Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-48

Modelling pile installation in soft natural clays

J. Isaksson[1,2] , M. Karlsson[1] , J. Dijkstra[1]

[1]*Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden*
[2]*NCC AB, Sweden*

ABSTRACT: This paper presents the results from numerical simulations of displacement pile installation in a natural clay. The simulations combine the SCLAY1S constitutive model with a large deformation Finite Element framework and a coupled deformation and porewater pressure formulation. The impact of drainage conditions in the soil is studied with respect to tip resistance during installation, displacement paths of soil and the impact of the installation on the post-installation stress-strain response of the clay adjacent to the pile. The tip resistance is found to vary between the practically drained and undrained limit states. The soil displacements due to drained pile installation are larger closer to the pile and smaller further away from the pile when compared with the undrained installation. After the undrained pile installation, deformations due to consolidation are in the reversed direction and mainly in the vertical direction for the intermediate drainage situation. The installation is affecting the triaxial response of the soil in the vicinity of the pile. The initial structure found in the soil near the pile reduces due remoulding during the pile installation phase.

Keywords: pile; installation; displacement; disturbance; SCLAY1S;

1 INTRODUCTION

Precast solid displacement piles are the most used piling system for foundations on the soft clay deposits found in Sweden. The piles are primarily installed by driving or jacking into the natural clay. Despite the large number of piles installed, the impact of the installation on the displacements in and state of the surrounding soil remains an uncertainty in foundation works.

Randolph and Gourvenec (2011) propose the *Pile cycle,* a framework for the systematic study of piling. The *Pile cycle* consists of i) the in-situ condition of the site, ii) the installation of the pile iii) the equalisation of pore pressures iv) the loading of the pile. An understanding of and the ability to predict how the previous stages in the *Pile cycle* are affecting the current stage is essential to enable sound estimations of the final load-displacement behaviour of the pile. The evolution of the stress state at the pile surface has been studied during installation, equalisation and loading (Karlsrud, 2012, Lehane and Jardine, 1994). Additionally, studies on the impact of pile installation on the surrounding clay during the different stages of the pile cycle have found changes in pore pressures, impact on the strength and stiffness properties and time-dependent displacements of the clay away from the installed pile. (Bozozuk et al., 1978, Hunt et al., 2002, Karlsrud, 2012, Pestana et al., 2002, Roy et al., 1981). The behaviour of soft natural clays is characterised by a stress- and time-dependent response, an anisotropic yield envelope and a loss of strength during plastic loading in addition to creep deformations under constant stress (Leroueil and Vaughan, 1990).

Even the most well instrumented field test will lack the possibility to track the evolving state in the soil. As a complement, numerical modelling has extensively been used to generalise the observed field behaviour by bridging the gap between the monitoring data obtained at discrete points. Numerically, a realistic description of the full pile cycle in natural soft clay is challenging due to i) the complex stress-strain behaviour of natural clays, ii) the coupled porewater pressure and soil deformation behaviour iii) the large deformations around the vertically advancing pile, causing numerical difficulties in commonly used small-strain finite element (FE) formulations. These have been discussed in length elsewhere, e.g. Staubach (2022) presents a recent overview of numerical methods suitable for vertically installed piles such as e.g. the Updated Lagrangian, Coupled Eulerian-Lagrangian, Arbitrary Lagrangian Eulerian, Material Point Method, Particle FEM, Discrete Element Method and Smoothed Particle Hydrodynamics method.

This study proposes a framework for the systematic study of the impact of pile installation into on the response of natural clays. A hydro-mechanically coupled Eulerian framework combined with the SCLAY1S model is used, an effective stress based model that considers strain-softening, anisotropy as well as a stress dependent stiffness. The impact of drainage conditions on the resulting displacement and penetration resistance is studied, where the latter is used as a validation of the coupled formulation for modelling pile installation. The framework is further used to quantify the evolving state by looking at the triaxial test response of soil close to the pile during different stages of the pile cycle.

2 NUMERICAL MODEL

Natural soft clays exhibit fabric anisotropy and an initial bonding in the soil, features which are captured by the SCLAY1S constitutive model (Karstunen et al., 2005, Koskinen et al., 2002). SCLAY1S is an elastoplastic model using the critical state framework and is based on the constitutive models of Modified Cam Clay (MCC; Roscoe and Burland, 1968) and SCLAY1 (Wheeler et al., 2003). In addition to the volumetric hardening law of MCC and the rotational hardening law of SCLAY1 the SCLAY1S model incorporates a gradual degradation of bonding driven by plastic strains. The model is hierarchical and the features related to anisotropy and destructuration can be switched off.

The SCLAY1S model was implemented in Tochnog Professional (Roddeman, 2022) Finite Element framework. Tochnog allows for a Eulerian mesh description to overcome numerical difficulties related to the large deformations around the pile tip. The large deformation numerical formulation of Tochnog is described in more detail by Crosta et al. (2003). In addition, a fully coupled porewater and stress formulation is used, hence the hydromechanical response is governed by the relation between the loading rate and hydromechanical properties of the soil. The analysis is performed using the moving pile method proposed by Dijkstra et al. (2011) in an axisymmetric domain. The penetration of the pile is controlled by a gradual vertical expansion of a geometric entity, representing the pile, at the axisymmetric boundary. All nodes in the pile geometry are prescribed with a vertical velocity corresponding to the penetration velocity of the pile. In each time step, the geometry is expanded downwards, and a nodal sweep is performed to check if new nodes are inside the geometry.

The axisymmetric numerical model is presented in Figure 1. The solid pile is given a radius (*R* = 0.155 m) which will be the basis for all other length measures stated in the paper. The pile is installed down to a depth equal to a pile length *L* of 40*R* in a domain with a height *h* of 80*R* and width *w* of 240*R* and a velocity *v* of one pile radius *R* per second. All horizontal movement is prevented together with water flow along the axisymmetric boundary and the far-right boundary. Vertical movement and water flow are prevented at the lower boundary. At the top boundary, a uniform total stress σ_v is applied, corresponding to a fill layer. This top boundary is also the level of the phreatic surface giving the initial hydrostatic porewater pressure in the domain. The fixed structured mesh uses 4 noded quadrilateral elements in 479 identical horizontal strips, each with 108 elements. The elements located within 80*R* from the axisymmetric axis are illustrated in Figure 1. Between 80*R* and the far-right boundary at 240*R* a total of 9 equally sized elements is used in each strip.

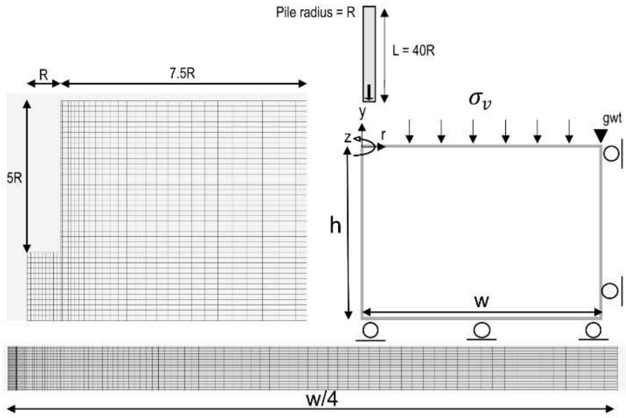


Figure 1. Numerical model and mesh

The clay properties in this study are based on a test site in Utby, located outside Gothenburg, on the west coast of Sweden. Utby has been used as a research site by Chalmers University of Technology, Karstunen and Amavasai (2017) present the model parameters for the Utby clay that has been used in this work, see Table 1.

Table 1. Model parameters used for the coupled SCLAY1S model.

Symbol	Parameter	Value
$K0$	Initial earth pressure coefficient [-]	0.6
OCR	Overconsolidation ratio [-]	1.45
ρ	Density [t/m^3]	1.6
e_0	Initial void ratio [-]	2.05
λ_i	Intrinsic compression index [-]	0.329
κ	Swelling index [-]	0.061
ν	Poisson's ratio	0.2
M	Slope of CSL line [-]	1.56
α_0	Initial anisotropy [-]	0.63
ω	Absolute rate of rotation [-]	30
ω_d	Relative rate of rotation [-]	1.0
χ_0	Initial amount of bonding [-]	5
a	Absolute rate of destructuration [-]	9
b	Relative rate of destructuration [-]	0.4

3 ANALYSIS

A series of 14 analyses were performed with a varying hydraulic conductivity *k* of the soil between 1.3 x10^{-6} and 1.3 x10^{-1} m/s to investigate the rate-dependent response of the pile-soil system. An initial equilibrium stage is followed by the installation of the pile into the clay. After the installation of the pile down to the full depth, a pore pressure equalisation stage is included allowing for the excess porepressures to dissipate.

3.1 Rate dependent pile head response during installation

Initially, the penetration resistance of the pile is studied as this reflects the change in response due to the change in the hydraulic conductivity of the soil. Figure 2 shows the resulting penetration resistance for the set of simulations. The penetration resistance was obtained from the vertical force needed to move the boundary, representing the pile, downwards normalised with the area of the pile tip. A clear trend is shown where an increase in the hydraulic conductivity is associated with an increase in the penetration resistance for the pile. An upper bound and a lower bound of the tip resistance emerges, reflecting the commonly used drained and undrained limit states of the hydro-mechanical soil response.

To enable a comparison of the results of this study with previous work, the normalised penetration velocity is introduced. The parameter was presented by Finnie and Randolph (1994) and is a nondimensional measure of the drainage conditions during penetration into soil defined as

$$V = \frac{vD}{c_v} \quad (1)$$

where v is the penetration velocity, D is the diameter of the pile and c_v is the consolidation coefficient of the soil. The consolidation coefficient is in this work based on the stress state at the middle of the pile and calculated as

$$c_v = \frac{k(1+e_0)\sigma'_{v0}}{\gamma_w \lambda_i} \quad (2)$$

where σ'_{v0} is the vertical effective stress in-situ and γ_w is the unit weight of water. Using the resulting tip resistance at the final penetration depth, at $40R$ in Figure 2, and subtracting the influence of the vertical effective stress at the depth the net tip resistance q_{net} can be obtained. The net tip resistance and the corresponding V are presented in Figure 3 as the difference between the q_{net} of the current V and the net tip resistance from the undrained simulation (q_{ud}) normalised with the difference between the drained (q_{dr}) and undrained net tip resistance.

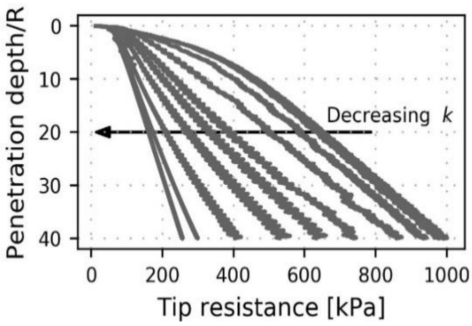


Figure 2. Penetration resistance during pile installation due to a variation of hydraulic conductivity of the

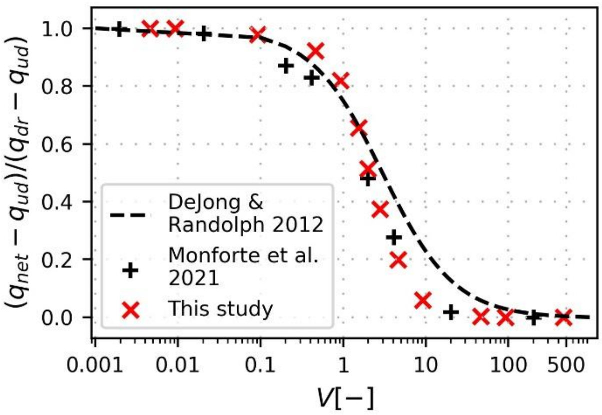
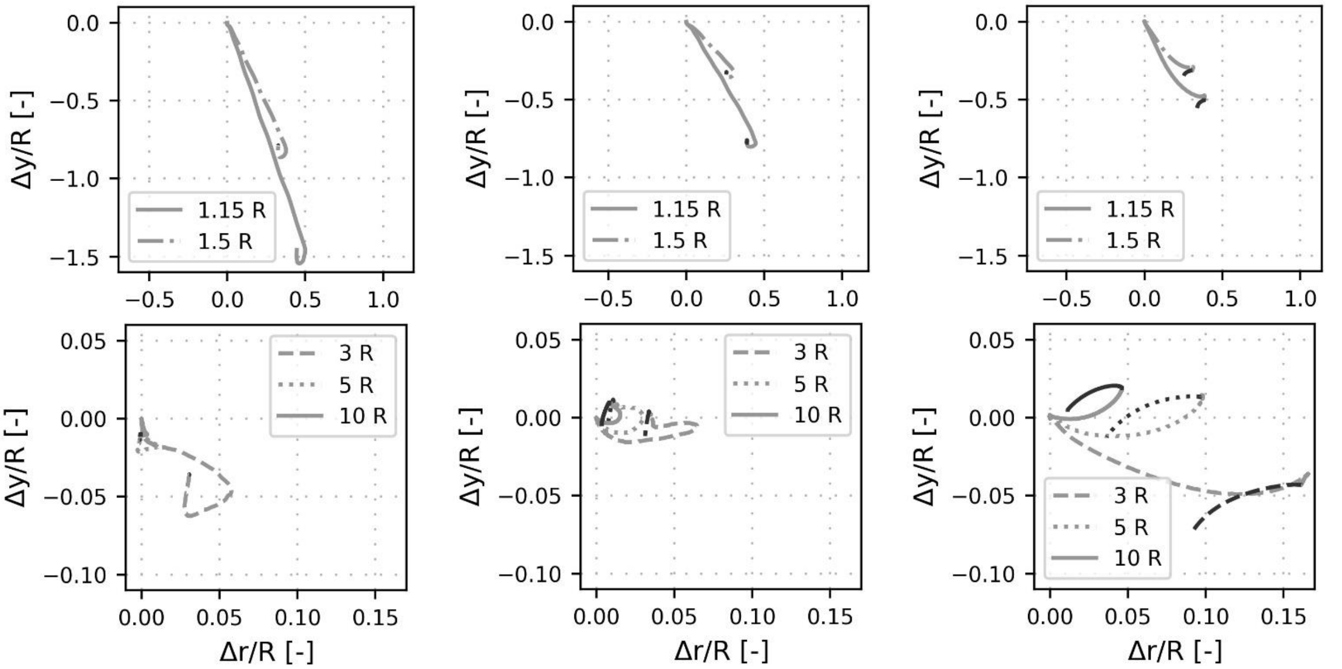


Figure 3. Change in net tip resistance with the variation of normalised penetration velocity.

The figure also includes a characteristic curve presented by DeJong and Randolph (2012) and data from a numerical simulation using a brittle soil response and varying hydraulic conditions presented by Monforte et al. (2021). The results of this study are in excellent agreement to the other two studies.

3.2 Soil displacements due to pile installation

In addition to the resulting pile tip resistance, the drainage conditions in the soil are also affecting the emerging displacements due to the pile installation. The displacement trajectories of 5 discrete soil elements at an initial radial distance of $1.15R$, $1.5R$, $3R$, $5R$ and 10R from the pile and an initial depth of $19R$ below the surface were tracked throughout the pile installation and subsequent consolidation processes. Figure 4 shows the resulting displacement trajectories for the drained ($V = 0.009$) and undrained ($V = 462$) conditions, as well as for one intermediate drainage condition ($V = 1.98$). Clearly, the drainage condition has a high impact on the displacements in the soil due to pile installation. Near the pile, the displacements, mainly vertically downward, are increasing with a decreasing V. In contrast, further away from the pile (at distances $3R$, $5R$, $10R$) the displacement, is increasing with an increasing V. The undrained radial displacement was shown to be approximately halved when the distance from the pile doubled. In contrast the displacement due to the pile installation in the intermediate and drained condition shows a different trend due to the compression of the consolidated or partly consolidated clay. Consolidation movement is largest for the undrained installation with a movement in the reversed direction of the initial outward displacement. The intermediate drainage situation shows small consolidation movement in comparison to the initial movement and mainly in the vertical direction. As expected, no additional movement is found for the practically drained case as the emerging pore pressures are negligible.



(a) Drained *(b) Intermediate* *(c) Undrained*

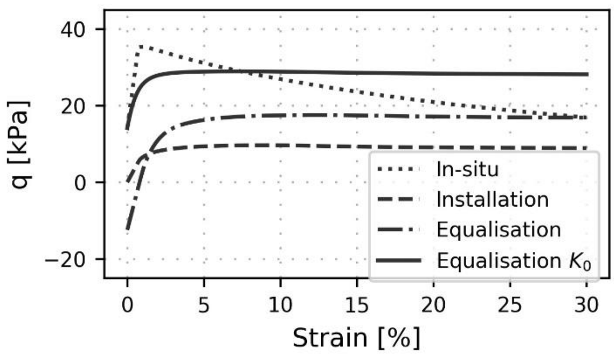
Figure 4. Displacement paths for soil at a depth equal to 19R due to pile installation under a) drained, b) intermediate and c) undrained conditions due to installation (grey) and subsequent consolidation (black).

3.3 *Impact of pile installation on soil response*

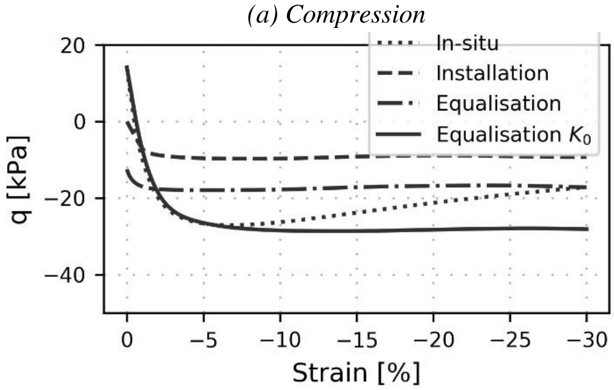
The vertical installation of a displacement pile is also affecting the state of the soil in the vicinity of the pile. The disturbance of the initial state will lead to a change in stress-strain response of the soil when compared to the in-situ condition before pile installation. A series of numerical displacement-controlled triaxial tests were performed on soil extracted from the undrained simulation of pile installation, *i.e.* the state variables and stress state in an element near the pile after installation were imposed as initial condition for a new numerical simulation of the triaxial test. The numerical triaxial test was performed on soil initially located at a radial distance of $1.5R$ from the centre of the pile, corresponding to the soil elements for which the trajectories were computed and shown in Figure 4. Four different cases were studied i) before installation (in-situ), ii) directly after installation (installation) and iii) after equalisation (equalisation) iv) soil state after equalisation in a K_0 stress state (equalisation, K_0). Figure 5 shows the result from the series of undrained triaxial tests simulated for compression and extension paths.

As a result of remoulding during the pile installation, the strain softening behaviour shown for the undisturbed soil is not present for any of the three samples extracted after the equalisation of pore pressures from pile installation, corresponding to slightly less than one-third of the undisturbed peak value in compression and one-third in extension.

Interestingly, the difference in peak stress in compression and extension seems to be strongly reduced for the disturbed soil due to the rotational hardening that is driven by large magnitudes of deviatoric strain. After consolidation, the soil regains some strength compared to the unconsolidated sample due to the increase in effective stress and decrease in void ratio.



(a) Compression

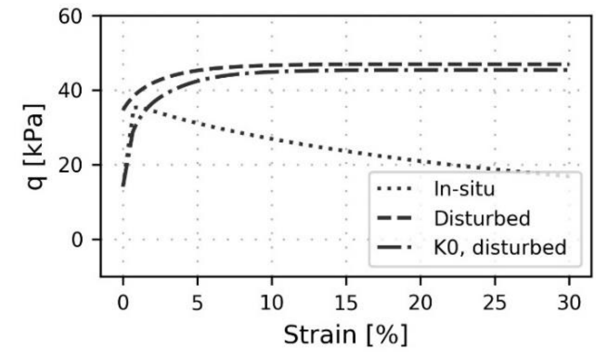


(b) Extension

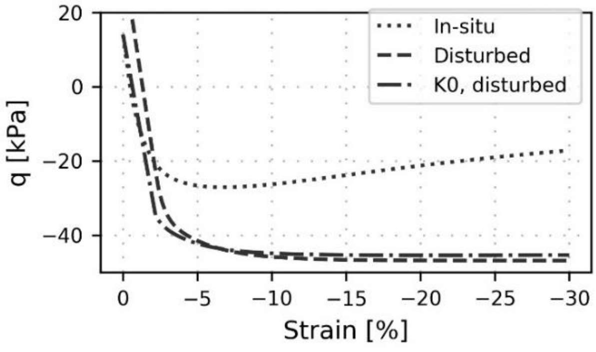
Figure 5. Numerical triaxial tests on soil close to a pile installed under undrained condition.

As the radial stress is larger than the vertical stress for the consolidated soil, the change in deviatoric stress is larger in compression and smaller in extension compared to the K_0 consolidated samples. The comparison between the K_0 consolidated sample with the undisturbed sample shows that the undisturbed soil has a higher peak shear strength and a more brittle behaviour. Hence, the decrease in the void ratio of the disturbed (remoulded) and consolidated soil seems to compensate for the loss of bonding and reduction of preconsolidation pressure.

Two similar series of displacement controlled undrained triaxial tests were conducted on soil extracted from the intermediate and drained simulated pile installation, to study the impact of drainage conditions. The triaxial tests conducted on soil extracted from the drained pile installation is presented in Figure 6 and the simulations for the intermediate condition in Figure 7. The intermediate test series only show a slight increase in peak shear stress due to consolidation, which is explained by the very small excess pore pressure (4 kPa) present at mid-pile depth at the end of pile installation. A very similar peak shear stress in compression is found for all tests in the intermediate series. However, the brittleness found in the undisturbed test is not present in any of the other tests. As in the undrained situation, due to the rotation of the fabric of the clay, the disturbed samples in extension exhibit a considerably higher peak shear stress compared to the in-situ condition and is very similar to the magnitude in compression.

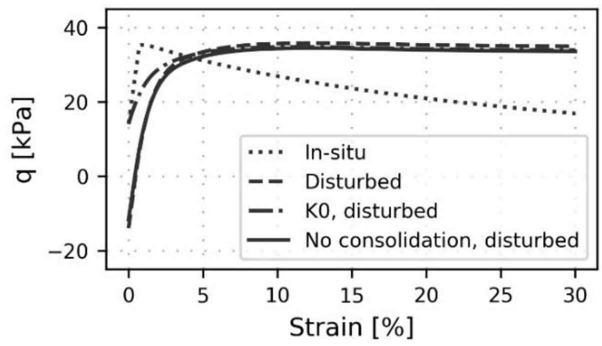


(a) Compression

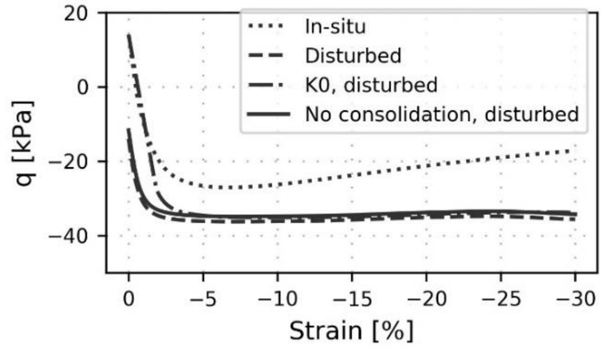


(b) Extension

Figure 6. Numerical triaxial tests on soil close to a pile installed under drained conditions.



(a) Compression



(b) Extension

Figure 7. Numerical triaxial tests on soil close to a pile installed under intermediate drainage conditions.

Similar to the intermediate and undrained situation, the brittleness and anisotropy shown in the in-situ condition are not present in the disturbed tests on soil from the drained pile installation. Furthermore, the undrained pile installation will result in a lower shear strength in triaxial compression and extension when compared to the intermediate and drained situation.

4 CONCLUSIONS

This paper presents the results from a series of numerical pile installations using different drainage conditions of the soil. The numerical formulation is considering partial consolidation by linking the material deformations to the coupled response of porewater flow. To avoid numerical issues associated with the large deformations occurring around the vertically advanced pile tip an Eulerian framework is used. The numerical model is used together with the constitutive model SCLAY1S, which is capturing the evolving anisotropy and bonding of the soil.

Initially, the impact of the full range of drainage conditions on the emerging pile tip resistance is studied, the transition from a drained state through an intermediate to a practically undrained situation is captured and compares well with previous studies using the normalised penetration velocity V as the indicator for relative drainage condition.

The resulting displacements due to pile installation are affected by the relative drainage condition during pile installation. The vertical displacements close to the pile were shown to be increasing with the decreasing normalised penetration velocity. In contrast, the displacements further away from the pile increased with increasing *V*. For the undrained situation, consolidation movement is towards the pile in the reversed direction from the initial outward displacement while the consolidation movement from an intermediate drainage condition is mainly in the vertical direction.

A series of numerical triaxial tests were subsequently conducted on soil numerically extracted from the vicinity of the pile. The results show that the brittleness and anisotropy present in the undisturbed soil are practically vanishing due to the installation of the pile. The reduction of shear strength is initially considerable due to the undrained pile installation. Some of the strength is regained due to consolidation of excess pore pressures, and an additional increase is achieved when the disturbed soil is K_0-consolidated before shearing. The disturbed soil due to pile installation in an intermediate and drained situation show an increase in strength compared to the in-situ condition prior to pile installation.

The numerical method presented in this study was able to quantify the evolving state in the soil during different stages of the pile cycle considering the soft soil features of strain softening and anisotropy. The method can thus in the future be used to interpret observed field data. Additionally, the method can be used for a systematic investigation to quantify the impact of main soft soil features on the soil-structure interaction and the (evolving) state in the soil during and after pile installation. Finally, the numerical simulations should be validated further against field or lab tests performed on samples extracted from the disturbed zone after pile installation. The present work might guide the initial stress conditions to be applied in those tests on disturbed soil.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by SBUF (Development fund of the Swedish construction industry, grants 13614 and 14186) and BIG (Better Interaction in Geotechnics, grant A2019-19, from the Swedish Transport Administration)

6 REFERENCES

Bozozuk, M., Fellenius, B. H., Samson, L. 1978. Soil disturbance from pile driving in sensitive clay; discussion. Canadian Geotechnical Journal, 15(3), 346–361.

Crosta, G. B., Imposimato, S., Roddeman, D. G. 2003. Numerical modelling of large landslides stability and runout. Natural Hazards and Earth System Science, 3(6), 523–538.

DeJong, J. T., Randolph, M. 2012. Influence of Partial Consolidation during Cone Penetration on Estimated Soil Behavior Type and Pore Pressure Dissipation Measurements. Journal of Geotechnical and Geoenvironmental Engineering, 138(7), 777–788.

Dijkstra, J., Broere, W., Heeres, O. M. 2011. Numerical simulation of pile installation. Computers and Geotechnics, 38(5), 612–622.

Finnie, I. M. S., Randolph, M. 1994. Punch-through and liquefaction induced failure of shallow foundations on calcareous sediments. *Seventh International Conference on the Behaviour of Offshore Structures* Vol. 1, 217-230. Pergamon. Massachusetts, USA.

Hunt, C. E., Pestana, J. M., Bray, J. D., Reimer, M. 2002. Effect of Pile Driving on Static and Dynamic Properties of Soft Clay. Journal of Geotechnical and Geoenvironmental Engineering, 128(1), 13-24.

Karlsrud, K. 2012. Prediction of load-displacement behaviour and capacity of axially loaded piles in clay based on analyses and interpretation of pile load results., Norwegian University of Science, and Technology. Trondheim, Norway.

Karstunen, M., Amavasai, A. 2017. BEST SOIL: Soft soil modelling and parameter determination., Chalmers University of Technology, Gothenburg Sweden.

Karstunen, M., Krenn, H., Wheeler, S. J., Koskinen, M., Zentar, R. 2005. Effect of Anisotropy and Destructuration on Behavior of Murro Test Embankment. International Journal of Geomechanics, 5(2), 87–97.

Koskinen, M., Karstunen, M., S. Wheeler 2002. Modelling destructuration and anisotropy of a natural soft clay. Mestat, Proc., 5th European Conf. Numerical Methods in Geotechnical Engineering, pp. 11–19., Presses de l'ENPC/LCPC,, Paris.

Lehane, B. M., Jardine, R. J. 1994. Displacement-pile behaviour in a soft marine clay. Canadian Geotechnical Journal, 31(2), 181–191.

Leroueil, S., Vaughan, P. R. 1990. The general and congruent effects of structure in natural soils and weak rocks. Géotechnique, 40(3), 467-488.

Monforte, L., Gens, A., Arroyo, M., Mánica, M., Carbonell, J. M. 2021. Analysis of cone penetration in brittle liquefiable soils. Computers and Geotechnics, 134, 104123.

Pestana, J. M., Hunt, C. E., Bray, J. D. 2002. Soil deformation and excess pore pressure field around a closed-ended pile. Journal of Geotechnical and Geoenvironmental Engineering, 128(1), 669–671.

Randolph, M., Gourvenec, S. 2011. Offshore Geotechnical engineering, Taylor & Francis, London

Roddeman, D. 2022. Tochnog professional user's manual, october 22. https://www.tochnogprofessional.nl/manuals/user/user.pdf. Accessed: 2022- 10-21.

Roscoe, K., Burland, J. 1968. On the generalized stress strain behaviour of wet clay. Engineering plasticity, 553‑609, Cambridge Univ. Press, Cambridge U.K.

Roy, M., Blanchet, R., Tavenas, F., Larochelle, P. 1981. Behaviour of a sensitive clay during pile driving. Canadian Geotechnical Journal, 18(1), 67–85.

Staubach, P. 2022. Contributions to the numerical modelling of pile installation processes and high-cyclic loading of soils, Ruhr-Universität Bochum, Bochum, Germany.

Wheeler, S. J., Näätänen, A., Karstunen, M., Lojander, M. 2003. An anisotropic elastoplastic model for soft clays. Canadian Geotechnical Journal, 40(2), 403–418.