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Benchmarking of a contemporary soil model for simulation of deep excavations in soft clay

Analyse comparative d'un modèle contemporain de sol pour la simulation d'excavations profondes dans de l'argile mole

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ABSTRACT: Measurement data from previous excavation works in soft clay deposits are revisited to benchmark a contemporary constitutive soil model, referred to as the Creep-SCLAY1S. The research is motivated by the planned deep excavations for the West Link tunnel in Gothenburg that require analyses of both short- and long-term performance. Unique data on prior excavation works, which were instrumented and monitored during the construction period, will be utilised. In contrast to previous studies, that focused on the construction period, also the long-term performance will be assessed using satellite data. The analyses are carried out using a contemporary rate-dependent model, considering the on-going (background) creep deformations in the clay deposit. The study shows that while the recent model developments result in improved predictions, additional features need to be further developed: most notably, the formulations for the rate-dependent small strain stiffness in loading and unloading stress paths requires attention. Also, it is evident that modelling details, such as installation effects (sheet pile wall and pre-cast concrete displacement piles) are important for prediction of the subsequent response.

RÉSUMÉ: Des données mesurées antérieurement lors de travaux d'excavation dans des gisements d'argile molle ont été réexaminées afin d'évaluer un modèle contemporain de comportement des sols, appelé Creep-SCLAY1S. La présente recherche est motivée par les fouilles profondes prévues pour le tunnel Connexion Ouest à Gothenburg, qui nécessitent des analyses de performance à court terme et à long terme. Les données uniques des travaux d'excavation antérieurs, qui ont été instrumentés et contrôlés pendant la période de construction, sont utilisées comme référence. Contrairement aux études précédentes, qui portaient principalement sur les structures de retenue et leur impact sur le milieu environnant pendant la période de construction, la performance à long terme est également évaluée. Les analyses sont effectuées à l'aide d'un modèle contemporain dépendant de la vitesse de déformation, prenant en compte les déformations de fluage en cours dans le gisement d'argile. L'étude montre que, si les développements récents du modèle ont permis d'améliorer considérablement les prévisions, des fonctionnalités supplémentaires doivent encore être développées. Il est nécessaire de prêter une attention particulière aux formulations de la rigidité à faible déformation dépendant de la vitesse de déformation sous les chemins de contraintes de chargement et déchargement. Aussi, c'est évident que les détails de la modélisation, tels que les effets d'installation (mur de palplanches et pieux de déplacement en béton préfabriqué, sont importants pour une estimation correcte de la déformation subséquent et de la réponse des pressions interstitielles.

Keywords: Soft clay; excavation; settlements.

1 INTRODUCTION

Tunnels are an essential part of the transportation system in cities. In 2018-2026 a new railway tunnel, the West Link, will be constructed in central Gothenburg, Sweden. The project involves excavation for three new railway stations. The excavations will range in depth from ca 15 to 25 meters below ground level and will be carried out in deposits of soft sensitive clay with thickness up to 100 m and on-going creep settlements.

To ensure that the excavations and permanent structures are constructed appropriately, and to minimize deformations in the surroundings, reliable predictions are necessary concerning for example earth pressures and deformations, not only for the construction period but also for the design period of 120 years. Hence, it is crucial to model and predict the soil response not only in the short term during construction works, but also in the long term. Long term analyses are needed for example to make sure that the tunnel and the surroundings settle in the same rate, or fulfil the requirements on maximum allowable differential settlements. Analyses therefore need to account for characteristic clay properties, such as rate-dependency (including effect of on-going creep settlements) in addition to for example anisotropy and destructuration of the sensitive clay.

The crucial necessity of accurate predictions is strongly supported by a number of failures of excavations in soft clay as described for example in COI Report (2005) on the Nicolle Highway collapse, Chen et al. (2015), Do et al. (2016). Together, these reports make it evident that geotechnical design must incorporate the relevant features of the actual soil response. Furthermore, Whittle et al. (2015) points out that there is a scarcity of case studies comparing well instrumented retaining structures with numerical predictions.

From 2000-2006 the Göta Tunnel was constructed in Gothenburg with excavation depths up to about 15 m in soft clay deposits. Some parts were extensively instrumented and monitored during the construction period. Advances in the capabilities of advanced constitutive models makes it possible to revisit these measurement data. In this paper measurement data from the Göta Tunnel (section 1/430) are revisited to benchmark a contemporary constitutive soil model, referred to as the Creep-SCLAY1S, which among other features consider the on-going (background) creep deformations in the clay deposit.

The aim of this paper is to consider the measurement data from one section, 1/430, of the excavation. Results from numerical analyses are compared with measurement data of horizontal- and vertical deformations, as well as pore pressure dissipation. Concluding comparisons with measurement data of strut forces etc. are being analysed for additional sections, and the results will be presented in a forthcoming journal paper.

In contrast to a previous study of the Göta Tunnel excavation, that focused on the retaining structures and their impact on the surroundings during the construction period, the time-dependent response during excavation as well as the long-term performance will be the focus in this paper.

2 GÖTA TUNNEL EXCAVATION

2.1 Site description

The Göta Tunnel is located south of the Göta river in central Gothenburg. In this paper excavation works and monitoring of ground movements etc. are studied for section 1/430 close to the river and an adjacent channel, see Figure 1. A historic 4-storey building from the 1920s is located northeast of the excavation, and a more recent 5-storey building (from the 1950s) to the south. The ground level at the site corresponded to +12.1 before excavation. The soil layers consist of fill down to a depth of approximately 2 m. Underneath, soft sensitive clay is found down to approximately level -16 at the location of the sheet-pile wall in the studied section. Friction material is present under this clay layer above the bedrock.

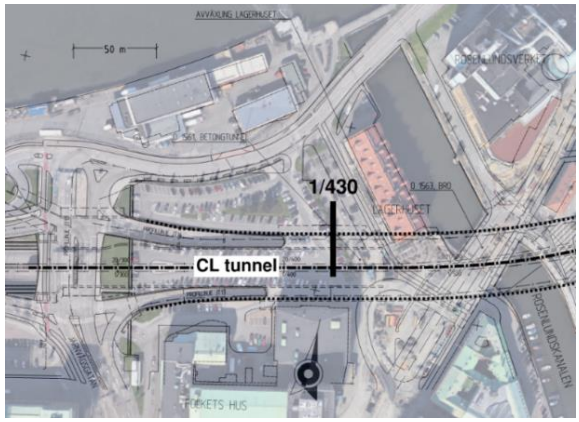

Figure 1. Overview of part of the Göta Tunnel. The studied section (1/430) is highlighted as well as the centreline and extent of the tunnel.

Index properties of the clay layer are presented in Figure 2. The unit weight of the clay is ca 15 kN/m^3 in the top of the clay layer and increases almost linearly to ca 18 kN/m^3 to the bottom (level -16). CPT and fall cone tests indicate an (uncorrected) undrained shear strength of 15 kPa at level +10, with an increase of ca 1 kPa/m towards depth. The sensitivity varies from ca 10-25. The permeability, evaluated from CRS-oedometer tests at effective stress levels corresponding to the in-situ stress, varies between ca 5E-10 to 1E-9 m/s. The horizonal permeability is expected to be the same as the vertical based on tests by Larsson (1981) on soft clay from e.g. Bäckebol ca 10 km north of the Göta Tunnel.

The in-situ vertical effective stresses and vertical preconsolidation pressures (evaluated from undrained triaxial compression and CRS-oedometer tests) indicate trend values for OCR (overconsolidation ratio) varying between 1.1-1.4 in section 1/430, and 1.4-2.0 in an adjacent section (1/470). The higher OCR-values in the adjacent section is due to historic use of that sub-area for the storage of iron.

The background creep settlements in Gothenburg in general vary between 2-5 mm/year, and in the area around the studied section 1/430, the rate of settlement varied between 3-8 mm/year based on the documents for the original tunnel design.

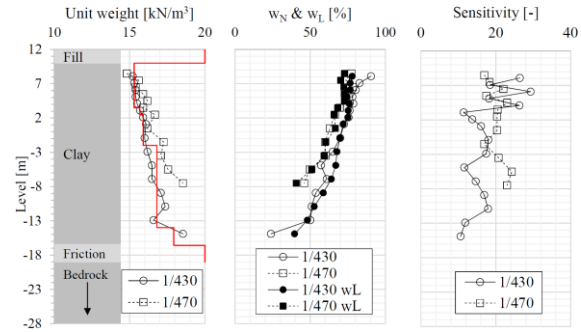

Figure 2. Soil profile and index properties of the clay layer at site, red line indicate unit weight used in the FE-analyses.

2.2 Working sequence and instrumentation

The excavation works was carried out by underwater excavation and casting of an (anchored) concrete slab before dewatering. Figure 3 shows a photo after final dewatering of the excavation.

An outline of the main activities of the excavation procedure, including approximate start dates for some activities, is given in the following. Note that the length of activities and the intermediate stall-times (due to for example work on other parts of the project) are approximate, and therefore incorporate some uncertainties when modelling the construction process as a time-dependent coupled flow-deformation analyses.

1. Installation of floating sheet pile wall (SPW), AZ-36, L=26 m (start 2002-07-15).
2. Exc. to +10.1 inside and perimeter of SPW.
3. Installation of pre-cast concrete displacement piles (start 2002-11-21).
4. Fill to +11 inside SPW (working platform).
5. Under-water excavation incl. inst. of struts.
6. Casting of 0.7 m concrete slab (start 2003-05-12).
7. Installation and pre-stressing of anchors to slab.
8. Dewatering (start 2003-08-05).
9. Construction of tunnel (start 2003-09-01).
10. Fill between tunnel and SPW.
11. Strut removal (end 2005-02-15).

Figure 3. Excavation after dewatering.

Before installation of each pre-cast concrete pile, soil was removed using a hollow cylinder with an area the same size as the concrete pile and a "trapper" in the end, down to level ±0. Each pile was jacked down, so that the pile head was at level ca +3. Thus, the concrete piles displaced soil below level ±0, whereas above level +3 there was an "outtake" of volume.

During excavation works (step 1-11 in previous outline of work) section 1/430 was monitored, as indicated in Figure 4. In this paper monitoring data from the inclinometers and the bellow hoses are studied.

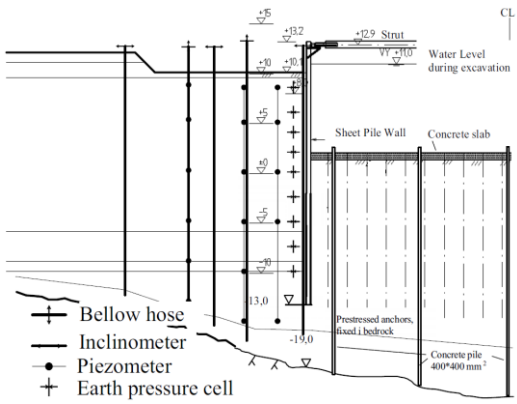

Figure 4. Monitoring at section 1/430 during construction period, from Kullingsjö (2007).

2.3 Previous analyses

Field measurements were carried out by Kullingsjö (2007) and the results were compared with classical earth pressure calculations, as well as the results from numerical analyses. Undrained analyses were conducted, these were then and now, the most common design method/practice in Sweden for retaining structures in soft clay. No analyses were made at that time as a coupled, time-dependent, flow-deformation analyses, considering the generation and dissipation of excess pore water pressures.

2.4 Long-term monitoring

Since the excavation works and construction of the tunnel, the Swedish Transport Administration has been surveying the on-going settlements in Gothenburg using satellite data (InSAR) as part of the new West Link tunnel project. Some data from satellite monitoring is presented in Figure 5.

Figure 5. Data from satellite monitoring showing rate of on-going settlements at ground surface level (green=0 mm/year to red ≥10 mm/year) with section 1/430 highlighted in blue.

InSAR data above the Göta Tunnel indicate no on-going settlement nor no heave of the tunnel itself. However, just north of the tunnel settlements of 1-2 mm/year are indicated east of the studied section, 1/430, and 5-7 mm/year to the west. No satellite data is available directly at section 1/430 due to the lack of objects resulting in reflected signals. At ca 30-50 m distance north of the tunnel, the rate of settlement is ca 10 mm/year. The different settlement rates are due to the history of

the Gothenburg harbour area and relate to the historic changes in the land use (harbour basins, piers, storage facilities, warehouses, etc).

2.5 Analyses

Numerical analyses of the construction process were made using the Creep-SCLAY1S constitutive soil model in the FE-program Plaxis 2D version 2018. The Creep-SCLAY1S model incorporates effects of characteristic soft clay features, such as rate-dependency, anisotropy and destructuration. The model in its current form lacks incorporation of small-strain stiffness for loading and unloading stress paths. Required model parameters are summarized in Table 1. For details of the model, see for example Wheeler et al. (2003), Leoni et al. (2008), Grimstad et al. (2010), Sivasithamparan et al. (2015) and Gras et al. (2018). Parameter values used in the analyses are outlined in Tables 1-2. The horizontal and vertical permeability were assumed to be equal.

Table 1. Creep-SCLAY1S parameter values.

Parameter	Value
Modified swelling index, κ^*	0.013
Poisson's ratio, ν'	0.20
Intrinsic modified compr. index, λ^*_i	0.09
Slope of CSL in compression, M_c	1.45
Slope of CSL in extension, M_e	1.10
Intrinsic modified creep index, μ^*_i	0.00125
Reference time, τ (days)	1
Initial inclination of yield surface, α_0	0.56
Rate of rotational hardening, ω	70
Relative rate of rotat. hardening, ω_d	1.0
Initial amount of bonding, χ_0	15
Rate of destructuration, a	8
Relative rate of destructuration, b	0.5

Table 2. Parameters of clay layers.

Layer	Level	OCR	e_0	k (m/s)
1	+10.0 to +3.5	1.4	2.26	1E-9
2	+3.5 to +2.5	1.2	2.10	1E-9
3	+2.5 to -2.0	1.1	1.99	1E-9
4	-2.0 to -14.0	1.2	1.55	5E-10
5	-14.0 to -16.6	1.5	0.96	5E-10

The in-situ K_0 was set to 0.6 and K_0^{nc} to 0.42. The K_0^{nc} value of 0.42 is rather low compared to what has been measured in laboratory tests on Gothenburg clay (0.50-0.55), see for example Olsson (2013) and Kullingsjö (2007). The value of 0.42 results from having a consistent set of the parameters M_c, α_0 and K_0^{nc} with respect to the critical state friction angle. The chosen friction angle is based on the M_c value derived from undrained triaxial compression tests, performed at a constant rate of deformation 0.01 mm/min (0.6%/h). The M_c value of 1.45 corresponds to a critical state friction angle of 35.7º (c'=0). Recent experience at Chalmers suggest that M_c values based on undrained tests may be overestimates, due to rate-effects. Preferably the M_c (and M_e) values should be derived from drained tests, however such tests, especially compression tests from deeper clay layers, are scarce in the Gothenburg area.

Calibration of the model parameters was done solely based on laboratory data (CRS-oedometer and undrained triaxial compression and extension tests). Comparisons of element level simulations and laboratory data from triaxial tests on samples from 9 and 13 m below ground surface are presented in Figure 6, showing an acceptable match.

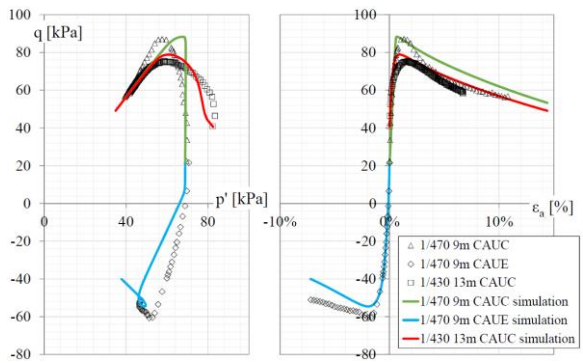

Figure 6. Anisotropically consolidated undrained (CAU) compression (C) and extension (E) tests from sections 1/430 and 1/470 compared to simulations; (a) p'-q stress space; (b) plot of ε_a-q. Lab test 1/430 was consolidated to $\sigma'_{vc(CRS)} / \sigma'_v$=0.94 before shearing, in the simulations OCR was set to 1.0.

3 RESULTS AND DISCUSSION

In Figure 7 the results of measured horizontal- and vertical deformations are compared with the results from the FE-simulations. Three different stages (i.e. stage 3, 6 and 11 in Section 2) of the construction process are discussed.

The simulations indicate that the shape of the horizontal deformation pattern is well-predicted, but the actual deformations after pile installation are underestimated by ca 20 mm in the top part of the soil profile. This is probably due to the following; 1) The installation of the concrete piles is modelled as cavity expansion in soil clusters, thus, the effect of pile installation is "smeared" in the plane strain model; 2) Before installation, a hollow cylinder with an area the same size as the concrete pile was used to extract soil down to level ±0, after which the piles were hammered down to level +3. The effect of this is difficult to simulate. It was simplified as a negative cavity expansion (collapse) corresponding to half the volume of the hollow cylinder. However, this probably underestimate the soils ability to arch around the cavities. The results in Figure 7 (a) confirm this.

After underwater excavation and the final dewatering, the pattern of the horizontal movements is captured well by the simulations. The soil and sheet pile response, however, slightly underestimate the horizontal deformations below the bottom edge of the concrete slab, level +1.6. This is likely a result of the modelling assumptions; wished in place pre-stressed anchors installed before dewatering the excavation. In reality, the anchors were pre-stressed in a sequence, thus most likely not all anchors were activated to the prescribed prestress force (no post-tensioning occurred), and some 'slack' occurred. Also, installation of the anchors may have disturbed the clay on the retaining side.

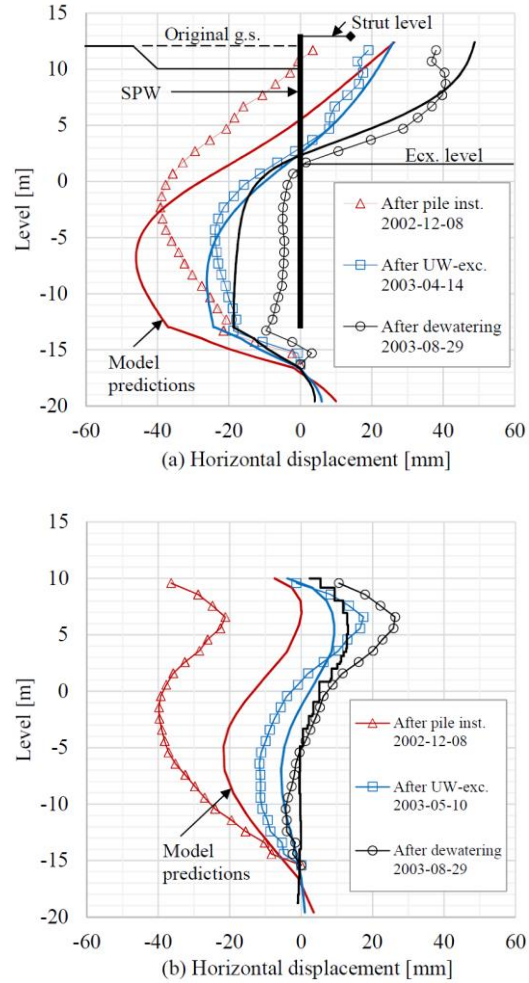

Figure 7. Comparison of measured and calculated horizontal displacements; (a) at and (b) 9.0 m behind sheet pile wall.

The measured and simulated vertical displacements are presented in Figure 8. At the time after installation of the pre-cast concrete piles the measurements are matched relatively well by the FE-simulations. After the underwater excavation and the final dewatering, the calculations overestimate the amount of heave compared to the measurements. Differences between simulations and measurement data may arise from the fact that the constitutive model does not incorporate all features of varying stiffness during load-reversal (unloading), as well as small-strain stiffness.

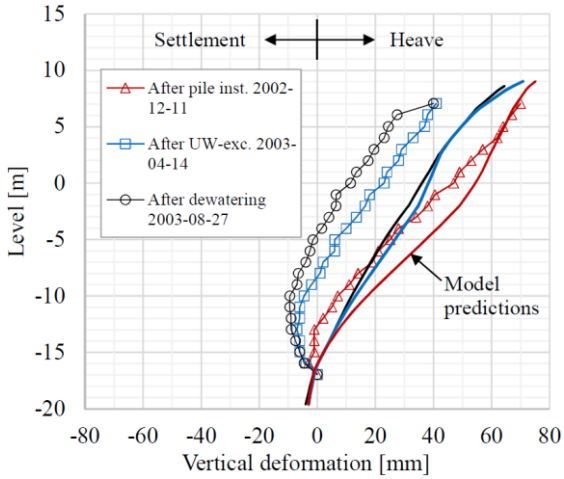

Figure 8. Comparison of measured and calculated vertical displacement 5.5 m behind sheet pile wall.

3.1 Pore water pressures

The measured pore water pressures at 6 m distance behind the excavation, as well as the results from simulation are presented in Figure 9. The measurements indicate that installation effects of the sheet pile wall, which were not modelled, caused excess pore-pressures which are not included in the calculations. The excess pore pressures measured after installation (starting 2002-07-15) of the sheet pile wall, however, seem unrealistically high and result in an offset in the subsequent measurements.

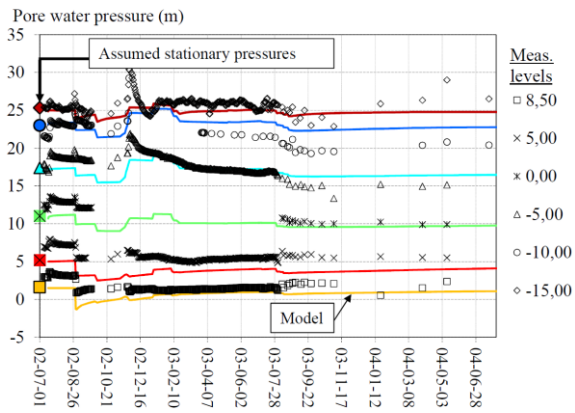

Figure 9. Porewater pressure at 6 m distance behind sheet pile wall.

Although the simulations capture the changes in porewater pressure over time relatively well, the results indicate the difficulty in capturing the development of excess-pore pressures at correct time-intervals during the construction process (correct start and end times for each activity at the site, including overlapping activities near the instrumented section).

3.2 Long term settlements

The simulations predict continued background creep settlements of 2 mm/year compared to InSAR measured settlement rates varying from 2-6 mm/year adjacent to the tunnel. Notably, settlements are on-going adjacent to the tunnel, i.e. in this case unloading has not had any major impact of reducing settlements in the area. This indicate that settlements take place also in the bottom parts of the clay layer and in reality there is a relatively sharp movement in the vertical tunnel-clay interface.

4 CONCLUSIONS

The analyses show that realistic predictions of the short- and long-term performance of excavations in soft clay can be obtained using advanced effective stress based soil models.

The trends of the horizontal and the vertical displacements are captured well by the simulations with the Creep-SCLAY1S model.

More studies are needed to investigate installation effects of sheet pile walls, pre-cast displacement piles, etc., and how these processes could be modelled to better capture the generated deformations and excess pore water pressures in soft sensitive clays.

Displacement due to installation of pre-cast concrete piles were modelled as cavity expansion in soil clusters aligned with the pile rows. An option to use a prescribed line displacement may be more numerically stable. Negative cavity expansion (volume outtake) was modelled down to level +3 (level at which piles where hammered down) due to pre-boring with a hollow cylinder.

This is probably to simplified since the effect of the cavity is smeared over the volume cluster in the numerical plane strain analyses and thus underestimates the soil's ability to arch around the cavities.

The M-values were based on undrained triaxial compression tests. This might, due to rate effects, result in high M-values. Preferably, the M_c (and M_e) values for effective stress analyses are derived from drained tests. Preliminary results of drained triaxial tests on comparable soil indicate good agreement between M_e-values derived from undrained and drained extension tests, whereas drained compression tests yield lower M_c-values compared to the undrained tests.

Further analyses are on-going in order to:

- Investigate the details of the construction process at the specific site, including for example the effects on consolidation etc. due to the installation of vertical anchors.
- Model the pile installation process in detail and adapt a robust way to model displacement piles in soft clay in FE.
- Compare FE-simulations with measurements of strut forces and earth pressures.
- Calibrate the model parameters, such as for example the hydraulic conductivity of the soil, against the field measurements of excess pore pressure variations with time.

5 ACKNOWLEDGEMENTS

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