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Evaluation of Pile Driving Effects in Extremely Soft Gothenburg Clay

Etude des effets du battage des pieux dans l'argile molle de Göteborg

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ABSTRACT: Driven pile installations in soft soil deposits displaces the soil, causing construction sites to expand laterally outwards, stressing the existing foundations of adjacent structures. Hence, predicting movements induced by the proposed pile driving activities becomes an important prerequisite to avoid negative impact on adjacent structures. This paper discusses the procedures applied for predicting soil movements induced by driving 300 precast reinforced concrete piles at a constrained triangular site located in Gothenburg in an area covered by deep soft clay deposits. This analysis was conducted by employing Cavity Expansion Theory, using "Volumetric Expansion" feature in Plaxis 3D Finite Element Analysis package, by generating volumetric strains within the soil body to simulate pile installation. The numerical procedure was initially validated by modelling a single pile expansion and calibrations were fitted against empirical data related to similar project results. The numerical analysis was then expanded to take into account multiple pile installations by defining representative volumes related to groups of piles near each other. The models also considered the effect of pre-boring intended to be performed during construction as a mitigation-measure against excessive soil heave. Furthermore, existing foundations of adjacent bridge structures and railways were modelled as piled rafts surrounding the new piling location. During construction phase, soil displacements were measured and compared with the numerical results. The predicted movements of the soft clay accurately represented the lateral displacements observed during construction. As a result, The Gamlestad project was successfully completed with no negative impacts on surrounding structures.

RÉSUMÉ: Le battage de pieux au sein de sol très compressible argiles molles provoque un déplacement latéral du sol ce qui peut provoquer des désordres au niveau des fondations des structures adjacentes. De ce fait, pour la bonne réalisation du battage de pieux et afin de ne pas impacter les structures existantes, il devient nécessaire de pévoir ces déplacements. Cet article traite des procédures effectuées pour prévoir le mouvement du sol induit par le battage de 300 pieux en béton armé au sein d'une couche d'argile molle à Göteborg, dans une zone limitée par des structures existantes. Cette étude s'appuie sur la théorie de l'expansion des cavités. Le battage de pieux est ainsi modélisé en générant des déformations volumétriques dans le corps du sol par le moyen de la fonction «Volumetric Expansion» du logiciel d'analyse aux éléments finis Plaxis 3D. Le modèle numérique a été tout

d'abord ajusté et validé en calculant les déplacements provoqués par le battage d'un seul pieux et en confrontant les résultats théoriques aux résultats expérimentaux de projets similaires. La modélisation a ensuite été ajustée pour prendre en compte l'effet du battage de plusieurs pieux en appliquant des techniques précises et en définissant des volumes représentatifs d'un groupe de pieux voisins les uns des autres. Les modèles prennent également en compte l'effet du pré-forage devant être effectué pendant la construction comme mesure d'atténuation du gonflement excessif. De plus, les fondations existantes du pont attenant et des voies ferrées adjacentes ont été modélisées par des radiers sur pieux a proximité des pieux battus. Pendant la phase de construction, les déplacements de sol ont été mesurés et comparés aux résultats numériques. Les déplacements théoriques au sein de la couche d'argile molle concordaient avec les déplacements latéraux observés pendant la construction.

Keywords: Pile driving, Finite Element Modelling, Ground Movement Prediction, Soft Clay, Cavity Expansion.

1 INTRODUCTION

Driven pile installations in soft soil deposits disturbs and displaces the surrounding soil which may impinge on adjacent sites. Pile driving activities can apply excessive stresses in the existing foundations of adjacent structures, and in certain situations, trigger slope failures. In congested urban areas, prediction of movements induced by pile driving activities becomes an important prerequisite prior to piling to ensure that the installation does not negatively affect the adjacent infrastructure. Understanding the effects of pile driving in soft clay deposits has been a challenging task for geotechnical engineers. However, the prevalence of Finite Element Methods (FEM) in engineering has made dealing with these problems easier. Advanced soil models and simulation techniques have been offered and are constantly being optimized to accurately predict changes in the soil during pile driving activities. However, employing complex constitutive soil models that require numerous inputs and numerical models that are highly time-consuming and hence, expensive, are not always an attractive or even practical solution for analyzing a large-scale problem in the industry with a tight deadline and budget. This paper presents a simplified method that was employed to predict the effects of driving 300 number of 40m long piles into extremely soft clay deposits for a major development in Gothenburg, Sweden.

The proposed development, Gamlestads Torg, comprised three buildings ranging between five to eighteen stories in addition to two basement levels, planned for construction on a triangular shaped site in a highly populated area in Gothenburg (see Figure 1).

Figure 1 Aerial photo of the triangular shaped piling site bounded by Railway Bridge, river and tram lines, (www.hitta.se)

The site is bound by the Gamlestad Bridge (supported on piles) to the West and the River Säveån to the South. Neighboring works by Trafikkontoret included new double tram tracks on two sides of the property. All tramlines around the property were designed as elevated bridge structures or piled deck structures and the dual

train line included a station on a piled bridge structure (see Figure 2). The building suite was planned to act as a transport hub interlinking trains, trams and buses connecting the eastern parts of Gothenburg. The foundation designed for Gamlestads Torg comprised 300 precast reinforced concrete piles with square dimensions ranging from 235 mm to 350 mm. The piles needed to be driven to 40m below ground to support the new structure. Hence, there were substantial risks concerning ground interactions between the different piled structures for tram, train and the new development. Therefore, the primary geotechnical challenge for this site was predicting lateral soil displacement as a response to foundation installation. In addition, the piling layout of the buildings did not follow a grid or any specific order. This made the analysis more challenging and eliminated the possibility of using theoretical methods suggested for this problem. The following points detail the literature review involved in the project.

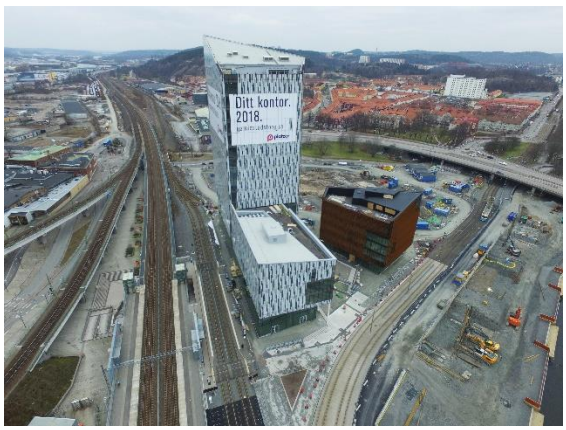

Figure 2 Gamlestads Torg Development, after construction. (Photo credit: Platzer AB).

2 GROUND CONDITIONS

The ground conditions represent some of the most challenging soils that exist worldwide, with the soft clay extending to more than 40m depth, necessitating extensive deep piling works for all major constructions in the area.

GDG reviewed the site-specific geotechnical information to produce a ground model that incorporated the stratigraphy and mechanical soil characteristics. The site investigation testing identified the ground conditions as comprising approximately 40m of soft soil overlying bedrock. CPT results from site investigations in the area were reviewed and ...and compared against recommended soil properties by Edstam & Kullingsjö (2010) for Gothenburg soft clay for a nearby project. Accordingly, the undrained shear strength of the soil (c_u) was considered to be 15 kN/m^2 for design with a gradient of 1 kN/m^2/m. A constant average stiffness of 9.6 MPa was assumed. Furthermore, an undrained behaviour was defined for the surrounding soil to allow for the occurrence of lateral and vertical displacements generated as a result of volumetric expansion during pile installation. The type of undrained analysis used in Plaxis (Undrained A) required effective input parameters as detailed in Table 1.

Table 1. Soil material properties on site

Description	Value
Soil Unit Weight (kN/m3)	17
Effective Poisson's Ratio, ν'	0.2
Effective Young's Modulus, E (MPa)	9.6
Undrained Shear Strength (kPa)	15+1z

3 LITERATURE STUDY

Generation of heave due to pile driving is a common problem for geotechnical engineers. This problem is more remarkable within saturated insensitive clay deposits (Hagerty and Peck 1971). Throughout the years, various methods have been put into practice to predict displacements generated in the soil as a result of pile driving. Initially, empirical solutions were suggested by Hellman (1981) for predicting pile driving induced movements in Geotechnics. He suggested that displacements in the soil due to pile driving correlate to the total volume of driven piles in the soil. This theory was developed by S-

E Rehnman and eventually published by Olsson & Holm (1993). The empirical formula to obtain horizontal and vertical movements proposed for the problem is presented below (see Equation 1). This formula provides the movements due to driving a group of piles in a rectangle with dimensions a and b. Based on this formula, the extent of the ground surface heave is limited by one pile length and displacements vary linearly as depth increases (Olsson & Holm, 1993), hence, ground displacements can be defined by a line with 45 degree inclination vertically to the pile tip.

$$\delta_h = \delta_v = \frac{V}{\left(\frac{4}{3}L+a+b\right)L+ab}\left(1-\frac{x}{L}\right) \quad (1)$$

where, V is the total volume of driven piles, L is the pile length, a and b are the horizontal extent of the pile group and x is the distance from the edge of the pile group.

Many predictive methods using Large Strain FEM have since been introduced for this problem. However, the application of such models in commercial projects is not deemed feasible due to extensive computing requirements and highly complicated numerical models which are not widely available (Xu et al., 2006). More accurate, simpler methods suggested for this problem are Cavity Expansion Method (CEM) and Shallow Strain Path Method (SSPM).

The application of Cavity Expansion theory in Geotechnical Engineering was first introduced by Gibson & Anderson (1961), and was used for this purpose by Randolph (2003). CEM explains that the installation of a pile in a soil medium generates movements in the soil similar to the manner in which an expanding cylindrical cavity would cause displacements in the soil. This assumption allows the use of closed-form solutions to establish stress and strain changes in the soil during pile driving operations. According to Lehane & Gill (2004), this technique has proven to show reliable predictions of radial movements (using Equation 2) in the soil due to pile installations, where r is the radial distance from the pile center with radius R.

$$\frac{\delta_r}{R} = \sqrt{1+\left(\frac{r}{R}\right)^2} - \frac{r}{R} \quad (2)$$

However, it often fails to predict displacements in the area close to the pile itself, which can at times lead to inaccurate results (Baligh, 1985). Applying CEM in pile driving has nonetheless provided desirable results of excess pore pressure and stress changes in the area further from the pile (Xu et al., 2006). Another method proposed for tackling this problem is the SSPM. This method, which is an extension to what was initially developed by Baligh (1985), suggests that during pile installation, movements in the surrounding soil are relative to the pile tip movement similar to the flow of an incompressible fluid around the pile tip, regardless of the undrained shear strength or friction angle of the soil material (Sagaseta et al., 1997). Based on this method, vertical and radial movements of the surficial soil due to a closed ended pipe installation can be predicted using Equation 3 and 4 recommended by Sagaseta, where L is the pile embedment length, R is the pile diameter and r is the radial distance from pile centre axis (see Equations 3 and 4). Xu et al. (2006) managed to accurately predict ground movements caused by pile installation in clay deposits using SSPM. The normalised results of their research was further used as a bench mark for the calibration of the initial numerical model in this project.

$$\delta_z = -\frac{R^2}{2}\left(\frac{1}{r} - \frac{1}{\sqrt{r^2+L^2}}\right) \quad (3)$$

$$\delta_r = -\frac{R^2}{2}\left(\frac{L}{r\sqrt{r^2+L^2}}\right) \quad (4)$$

The aim for this review was to select a feasible method to analyse the effect of foundation installation for Gamlestads Torg. This was

coupled with reviewing research and projects focused on predicting soil movements due to piling in Gothenburg, such as Edstam & Kullingsjö (2010) and Nenonen & Ruul (2011).

4 APPLIED METHODOLOGY

The task of predicting pile driving induced movements in the soil was initiated by performing a series of calculations using Equations 3 and 4 for individual piles and applying superposition technique to analyze the combined displacements likely to happen in all directions. This method was deemed time consuming and complicated considering the complexity of the piling plan and the large number of piles involved. The project's timeline required employing a more efficient approach for achieving an overall prediction around the whole area. This was done by performing a 3-Dimensional analysis by using Plaxis 3D Finite Element Analysis package.

The pile driving activities were simulated using the Volumetric Expansion Method, by generating volumetric strains within the soil body. This feature allows changes in an element's volume that induces additional stresses in the surrounding soil, which introduces deflections around the model until a global equilibrium of stresses is reached. The challenge in this part was selecting a relatively simple constituive soil model considering the complexity and large size of the final model. This soil model needed to be calibrated inititally in order to ensure providing accurate results. Hence, the first phase of the numerical analysis comprised a parameter study of soil models, drainage options and interface elements for a single pile case. This is further discussed in Section 4.1.

4.1 Constituitive soil model and calibration practice

The single pile analysis practice was repeated using Linear-Elastic, Linear Elastic-Perfectly Plastic and Hardening Soil models. Although the Linear Elastic (LE) constitutive model is recognised as a very simple stress-strain model in comparison with non-linear elasto-plastic models

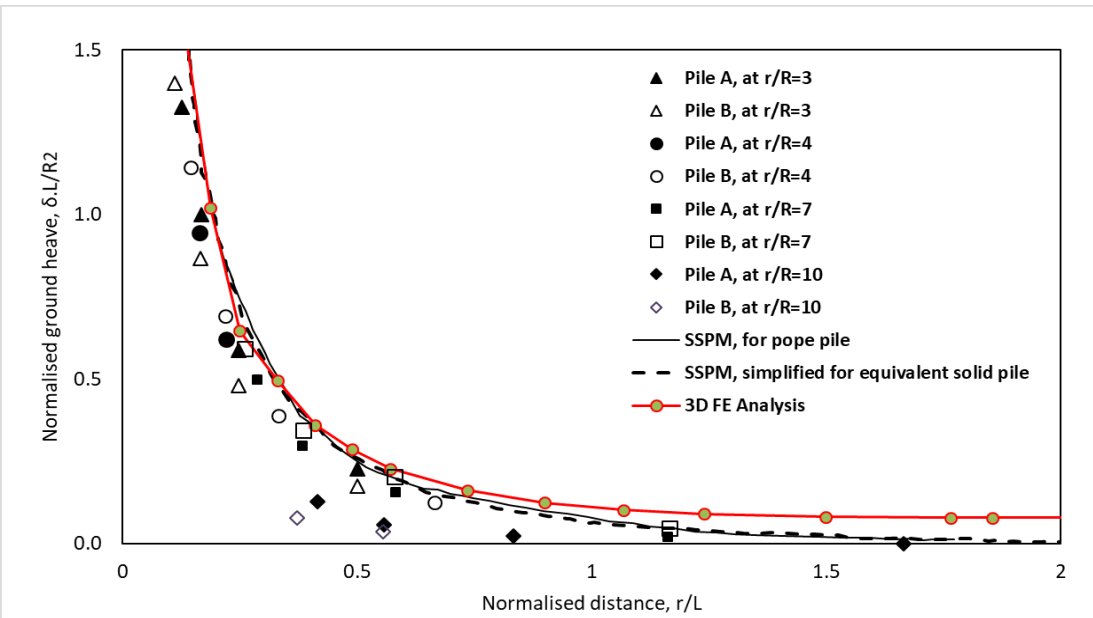

Figure 3 Comparison of predicted normalised heave generated due to a single pile driving in soil using Plaxis 3D by GDG (Green dots and Red line) with Xu et al. (2006) experimental results

that are frequently used to model soil, the successful use of it in similar projects related to Gothenburg Clay soil movements made it an interesting choice. It shall be noted that even though the soil close to the piles experiences large strains and therefore, shows non-linear behaviour, most of the soil in the adjacent site will be in the elastic range. The LE model may therefore represent the average behaviour in a good manner. Using this soil model had also provided satisfactory results in soil movement predictions due to pile driving according to Edstam & Kullingsjö (2010). Hence, a further calibration practice was conducted to validate its use.

The generated displacements in the soil resulting from the numerical anaysis of a single pile installation using the LE soil model were normalised according to the pile radius and length and compared with normalised soil displacement results from a similar project. Xu et al. (2006) carried out an experimental programme to investigate the displacements associated with cast-in-place concrete pipe pile installation in Shanghai Clay. The experimental site is located in a northern suburb of Shanghai on the deltaic deposit of the Yangtze River, with normally consolidated or very lightly overconsolidated clay deposits. The normalised results of their research (on piles referenced as Pile A and B) were used as a benchmark for the calibration of the initial numerical model in this project. The very good agreement found between these results (see Figure 3, where r, R and L are defined as for Equations 3 and 4) provided more confidence and the model was expanded to include all 300 piles. This is further discussed in Section 4.2.

4.2 Development of full numerical model

Following validation, the numerical model was expanded to take into account multiple pile installations according to the piling layout of the site. One of the challenges regarding the piling plan was that the piles were not spread evenly throughout the site in a grid layout. Due to the extensive number of piles, the effect of the pile-driving was simulated using an averaging approach. This methodology allowed groups of smaller piles supporting the structure to be

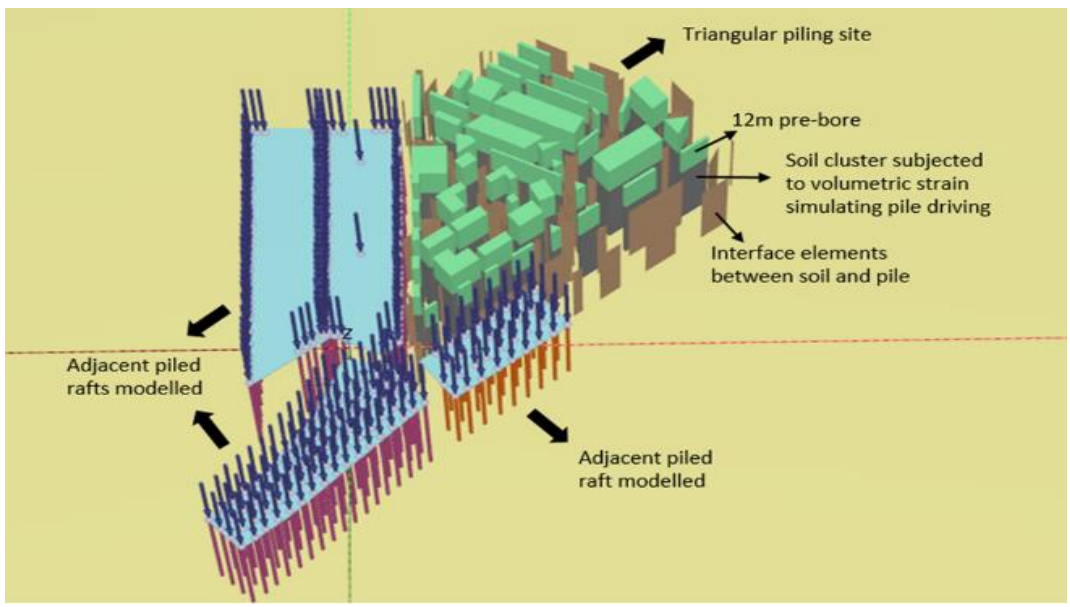

Figure 4 Screenshot of Plaxis 3D model developed by GDG Ltd.

represented as single 'super piles' which were expanded to the equivalent volume of soil displaced by the sum of the real piles inside them. Reducing the number of piles reduced the computational time required to complete the analyses.

Furthermore, the model could take into account the effect of the pre-bore before the installation of the piles by limiting the deformation to below the level of the pre-boring. For this reason, no volume expansion was assigned to the top 12 m of the piles.

4.3 Numerical analysis results

After successfully having achieved a model based on pile groups, a secondary phase was initiated generating probable effects on surrounding structures and their piled foundations. At this stage, the existing foundations of the adjacent structures were modelled as piled rafts surrounding the new piling location, based on the as-built drawings submitted to GDG (see Figure 4 for a view of the complete numerical model). The final models were reviewed by Swedish Trafikkontoret on behalf of Fastighetskontoret and it was finally concluded that a maximum lateral displacement of approximately 50 mm was to be expected for the most critical adjacent pile due to this installation.

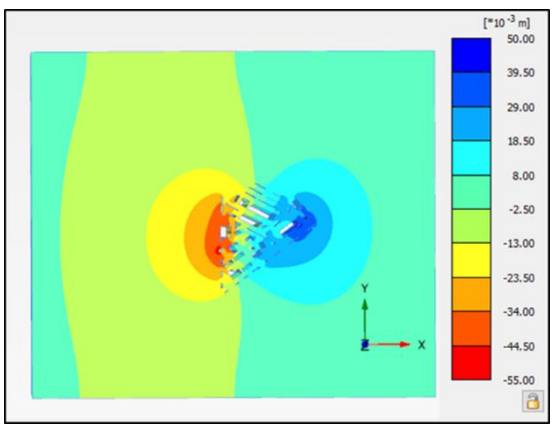

Figure 5 Lateral displacements predicted to occur in the surrounding soil due to pile driving activities

5 COMPARISON BETWEEN MEASURED DISPLACEMENTS AND NUMERICAL PREDICTIONS

It was agreed that 50 mm displacement in the piles would be an acceptable limit for maximum lateral displacements by the Swedish authorities. Due to the sensitivity of the project, ground movements were recorded during piling. In total, four inclinometers were installed on site (at the four sides of the piling site) in order to monitor the soil displacements. All structures were additionally monitored by surveying structural movements in all directions. It can be concluded that the FEM analysis gave a very accurate result and actual maximum soil movements were recorded at 53.5 mm. This has eversince decreased since the effective stress has normalized after finalizing the piling works. The only deviation from the analysis were soil movements recorded mainly in the Northern portion of the site. This is assumed to be the result of a major archealogical investigation pit located approximately 20 m North of the construction site. All other sides of the site recorded movements far below 50 mm and according to FEM predictions.

6 CONCLUSIONS

The extensive depths of soft clay (circa 40 m) underlying Gothenburg pose a significant challenge for constructing deep foundations. Lateral displacement of soil due to pile driving is a particular concern for adjacent structures. Extensive piling operations for a development in Gothenburg required analysing the effect of pile-driving on adjacent structures and their foundations. The scale of the project and tight timelines involved, required an efficient engineering approach to evaluate the effect of foundation installation. This task was fulfilled by employing detailed 3D numerical modelling using cavity expansion approach, while calibrating the initial FE model against empirical

methods to predict soil movement due to driving a single pile. The results of the project conclude pile driving effects in soft clay deposits can be accurately simulated using the suggested numerical method. As a result of the accurate method of prediction, the Gamlestad project was successfully completed with no negative impact on the surrounding structures and the predicted movements of the soft clay were seen to accurately represent the lateral displacements observed during construction.

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8 REFERENCES

Baligh, Mohsen M. 1985. “Strain Path Method.” *Journal of Geotechnical Engineering* 111 (9): 1108–36.

Edstam, T., and Kullingsjö, A. 2010. “Ground Displacements Due to Pile Driving in Gothenburg Clay.” In *Proceedings of the 7th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE), Trondheim, Norway. Taylor and Francis, London, UK*, 625–30.

Gibson R. E. and Anderson W. F. In situ measurement of properties with the pressuremeter. *Civil Engineering and Public Works Review, 1961, 56, No. 658, 615–618.*

Hagerty, D. Joseph, and Ralph, B. Peck. 1971. “Heave and Lateral Movements Due to Pile Driving.” *Journal of Soil Mechanics & Foundations Div*.

Hellman, L. 1981. On foundation technique in urban areas *(in Swedish; original title Om grundläggningsteknik i tätort). Byggnadskonst, Vol. 73 No. 10: 13–16.*

Lehane, B. M., and Gill, D. R. 2004. “Displacement Fields Induced by Penetrometer Installation in an Artificial Soil.” *International Journal of Physical Modelling in Geotechnics* 4 (1): 25–36.

Nenonen, Paulina, and Johanna Ruul. 2011. “Environmental Impact of Pile Driving: An FE-Analysis of the Displacement of the Skäran Bridge.”

Olsson, C. & Holm, G. 1993. Piled foundations *(in Swedish; original title Pålgrundläggning). Swedish Geotechnical Institute, Linköping.*

Randolph, Mark F. 2003. “Science and Empiricism in Pile Foundation Design.” *Géotechnique* 53 (10): 847–76.

Sagaseta, C., Whittle, A. J., and Santagata, M. 1997. “Deformation Analysis of Shallow Penetration in Clay.” *International Journal for Numerical and Analytical Methods in Geomechanics* 21 (10): 687–719.

Xu, Xiangtao, Hanlong Liu, and Barry M. Lehane. 2006. “Pipe Pile Installation Effects in Soft Clay.” *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering* 159 (4): 285–96.

Plaxis 3D AE Tutorial Manual (2015). Plaxis bv, Delft, the Netherlands.

www.hitta.se