Studying the behavior of soft soil improved with prefabricated vertical drains. Case study

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ABSTRACT: This study is about the changing in the soft soil properties after improved using a combination between prefabricate vertical drains, PVD and surcharge. The data is from case study for a mega project in Egypt, where the soft soil is extended up to 50m depth. A vertical drains is 25m deep were used with 6.5m of surcharge. The dissimilarity in the soil profile from area to other offered a wide variation in the improved parameters. The built trail area - including several types of instrumentations for intensive monitoring- was not enough to understand the whole behavior, which needed more instrumentations and CPTu`s in different locations from the site. The challenge was how to connect all these measurements together for better understanding to the occurred improvement. Several models were built and calibrated using the collected data to predict the soil behavior and the development of the settlement. Laboratory tests were performed using boreholes samples from the site and the measured parameters used as well for the soil models. Pre and post CPTu tests were combined in building model – especially the horizontal soil parameters from dissipation tests – and used after for the verification. An acceptable agreement was found based on the developed numerical model where also used after to expect the long term settlement which was the key function from this model. The combination between surcharge and vertical drains can be successfully used to improve the soft soil, where the improved parameters can be evaluated numerically and back calculated to be used later on.

Keywords: (prefabricated vertical drains, soft clay, finite element, consolidation, preloading)

1 INTRODUCTION

Soft soils which are recognize with low shear strength, high compressibility and low bearing capacity are widely spread all over the world particularly in coastal areas. Several technics have been applied successfully to improve the soft soil such as mixing with binders or fibers or even a combination between binders and fibers (Ayeldeen et al. 2017). Stone column as well shows noticeable success as improvement technique for soft soils (Sivakumar et al. 2007), however one of the most economics and ecofriendly technics is preconsolidate the soft soil which will eventually increase its stiffness and reduce the expected settlement. The pre-consolidation process can be performed by using preloading pressure (surcharge) in combination with or without vertical drains in the soil. Generally, the idea behind the Prefabricated Vertical Drains is to shorten the drainage path of the water from clay layers by installing vertical drains which allow the groundwater to migrate inside the clay layer to drain horizontally towards the vertical drains instead of taking a longer drainage path equals to half the thickness of the clay layer or it might be the whole clay thickness if the drainage is allowed from one side only (Indraratna et al. 2015). In other words, it accelerates the consolidation process during the pre-loading which will lead to an increase in the soil stiffness and reduction in the final settlements for the final / long term stage.

The soil profile of the area under the study is consists of 10 to 15m 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 50m 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 TRIAL ZONE

Vertical drains with depth of 25m were installed in a combination with 6.5m surcharge height under preloading duration of 6 to 9 months. 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. Piezometers, extensometers, inclinometers and ground measurement points were installed in the trial zone and continuously monitored for more than 9 months. Additional soil investigation was performed as well including boreholes, lab tests and CPTu's.

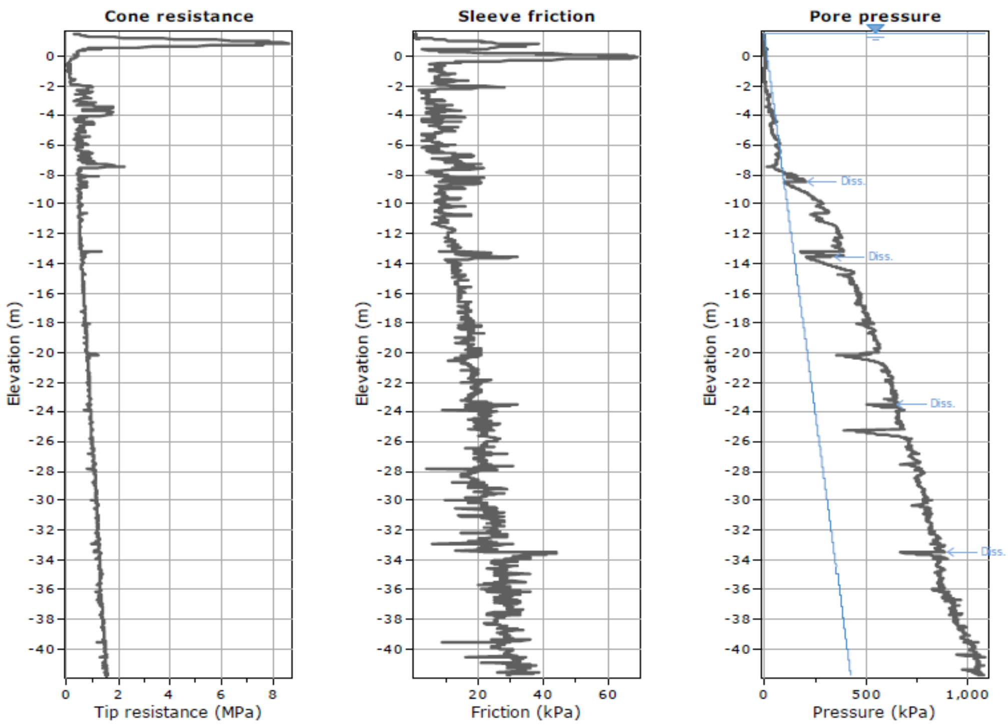

Figure 1. Typical results for the CPT for the area under study

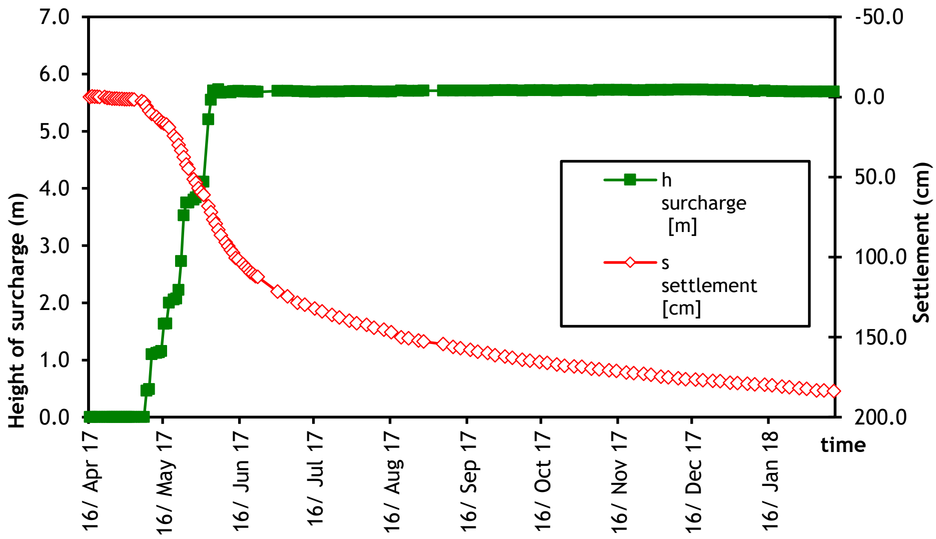

Figure 2 . Measured settlement and surcharge height with time

The settlement was measured for 18 ground measurement points, GMP all over the trial zone. The average settlement was about 180cm 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 25m after 6 months will not exceed 4%. The settlement / time curve corresponding to the surcharge construction can be seen in figure 2. 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 preloading can be seen in figure 3.

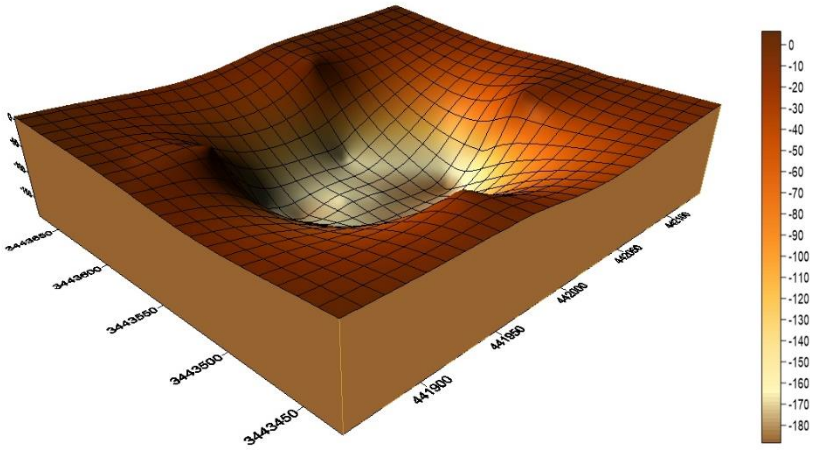

Figure 3. Measured settlement all over the trial zone after 6 months of preloading

3 INSTRUMENTATION MEASURMENTS

3.1 *Pore-water pressure*

It was necessary to observe and analyze the total and excess pore pressure during the consolidation process, however excess water pressure readings can be misleading. The distance between the piezometer and the drains can severely affect the results. In the current trial zone, four piezometers were installed, however the difference in the reading among the four piezometers was quite high which is a common observation (Holtz and 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). In all piezometers, four levels were chosen for the study (10, 20, 35 and 50m).

A high initial pore pressure than the hydrostatic was observed in all piezometers especially at 20 and 35m depths and gradually reduced to the hydrostatic at depth of 50m. The reason of the high initial water pressure could be an evidence of under-consolidated soil formations which is under investigation in the time being. The dissipation of water pressure was as expected and it was matching with the observed settlement as shown in figure 4. During the surcharge construction the pore pressure was increased due to the increasing in the total stress. This increasing was vary 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 no further reduction in the pore pressure. The final value of pore pressure in some piezometers was remaining higher that the initial was mentioned before which could be as a reason of some mechanical functions in the piezometers cells, however one more piezometer was installed later after 8 months of preloading and the measured pore pressure was almost as the initial measured values.

Some calculations were preformed to estimate the degree of consolidation, *DOC* from the piezometer reading (Indraratna 2012, Bergado 2002) and to be compared with the calculated degree of consolidation from the settlement, however both values were incomparable as the estimated *DOC* from piezometer is calculated at a certain point not as the average *DOC* which is calculated from the measured settlement (Chu et al. 2005).

3.2 *Inclinometer*

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).

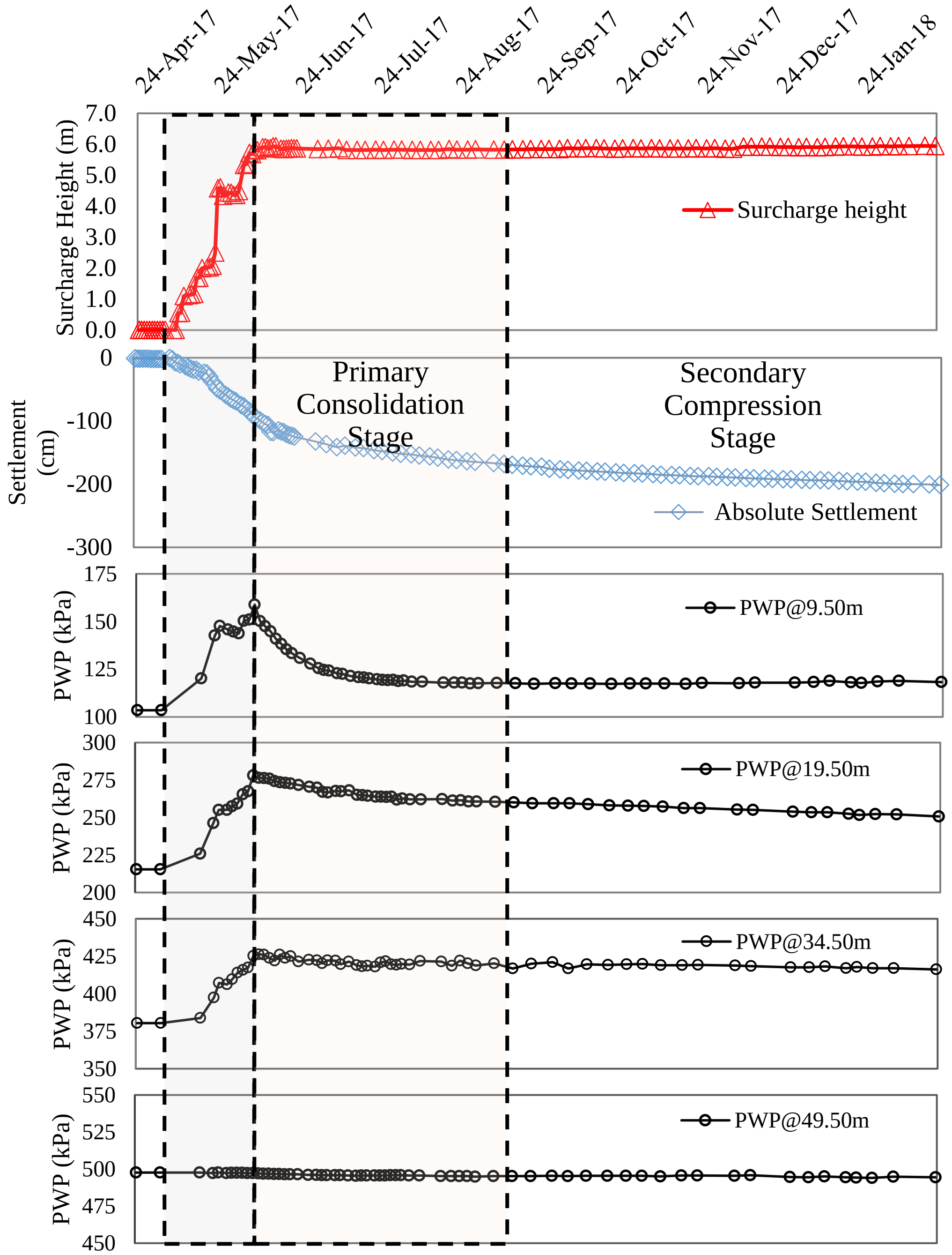

Figure 4. Variation in pore pressure with time

4 FINITE ELEMENT 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).

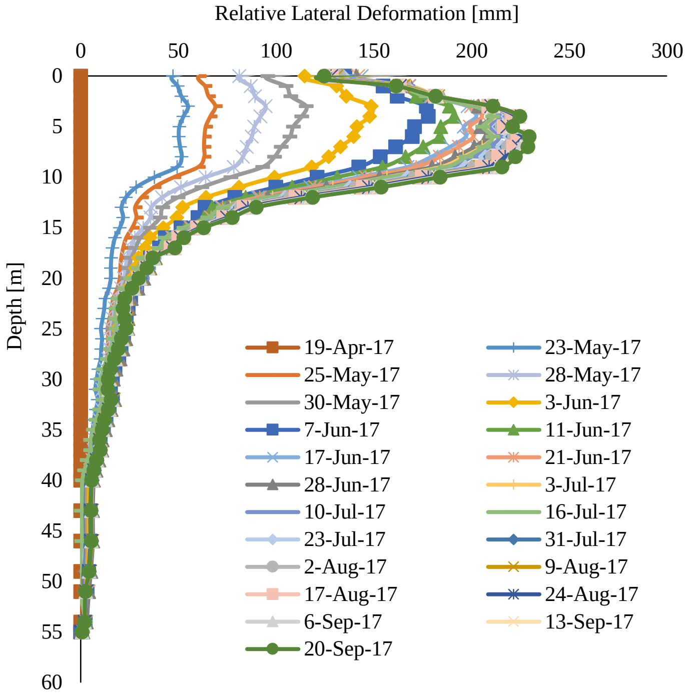

Figure 5. Lateral Deformation with depth

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 4th order. The FE model has a width of 0.788m (x-direction) and a depth of 81m (y-direction). Boundary conditions are horizontally fixed on both sides and fully fixed at the bottom of the model.

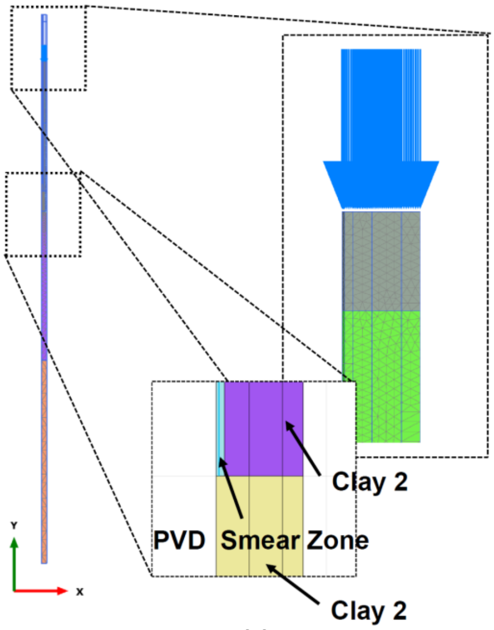

Figure 6. Illustration of finite element model

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 or 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).

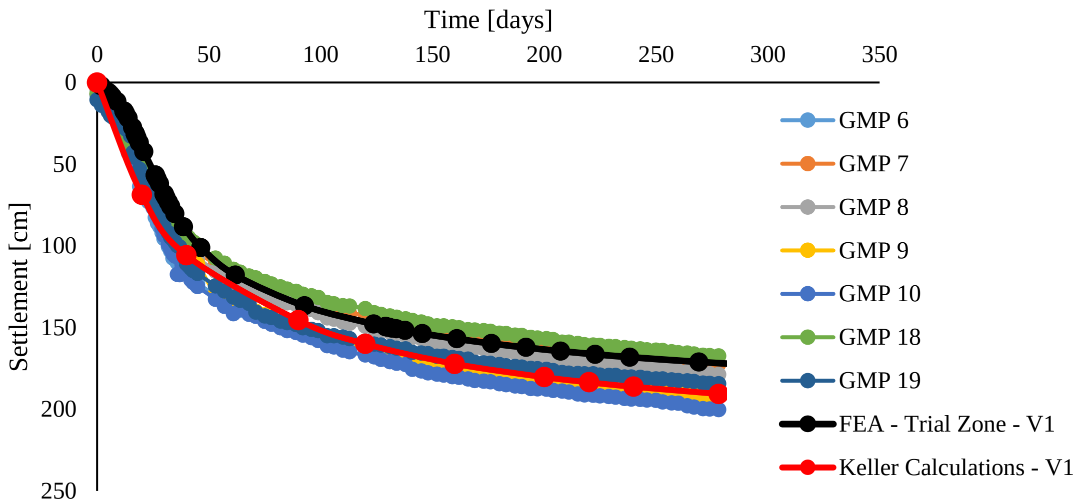

Figure 7. Time-settlement curve for both measured and estimated points

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 analyzing 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.

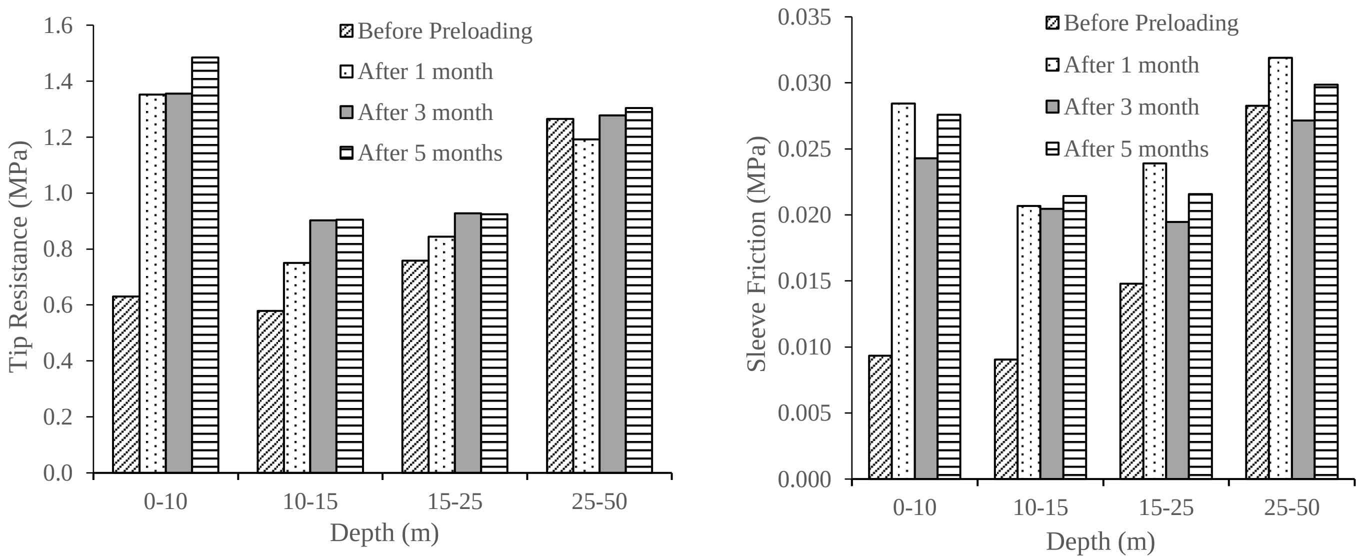

Figure 8. Improvement in tip resistance and Sleeve Friction

A simple comparisons between the cone tip resistance and sleeve friction before and after preloading can be seen in figure 8 for different depths. Both the tip resistance and sleeve friction increased for the upper 10m 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 15m and from 15 to 25m), though the increasing percentage is much less than for the upper layer and the time effect is clearer. For the deep unimproved layer (below 25m) 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 10m) 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 C_h 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 analyzing the CPTu results during preloading as it could be misleading in some cases.

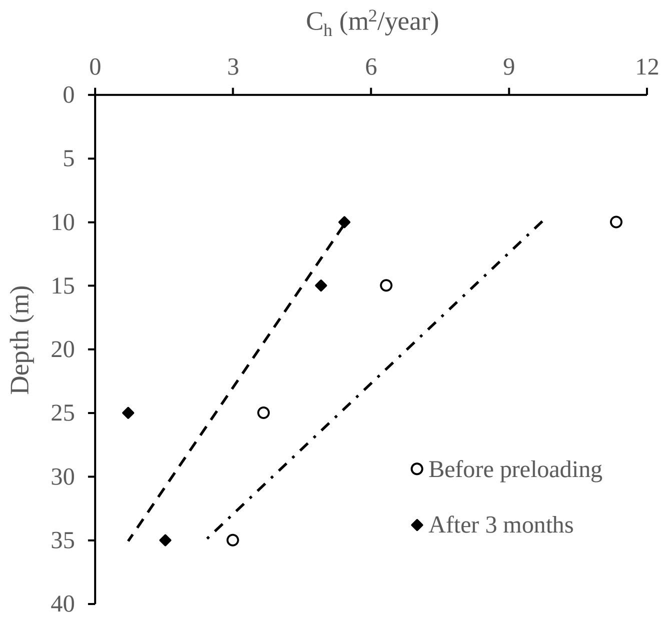

Figure 9. Reduction in C_h with time

6 CONCLUSION

The current study is part from mega 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 ecofriendly technique.

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