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Experience from short- and long-term performance of deep excavations in soft sensitive clays

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Abstract. Design of excavations and permanent underground structures requires accurate predictions of e.g. deformations and earth pressures for both the short- and long-term. As excavation depths increase and/or the proximity to adjacent infrastructure decreases, there is a need to improve and develop existing design methods and validate numerical models. The first part of this paper revisits the measurement data from a previous excavation, the Göta Tunnel in Gothenburg, Sweden, in order to benchmark a contemporary constitutive soil model, called Creep-SCLAY1S. This study looks into time series including e.g. final dewatering of the excavation, followed by the development of pore water pressures, earth pressures and deformations over time (until 2 years after excavation). The model predictions are in general in good agreement with the measurement data up to final dewatering. However, installation effects due to drilling are believed to have caused continued deformations which are difficult to capture in the numerical model. Part two of the paper presents details of a recently instrumented excavation in soft clay in Central Gothenburg. The measurement data comprises e.g. pore water pressures, deformations as well as vertical and horizontal earth pressures at three locations under the permanent structure. Continued long-term measurements are planned and the existing and future data are believed to provide valuable insights on the development of the stress state and earth pressures under permanent structures in soft clay.

1. Introduction

The necessity for new infrastructure systems such as railway tunnels, underground water retention systems and buildings with deep basements in urban areas requires accurate predictions of earth pressures and deformations. Predictions are needed both for the short-term (construction period), as well as the long-term (the design life time of infrastructure constructions in Sweden typically being 100-120 years). This is of special importance in cities such as Gothenburg, with deep deposits of soft sensitive clay including significant ongoing background creep settlements that needs to be accounted for. Furthermore, as the limits are extended concerning for example excavation depths, the proximity to existing structures, increased awareness of sample quality control (entire chain from field sampling to laboratory testing), and hence higher utilisation of the soil strength and stiffness in design - research is required to develop, verify and possibly review existing calculation methods and guidelines. Part of such research includes validation of numerical models against full scale field measurements.

This paper consists of two parts; part one consists of a review of a previous excavation for a part of Göta Tunnel in Gothenburg. The purpose here is to benchmark a contemporary rate-dependent soil model against a previously well instrumented cross section of a underwater excavation in soft clay. This enables validation of the soil model response against the soil-structure response at field scale, as the model previously has been successfully validated at element level and at field scale for embankment loading. Tornborg et al. [1] presented initial analyses of the extensive monitoring data from the Göta Tunnel, comparing model predictions versus field measurements of horizontal and vertical deformations for primarily three stages of the construction process (up to final dewatering). This paper focuses on comparing model predictions versus complete time-series (in total ca 3 years monitoring) of pore water pressures, deformations and earth pressures.

Part two of the paper introduces a recently instrumented excavation in Central Gothenburg. As data collection is ongoing, some selected preliminary results are presented, including the methodology for the installation of vertical and horizontal total pressure cells under the slab. The purpose of the instrumentation is to measure and analyse the response of an excavation in a deep soft clay deposit (ca 90 m) looking into e.g. heave within the excavation. The main focus will be short- and long-term measurements of pore pressures, as well as the horizontal and vertical earth pressures under the permanent structure (bottom slab).

2. Göta Tunnel, cross section 1/430 north

2.1. Site description and construction works

Göta Tunnel and the studied cross section is located in Central Gothenburg, Sweden, just South of Göta River. The geology of Göta River valley is dominated by deep deposits of soft sensitive clay, reaching up to ca 100 m depth at most in Central Gothenburg. At the studied section, the ground surface is located at a level of +12. The soil conditions before excavation comprised of 2 m fill material on top. The soft clay layer extends down to level -16 in the location of the sheet pile wall (SPW) in the studied section. The (uncorrected) undrained shear strength of the clay is about 15 kPa in the top of the clay layer, and increases with ca 1 kPa/m towards depth. The sensitivity varies between 10-25 and OCR (over-consolidation ratio) between 1.1-1.4. For more details see [1]. Under the clay layer there are some meters of frictional material on top of the bedrock (granodiorite). Before the construction of the tunnel, the ongoing background creep settlements were in a range of 3-8 mm/year at the ground surface based on conventional surveying of the asphalted surfaces [2]. The current settlement rate just north of the tunnel is between ca 2-6 mm/year based on satellite measurements (InSAR), see Figure 1.

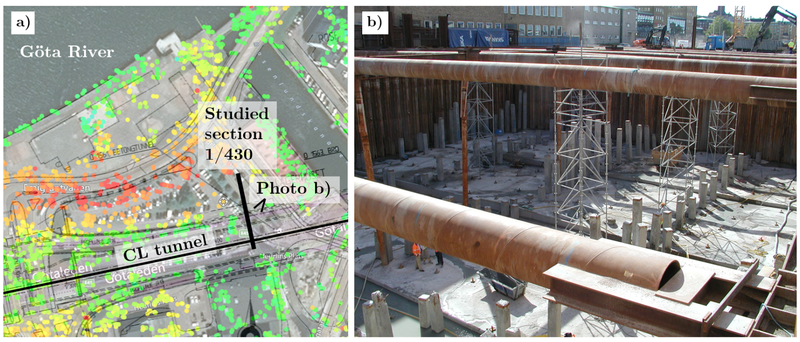

Figure 1. a) Overview of part of Göta Tunnel including data from satellite measurements, InSAR, indicating the current settlement rate (green=0 mm/year to red ≥10 mm/year) and b) Photo of the excavation after dewatering in August 2003.

The construction works started with the installation of sheet pile walls (AZ36, L=26 m) followed by pre-excavation to level +10 and installation of precast concrete displacement piles (0.4×0.4 m^2) to bedrock. Pre-augering was carried out down to level ±0 in order to minimise the deformations to the surroundings. The piles were hammered down to level ca +3, resulting in mass-displacement below level ±0 and outtake of volume above level ca +3. The excavation, including casting of a 0.7 m concrete slab, was carried out underwater. Before dewatering, the slab was anchored with vertical pre-stressed anchors grouted into bedrock. Measurements of horizontal and vertical deformations, pore water and earth pressures outside the excavation were carried out by Kullingsjö [3].

2.2. Analyses

Numerical predictions of the construction process were carried out with 2D finite element modelling using the Creep-SCLAY1S model. The model accounts for characteristic soft clay features such as rate-dependency, plastic anisotropy and destructuration. For model details see e.g. [4, 5, 6, 7, 8, 9]. The model parameters and values used for analyses are presented in Tables 1 and 2, and some element level simulations of laboratory data in Figure 2. No new laboratory tests were made for this study, so the laboratory data are based on [3]. The in-situ K_0 was set to 0.60 and K_0^{nc} to 0.42. The value of K_0^{nc} is rather low compared to what has previously been measured in laboratory tests on Gothenburg clay (range 0.50-0.55, see e.g. [3] and [10]). However, it results from a consistent set of the parameters M_c, α_0 and K_0^{nc} with respect to the critical state friction angle in compression. Since the presentation of [1], new incremental load (IL) oedometer tests were carried out by a consultant company for the foundation design of a new building block close to the Göta River. Although these IL tests were carried out on samples from deeper clay deposits than in the studied section, minor adjustments of relevant model parameters (λ_i^*, ω and μ_i^*) have been made compared to [1].

Table 1. Creep-SCLAY1S parameter values.

Parameter	Definition	Value
λ_i^*	Modified intrinsic compression index	0.085
κ_i^*	Modified swelling index	0.013
ν	Poisson's ratio	0.20
M_c	Stress ratio at critical state in compression	1.45
M_e	Stress ratio at critical state in extension	1.10
ω	Rate of rotational hardening	200
ω_d	Relative rate of rotational hardening	1.0
a	Rate of destructuration	8
b	Relative rate of destructuration	0.5
α_0	Initial anisotropy	0.56
χ_0	Initial amount of bonding	15
μ_i^*	Modified intrinsic creep index	0.0018
τ (days)	Reference time	1

2.3. Results and discussion

In Figure 3 model predictions and the measurements of horizontal deformations at the location of the SPW, and the total horizontal earth pressures 0.5 m behind the wall are presented for three stages; after pile installation, underwater excavation and final dewatering. As presented in [1], the model prediction captures the trend of the horizontal displacement relatively well, although the absolute values are off by ca 20 mm. This is considered to be an effect of e.g. the simplified (plane strain) modelling of the pre-augering and the pile installation. The prediction of the total horizontal earth pressures agrees well with the measurements.

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Table 2. Additional parameters of clay layers

Layer	Level [m]	ρ [t/m^3]	OCR [-]	e_0 [-]	$k_x = k_y$ [m/s]
1	+10.0 to +3.5	1.53	1.4	2.26	1E-9
2	+3.5 to +2.5	1.57	1.2	2.10	1E-9
3	+2.5 to -2.0	1.59	1.1	1.99	1E-9
4	-2.0 to -14.0	1.68	1.2	1.55	5E-10
5	-14.0 to -16.6	1.79	1.5	0.96	5E-10

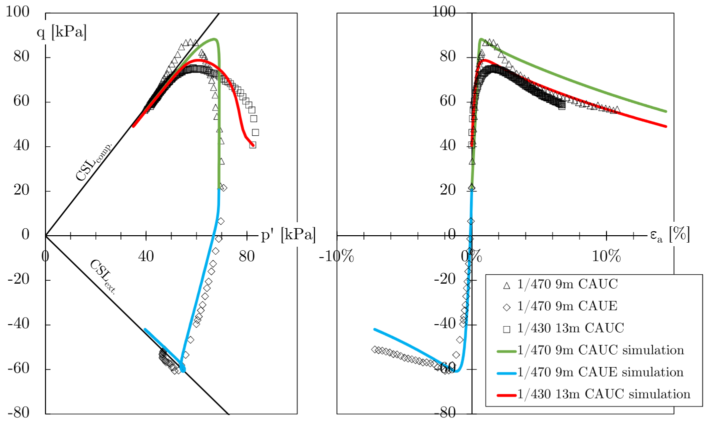

Figure 2. Anisotropically consolidated undrained compression (CAUC) and extension (CAUE) tests from sections 1/430 and 1/470 vs. simulations; (a) p'-q-space; (b) plot of ε_a-q. Test 1/430 was consolidated to $\sigma'_{vc(CRS)}/\sigma'_v$=0.94 before shearing, in the simulations OCR was set to 1.

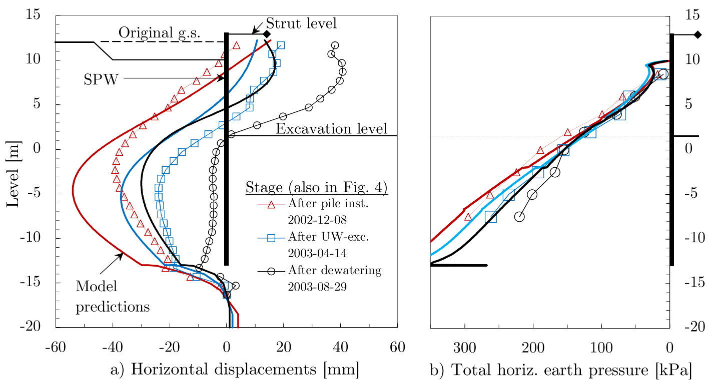

Figure 3. Comparison of measured and predicted a) horizontal displacements at location of SPW and b) total horizontal earth pressures 0.5 m behind SPW (for legend see figure a). Full lines indicate model predictions.

In Figure 4 the comparisons of the measured and predicted pore water pressures, earth pressures and horizontal displacements of the SPW, and at 9 m distance behind it, are plotted versus time. The results show that deformations continued to develop towards the excavation up to 6 months after the final dewatering, and also the vertical deformations (extensometers behind SPW) showed continued settlements. Detailed studies were made for possible explanations such as e.g. upward movement of the anchored 0.7 m concrete slab, extensive lowering of the pore water pressures, unbalance/shift of the entire earth retaining system, as well as doing a second round of going back to the project log-books and photos. Our conclusion to this date is that the continued deformations were caused by installation effects of the vertical anchors within the studied section, as well as tie-back anchors and circular solid steel piles in an adjacent part of the excavation for the tunnel. Installation of the vertical anchors (∅36 mm rods) within the studied section was carried out using ODEX drilling (ca ∅90 mm casing tubes). This may have caused

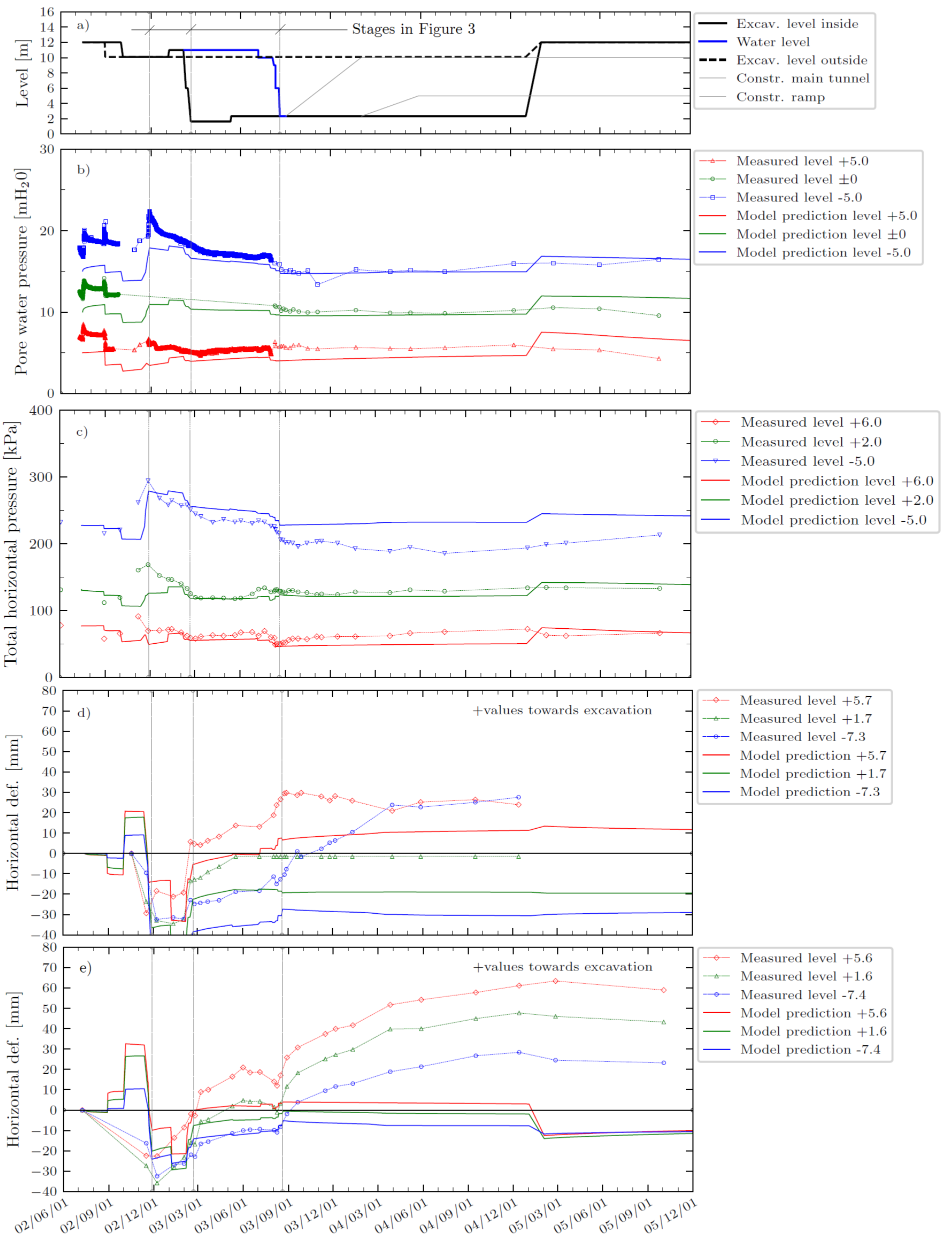

Figure 4. Time-series for a) construction sequence as well as selected levels of measured versus predicted b) pore water pressures 5.5 m behind SPW, c) earth pressure 0.5 m behind SPW, d) and e) horizontal deformation at SPW respectively 9.0 m behind SPW.

disturbance/destructuration of the sensitive clay and increased pore water pressures, in addition to possible disturbance and volume loss in the friction material under the clay layer. Similar effects were noted in field trials that investigated drilling installation effects in the Norwegian project BengrensSkade, see [11].

Finally, the current ongoing background settlement rate was predicted to a maximum of ca 4 mm/year in the studied cross section, as compared to satellite measurements varying between ca 2-6 mm/year adjacent to the tunnel in the studied section, which is most satisfactory.

3. Recent instrumentation at the Nils Ericsson site

This part of the paper describes the instrumentation and some preliminary results from ongoing field measurements. The aim of the instrumentation has primarily been to measure the vertical and horizontal earth pressures, pore water pressures and deformations under the bottom slab. The measurements in the current construction phase are the basis for continuing long-term measurements.

3.1. Site description, construction works and instrumentation

The instrumented excavation is located in Central Gothenburg, see Figure 5. The excavation is carried out to build a tunnel, on top of which trams and buses will connect to the new Hisings Bridge (currently under construction) across Göta River. The level of the ground surface varies between ca +3 to +4. The excavation depth is ca 5 m compared to the level at the perimeter of the excavation/SPW and maximum ca 7 m compared to the level of the embankment/ramp, West of the excavation, which connects to the old bridge (Göta River Bridge).

At the studied site the soil conditions before excavation comprised of ca 3-4 m fill material on top of a layer of soft clay, extending down to ca 90 m depth. The (uncorrected) undrained shear strength of the clay is ca 20 kPa in the top of the clay layer, and increases with ca 1.5 kPa/m towards depth. The sensitivity varies between ca 10-20 (the lower values towards depth). OCR varies from just above 1.0 in the top part of the clay layer (due to the proximity and surcharge from the embankment/ramp to the old bridge), and increases linearly to ca 1.3 at level ca -30 to -40 and below. Based on the satellite measurements, the ongoing settlement rate before excavation varied between ca 2 mm/year to a local maximum ca 7 mm/year.

Figure 5. Location of the recently instrumented excavation in Central Gothenburg. In the left picture also the Göta Tunnel site described in Section 2 is pointed out, to the lower left.

The construction works started with installation of piles (11.5 m top element of steel pipe ∅323.9-12.5 mm and 45.5 m pre-cast concrete pile elements 0.27x0.27m^2). Pre-augering was carried out to 18 m depth and the piles were then hammered down to levels just above final pile head level. The sheet piles (PU12 and AU23, L=14-20 m) were then installed, followed by the excavation and the installation of struts at two levels. The excavation to final depth was carried out in smaller sections, which were immediately and successively supported by casting of a concrete working platform, see Figure 6. Once this working platform was completely cast, the lower strut level was removed. Field measurements of horizontal and vertical deformations, pore water pressures, strut forces, as well as horizontal and vertical earth pressures under the bottom slab, were performed and are planned to be continued after the completion of the construction works (i.e. long-term measurements). A selection of some preliminary measurement results is presented in the following section.

Figure 6. Excavation to the final depth started from north (right in the photo). Photo taken 2019/06/05 from tower crane.

3.2. Preliminary results and discussion

Vertical and horizontal deformations were measured using earth anchors and a bellow-hose inside the excavation, as well as inclinometers behind the SPW. The bellow-hose measurements started in December 2018, before the installations of the piles. Measurements of vertical deformations were registered every 1.0 m throughout the bellow-hose, which was installed to ca 40 m depth centrally inside the excavation. 24 individual measurements have been made, for clarity simplified trendlines are shown in Figure 7 a) for five construction stages. As the bottom level of the bellow-hose ”floats” in the clay layer, the reference level of a customised tripod, see Figure 7 b), was established by surveying for each individual measurement setup. In particular, the dramatic effect of the pre-augering can be noted. The deformations during the pile installation were thus indeed reduced at the level of the ground surface. However, the settlement/collapse of the soil down to ca 18 m depth reveals that severe disturbance of the clay may occur adjacent to deep pre-augering in soft clay.

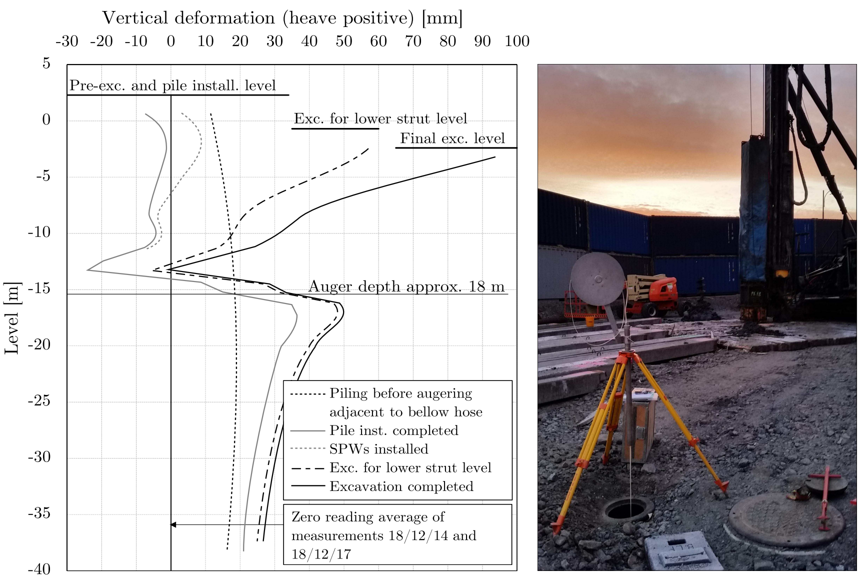

Figure 7. Results of bellow-hose measurements (left) and tripod for ”floating” bellow-hose (right). The reference levels were established by surveying for each measurement setup.

Piezometers (including thermistors) and total earth pressure cells were installed in the soft clay, below the level of the bottom slab, at three locations with different distances to the SPWs in a section centrally within the excavation. The installations were carried out immediately after excavation to the final depth, just before casting of the concrete working platform. This enabled continuous monitoring of pore water pressure, temperature as well as vertical and horizontal earth pressures immediately after the excavation reached the final depth. This was done in order to measure the development of earth pressure with time, including the stress paths and K_0 during the unloading and the subsequent reloading. In addition, an extensometer was installed to continuously monitor the relative movement of the bottom slab and the clay. The extensometer head was cast in the bottom slab and the bottom anchor (grouted spider anchor) was installed in the clay at a depth of 1.65 m below the slab. All installations were preceded by a number of "trial installations" at site, in order to develop a method for the installation of the instruments, and to ensure that the installations would work satisfactory, before the instrumented section reached final depth. The critical time with respect to ongoing construction activities was from reaching the final depth, until casting of the working platform over the instruments. In addition, verification of the unique calibration factors for all instruments, as well as the set-up for the data logger and channels, was carried out in a controlled laboratory environment at the ACE laboratory at Chalmers University of Technology.

The measured effective stresses under the centerline of the bottom slab are presented in Figure 8. The basis for these data are the measurements of pore water pressures (at level -3.1), as well as total stress in the vertical direction (cell flat at level -2.7) and horizontal direction (centre cell at level -3.3 and perpendicular to the SPW). The measured total stresses have been adjusted to the level of the piezometer. The in-situ vertical effective stress before excavation was approximately 75 kPa at this level. It can furthermore be mentioned that at the time for casting the bottom slab (t=1.0 m) an increase in the temperature of ca 15°C, ca 10-15 kPa increase in pore water pressure and ca 25 kPa increase in vertical total pressure were measured in the centerline of the excavation. Closer to the SPWs, a smaller increase in vertical total stress was measured, which most likely was caused by the fact that the weight of the wet concrete was partly carried by the concrete working platform, which was more or less constrained in-between the SPWs. Altogether, the registered values during the casting of the bottom slab (weight of the wet concrete) provided good indications on the performance of the instrumentation. Detailed presentation as well as analyses of measurement data will be performed in the ongoing PhD project at Chalmers University of Technology.

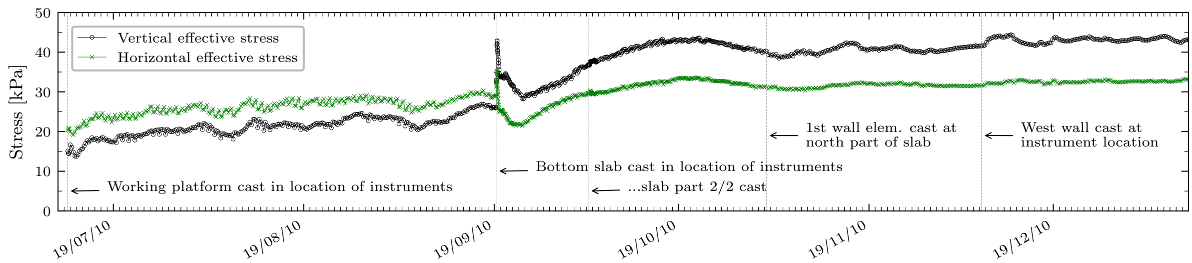

Figure 8. Preliminary results presented as time-series of vertical and horizontal effective stresses under the bottom slab in the approximate centerline of the excavation (one of three locations in one section).

4. Discussion and Conclusions

The first part of this paper dealt with benchmarking of the Creep-SCLAY1S model against a well instrumented cross section, 1/430, of Göta Tunnel in Gothenburg. The comparison of measurement data and model predictions revealed the following:

- Relevant short and long-term predictions of earth pressures and deformations acting against earth retaining and permanent underground structures are enabled by constitutive soil models accounting for the necessary features of soft natural clays, such as e.g. rate dependency (including background creep settlements), anisotropy and destructuration. Using an appropriate advanced effective stress based model simplifies the analyses as only one model and parameter set are needed for the predictions of the short term (construction period, normally the contractors focus) as well as the long-term performance (normally the clients focus).

- Excavations are complex problems to model, given the proximity to existing/historic buildings and infrastructure. Also, installation effects from pile driving and pre-augering may change the stress state in the clay layer before the excavation even has started. Furthermore, the construction sequence involves many details, which causes challenges in estimating the final time-steps beforehand. However, such challenges could be overcome if the contractor, the client and the designer work in collaboration early on and continuously during the projects, and update the numerical predictions based on the changes in construction sequence.
- Continued horizontal and vertical deformations were registered after final dewatering in the studied section. These deformations were likely caused by the installations effects resulting from the installation of vertical anchors within the excavation, as well as the tie-back anchors and the circular solid steel piles in an adjacent part of the tunnel. The measurements reveal that such effects can have a significant impact on the deformations, and that the effects are difficult to predict and model. The effects may also be operator dependent. Care should thus be taken in the choice of construction and installation methods.

The second part of this paper described the recent field measurements and instrumentation of an excavation as part of the new Hisings Bridge in Gothenburg. To summarize the preliminary results and experiences so far:

- The performance of the instruments with automated logging under the bottom slab were validated by the measured values during pouring of the wet concrete (1.0 m thick slab).
- The temperature in the clay under the bottom slab increased by ca 15°C after casting of the slab. This may cause an installation effect with respect to temperature, which might be exploited in the case of using underground structures (e.g. tunnel walls or basement slabs) for geothermal storage.
- As the excavation was recently instrumented, continued measurements and analyses will be carried out as part of an ongoing research project at Chalmers University of Technology.

In summary, the paper presented examples of two excavations where deformations and earth pressures were measured. The recent instrumentation of the excavation adjacent to the new Hisings Bridge is rather unique, since it will focus on the response under the permanent structure and not only during the construction. This is considered to provide valuable insights on the development of the stress state and earth pressures against underground structures in soft clays.

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