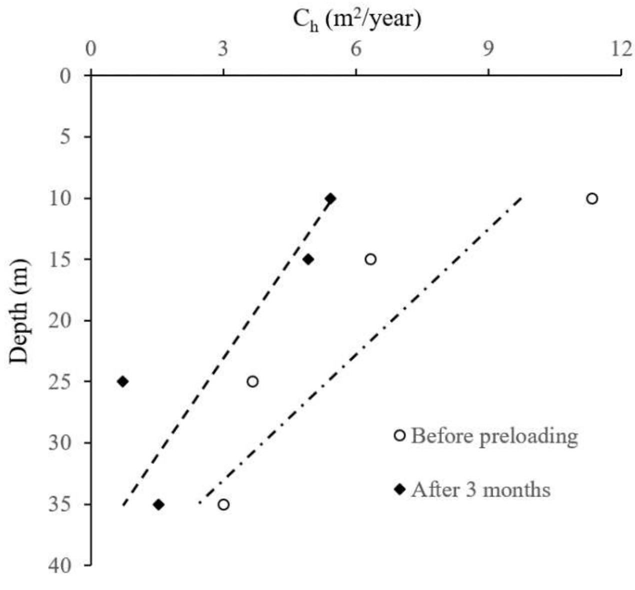



Figure 9. Reduction in $C_h$ with time

## 6 CONCLUSION

The current study is part of a large project and further investigation is still going on, however some important points can be concluded as following:

- Constructing a trial zone in mega project and being monitored well is essential and can give a clear idea about the system behaviour.
- The combination between intensive soil investigation work and data from monitoring the trial zone can be used in an efficient way to build up a trustable numerical model which can simulate the behaviour in high accuracy.
- The improvement in the soil parameters can be noticed by the CPTu results which is related in somehow to the degree of consolidation. However caution should be taken in analyzing the data which can be misleading as effect of the preloading.
- The combination between PVD and surcharge can improve the soil strength and reduce the settlement with high efficiency and as eco-friendly technique.

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