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Monitoring the long-term hydro-mechanical response below an excavation bottom in sensitive clay

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Abstract

Traditional monitoring solutions as part of construction works are often insufficient to extract the information required for the development of advanced numerical models. In the current work, a conventional instrumentation plan designed for control monitoring is extended to investigate the hydro-mechanical soil response below an excavation bottom in sensitive clay. This required the installation of instrumentation clusters, that were equipped with earth pressure cells, piezometers and an extensometer, so that the evolution of the total and effective stress, as well as the vertical displacements of a soil element below the excavation bottom could be quantified. The instrumentation was installed during the construction of an underground structure in soft sensitive clay. A such, the measurements were validated against known load history during the construction stage before the phase of long-term monitoring of evolving (effective) stresses and displacements during the serviceability phase. The time series of over 3 years of data revealed long-term seasonal temperature variations, affecting the sensors located beneath the structure and in the clay. This required careful evaluation of the results from the instruments, which all were of the vibrating wire type, and especially the hydraulic earth pressure cells. Other than providing unique data for benchmarking numerical analyses, results indicate that the stress ratio $K'=\sigma'_h/\sigma'_v$ during unloading approximately follows the relationship reported in literature that is based on laboratory studies. Finally, the research highlights the inherent difficulty in *in-situ* monitoring over long periods of time. However, with careful design and aided by thorough calibration and (numerical) analyses the data provides new knowledge on the evolving (effective) stress during the construction and serviceability phase below the bottom of an underground structure in sensitive clay.

Keywords: sensitive clay, earth pressure, excavation, construction, serviceability

1. Introduction

Monitoring is a vital part when constructing excavations in urban environments. However, traditional monitoring programs typically focus on controlling the global system response and/or to document the (hopefully limited) impact to specific parts of the surrounding infrastructure. Furthermore, design and consequently monitoring programs may be based on geotechnical modelling informed on rudimentary geotechnical site characterisation, as pointed out by Karlsrud & Andresen (2008). However, complementing traditional "control" monitoring programs with more detailed site investigations and additional instruments provides a means to extract more knowledge of full-scale soil-structure interaction. The additional investigations and more extensive monitoring performed for Göta Tunnel (Kullingsjö, 2007) was instrumental for benchmarking a contemporary constitutive soil model (Tornborg et al. 2021). The site investigation data was sufficient for calibration of the constitutive model used, whereas the monitoring data allowed to benchmark the numerical model at boundary value level against the full-scale system response of a deep excavation in soft sensitive clay during the construction phase. The monitoring data at Göta Tunnel, however, did not provide the information required to revise the constitutive model for the unloading regime. That requires a monitoring plan with clustered instruments that allows to extract the (incremental) response in terms of (effective) stress and displacements *in-situ* at soil element level. Furthermore, an open research question for construction activities in sensitive clays found in the Nordic countries requires more data on the evolution of (effective) stresses for excavation projects, both during the construction phase and including the (long-term) serviceability phase, as such reports are scarce.

This paper presents an example of how traditional control monitoring programs can be complemented with additional instrument clusters to gain better understanding of the hydro-mechanical response of soft clay, i.e. in this case the evolution of (effective) stresses and $K'=\sigma'_h/\sigma'_v$ over time in full-scale in the field below a tunnel/slab. The data thus complements previous laboratory and numerical studies that investigate the evolution of the stress ratio $K'=\sigma'_h/\sigma'_v$ (e.g. Schmidt 1966, Mayne & Kulhawy 1982, Watabe et al. 2003, Kullingsjö

2007, Grimstad et al. 2021). In addition to knowledge on the *in-situ* evolution of *K'*, the clustered instrument data provides a basis for benchmark simulations studying earth pressures from the construction to the serviceability stage. Furthermore, it may provide data and insights on e.g. effective heave pressures against slabs, a design question recently studied (Tornborg, 2017) and for which Simpson (2018) considered monitoring data to be very valuable.

2. Site and soil characterisation

A construction site in Central Gothenburg, Sweden, was selected for the installation of additional instrument clusters to study the evolution of the horizontal and vertical (effective) stress and their ratio. The site, shown in Figure 1, was selected for two reasons; the clay layer of the site is well characterised and, the contractors traditional monitoring program provided a strong basis to complement with, among other, instrument clusters for research purposes. However, to minimise impact on construction activities, a limitation was set to three clusters in one cross section (outlined in Figure 1) of the excavation/structure.

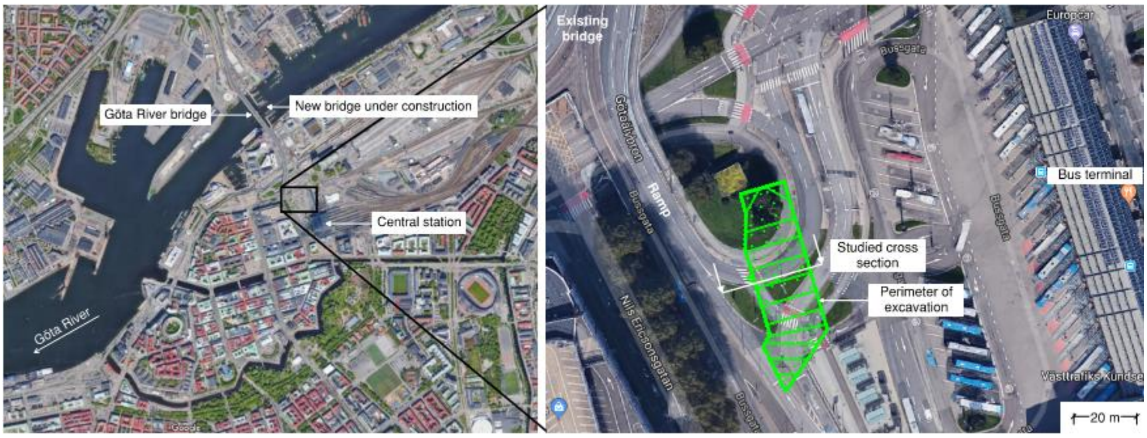

Figure 1: Location of instrumented site in Central Gothenburg, Sweden.

The geology of Central Gothenburg is dominated by deep deposits of soft sensitive clay, reaching depths of 110 m along the Göta river. At the instrumented site, a 3-4 m thick layer of fill lays on top of ca. 90 m homogenous clay. Index properties of the clay layer are presented in Figure 2. The undrained shear strength increases linearly with ca. 2 kPa/m from ca. 20 kPa in the top parts and the sensitivity varies from 10-30. The overconsolidation ratio varies from 1.1-1.3 and prior to construction InSAR satellite data showed ongoing settlements at the ground surface of 2-7 mm/year in the area.

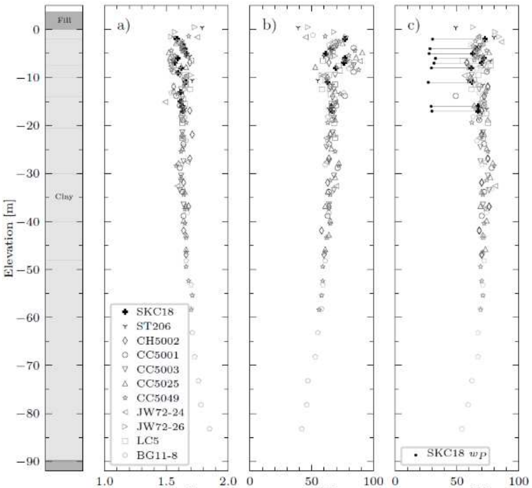

Figure 2: Index properties of the clay layer; (a) bulk density (b) natural water content (c) plastic and liquid limit.

3. Permanent and earth retaining structures

The permanent and earth retaining structures are presented in Figure 3. The permanent structure is a combined bridge abutment (for a newly constructed bridge over the Göta river, opened to traffic in 2021) which also will function as an access tunnel to a nearby shopping mall. The foundation consists of rows of 57 m long friction piles and a 1.0 m thick reinforced concrete slab. The piles were installed before the installation of sheet pile walls (SPWs) and subsequent excavation. Pre-augering was carried out to 18 m depth at each pile location to minimise mass-displacements to the surroundings. The excavation was carried out sequentially with successive casting of a 0.15 m fibre reinforced concrete working platform, which also acted as a support level for the retaining walls. As seen to the right in Figure 3, the excavation is located close to the ramp (part of which was founded on wooden piles) leading up to the old bridge across the Göta river. The excavation depth of the instrumented section was thus ca. 7 m to the west and 6 m to the east, resulting in a maximum of ca. 100 mm heave of the excavation bottom before the 1.0 m thick concrete slab was cast.

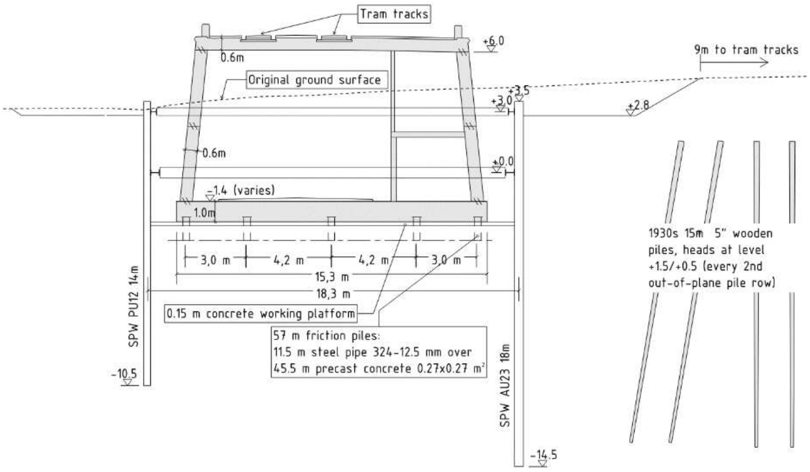

Figure 3: Permanent and retaining structures (see Figure 1 for location of cross section).

4. Layout of monitoring and installation of sensors

As mentioned previously, the client and contractor had a baseline program in place for the traditional control monitoring of the system response and impact to the surroundings. This entailed three inclinometers (in casings welded to the SPWs and extending down to their toes), surveying points and monitoring of strut forces. Combined they provided a sound base for additional instrumentation targeting specific research questions. However, to also gain a better understanding of the system response, additional "un-clustered" instrumentation was added by Chalmers University of Technology (see Figure 4 for locations):

- Piezometers (BAT-type) installed at various depths in the clay layer in- and outside the excavation
- Inclinometers in a casing installed in the clay layer and to greater depth than the toe of the SPW
- Extensometer of type bellow-hose (Bozozuk & Fellenius, 1979)

This equipment was installed prior to piling, SPW installation and excavation and thus provided knowledge on the system response during the entire construction phase.

Additional instruments were installed for addressing the specific research question on the evolution of (effective) stresses and their ratio during the construction as well as the serviceability stage. Therefore, in one section, instrument clusters were installed at three locations (with varying distance to the SPWs) containing:

- Earth pressure cells (EPCs) to monitor vertical as well as horizontal (total) stresses
- Piezometers for the measurement of the (absolute) porewater pressures
- An extensometer (in one location, close to the centremost cluster) to monitor the vertical relative displacement of clay-slab

These sensors were manufactured by RST Instruments and equipped with vibrating wire (VW) type transducers and connected to a datalogger (RST DT2040) using unspliced cables. The EPCs (item no. LPTPC09-V-LP) are hydraulic 24.1 cm diameter cells with a range up to 350 kPa and calibrated accuracy 0.15% F.S. The piezometers (item no. VW2100) have a range up to 350 kPa and accuracy of 0.10% F.S. Verification of supplied calibration factors was made in the Geotechnical laboratory at Chalmers University of Technology. This encompassed submerging the sensors in water tanks and applying pressure. For the EPCs no attempt was made in the laboratory to study apparent earth pressure changes due to thermal volume change of the hydraulic cell fluid. This topic is further elaborated in Section 4.1. The VW extensometer (consisting of items no. EXINLINE-1100, EXIL-0500, EXIL12000) has a range of 75 mm compression and 25 mm extension with an accuracy 0.25% of F.S.

The gauge length is 1.325 m from the middle of the anchor body up to the concrete working platform to which the extensometer head is cast into.

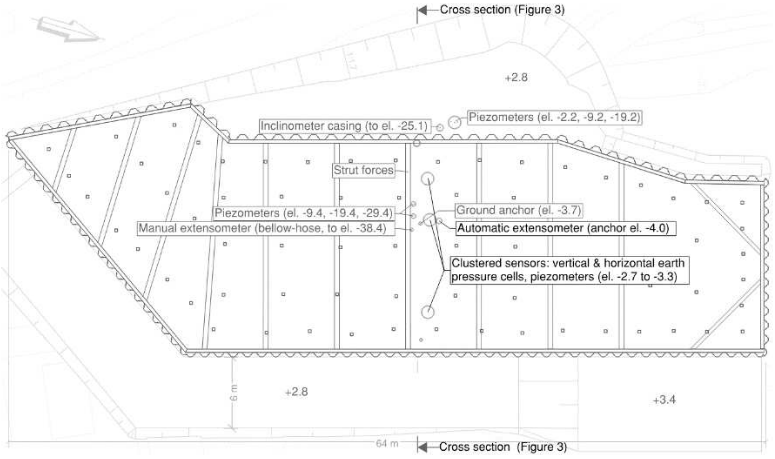

Figure 4: Layout of monitoring. Note: additional inclinometers and surveying points as part of the contractors control monitoring program are not included.

The sequential excavation was completed on June 26th 2019 in the instrumented section. Three well rings were placed on top of plastic film placed on the clay surface. The working platform was cast around these rings, i.e. slots were allowed for installation of the instrument clusters. Sensors were installed 28-29th of June and then concrete was cast within the well rings. All cables connecting the sensors to the data logger are routed through plastic tubes that had been cast into the working platform.

The sensor installation procedure (repeated in the three cluster locations) is described in brief in the following. The plastic film (preventing the exposed clay surface from drying and/or wetting) was cut and 2-3 cm clay removed by hand excavation to expose a fresh clay surface. A vertical cut 0.5 m deep and 0.1x0.3 m^2 wide was dug out. At the bottom of this cut an 8 mm trench was made for the installation of the EPC for monitoring the horizontal stress parallel to the SPWs. The trench was created using a custom-made blade penetrometer. This procedure, and all other details, were refined after trial installations at the site in the first parts of the sequential excavation process. The trials were carried out to ensure that the final installation could be carried out according to a working order with details tested in practice, as well as during as short time as possible (to minimise delay to construction works but also to prevent the clay from drying or wetting). The piezometer was installed in the face of the vertical cut before backfilling with remoulded clay. The EPC for monitoring of vertical stress was placed into a circular hole, 3 cm deep, filled with 10 mm gravelly sand (mean grain size 0-4 mm) for levelling. Another 10 mm sand layer was placed on top of the cell, as well as plastic film to prevent mortar going into the sand when the working platform was cast over the allocated slots. In addition to the trial installations, a key to successful installation and keeping the monitoring equipment "alive" was being present at site during critical stages (including e.g. hand shovelling around equipment). The first author being part of the organisation was certainly beneficial as well as engaging the workers at site with the purpose and benefits of the monitoring.

4.1 Temperature effects

Hydraulic earth pressure cells are susceptible to apparent earth pressure variations resulting from thermal volume change of the cell fluid. The temperature effect will, among other factors, depend on the *in-situ* confinement of the cell (Dunnicliff, 1993). As such, temperature compensation based on laboratory studies of change in apparent earth pressure due to change in temperature is of limited value. An empirical approach (e.g. Yang et al. 2001) could be possible. Temperature compensation is then, ideally, extracted from monitoring periods with constant stresses but change in temperature. The problem being identifying periods of constant stress in a static physical environment where only the temperature changes – and assuming that changes in temperature do not affect actual physical changes. For these reasons, the plots in Section 5 include results presented as with; i) no temperature compensation ii) temperature compensation only for the VW transducer itself (CT_{vw} as supplied from the manufacturer) and iii) as ii) but also introducing CT_{cell}, compensating for volume change of the cell fluid according to a theoretical approach (Sellers, 2000). For our case, Sellers' approach gives CT_{cell}=0.15 kPa/°C for embedded cells (the cells monitoring horizontal stress) and 0.3 kPa/°C for contact pressure cells (in this case taken as the cells monitoring vertical stress). These CT_{cell} are based on estimates of G_{max} and monitored strain (thus degradation) after completion of the excavation. In reality, the soil had strained during the excavation process and thus the CT_{cell} estimates likely are upper bounds. The grey ranges in Section 5, Figure 5, fill the range from i) to iii), whereas ii) lie in between these and is plotted as black lines.

5. Results

The results for the monitored stresses and pore pressures in the centremost cluster, including vertical strain, below the slab are presented in Figure 5 including annotations of major construction activities. The ranges in grey are included for transparency, to outline temperature compensation according to Section 4.1, and hence possible lower and upper bounds for apparent earth pressure variations. The presented results herein cover the period June 2019 to October 2021. July 2020 marks the end of major construction activities for the monitored structure.

A possibility for verification of the monitoring set-up, installation and sensor response was provided when part 1/2 of the slab was cast over the sensors on September 10th 2019 (24 kPa load from 1.0 m wet concrete). The registered increase in vertical total stress was 26 kPa in the centremost cluster (13 and 15 kPa in the West and East clusters). The smaller load registered closer to the SPWs is believed to be due to the concrete working platform being "locked-in" between the SPWs, thus possibly transferring parts of the load to the SPWs.

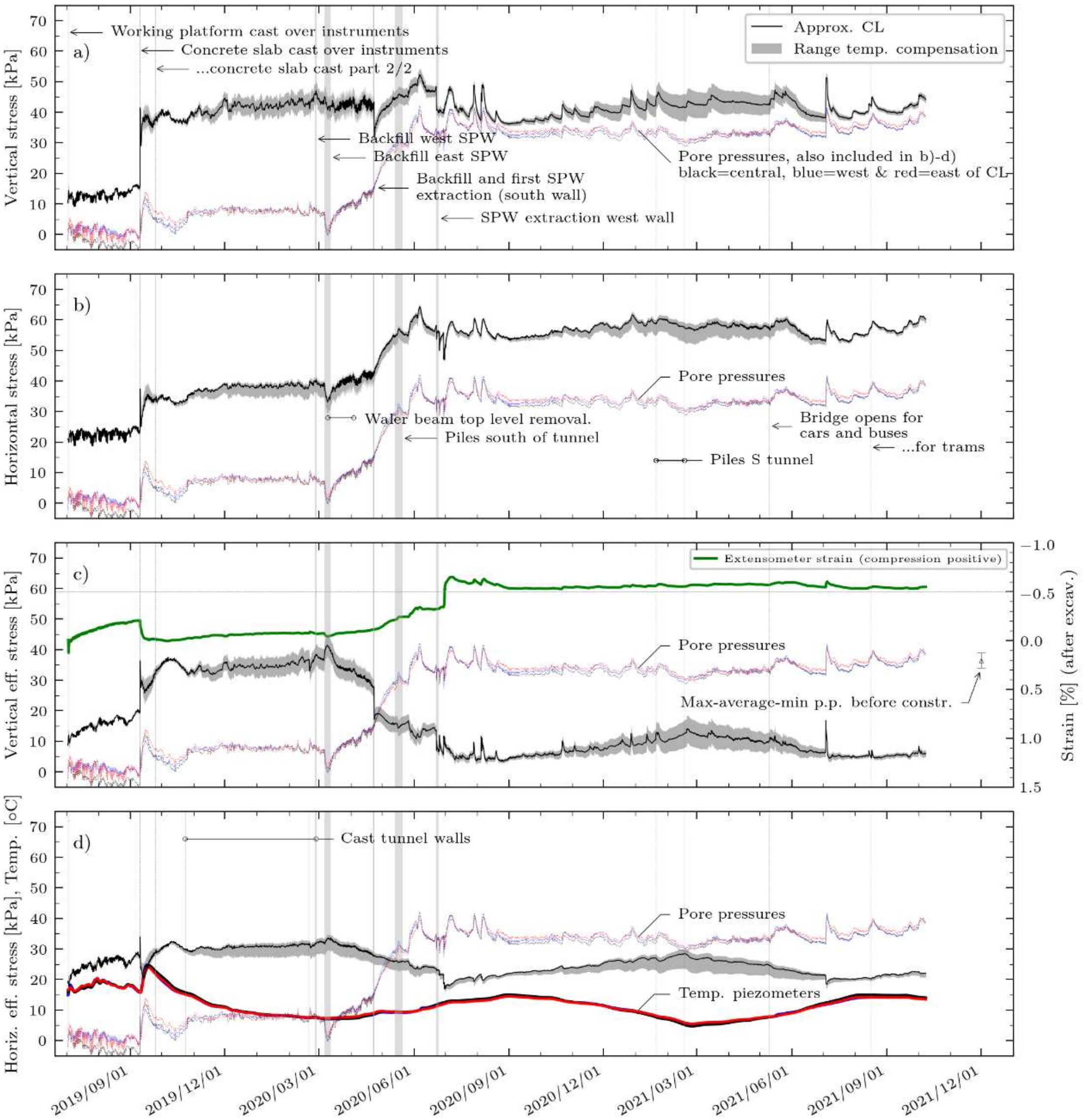

Figure 5: Results of monitoring in centremost cluster below the slab; (a) vertical total stress (b) horizontal total stress (c) vertical effective stress and extensometer strain (d) horizontal effective stress and temperature as recorded in the piezometers. Pore pressures measured in all clusters are included in (a)-(d).

The results of Figure 5 indicate that the total and effective stresses increase with time following the casting of the concrete working platform and the slab. However, in March 2020 the pore pressures started regaining to pre-construction levels (indicated in Figure 5c) due to backfilling between structure-SPWs and first SPW extraction. The increase in pore pressure resulted in a decrease in effective stresses, whereas the total vertical stress remained fairly constant, and the total horizontal stress increased. Extraction of the SPWs perpendicular (west) to the instrumented section (in the end of June 2020) resulted in a rather abrupt tension/strain registered by the extensometer. This was not anticipated, but may possibly be due to an “Poisson’s ratio effect” i.e. the clay “plug” under the structure temporarily lost its horizontal support when the SPWs were extracted. The analyses of the corresponding stress paths are still ongoing. A preliminary evaluation is presented in Figure 6.

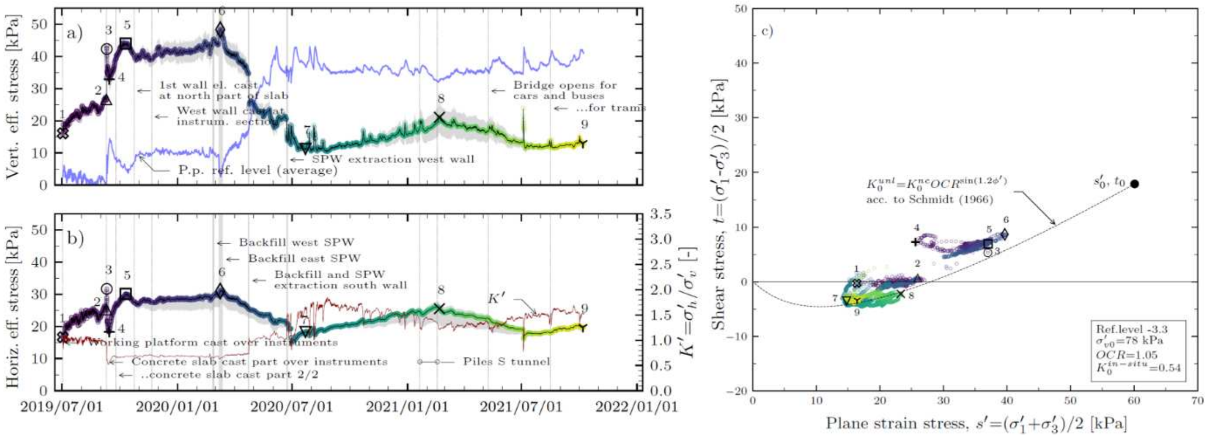

Figure 6: Evaluated (a) vertical and (b) horizontal effective stresses including *K′* and (c) associated stress path for the centremost instrument cluster below slab (cluster reference level -3.3).

Plotting the results as in Figure 6 and comparing *K*′ to Schmidt (1966) requires e.g. the following assumptions; the EPCs are assumed to be aligned with the directions of the principal stresses, the monitored stresses are offset to a common reference level (since the piezometer, vertical and horizontal EPCs are not located at the exact same level). However, keeping these assumptions in mind, the initial analyses of the centremost cluster indicate that the effective stress path approximately align with the relationship for *K′* during unloading as presented by Schmidt (1966). Ongoing work include Finite Element simulations of the temporal hydro-mechanical response during excavation, construction and serviceability phases.

6. Discussion and Conclusions

Traditional monitoring programs are typically intended for control of the system response and deformations to the surroundings. Such programs can provide a source of added knowledge on the hydro-mechanical response of soil *in-situ* if, as this paper demonstrates, they are complemented with; proper site characterisation and additional instrument clusters targeting specific research questions. Regardless, for complex geotechnical systems, thorough analyses and numerical modelling before, during and after monitoring has been completed, greatly enhances the value of the monitoring data and forms the first step towards generalisation of the observed response.

This paper presents an example of how a traditional monitoring program was successfully complemented with additional instrumentation clusters to gain increased knowledge on the hydro-mechanical behaviour of soil and soil-structure interaction. In this case, clustered sensors of piezometers and earth pressure cells targeted the evolution of stresses and $K'=\sigma'_h/\sigma'_v$ below a tunnel/slab in soft clay. Some keys to successful installation of the instruments and keeping the monitoring equipment “alive” were; careful planning including trial installations of the clustered instruments, being present at site during critical construction stages, engaging the workers at site with the purpose and benefits of the monitoring.

The full-scale field monitoring results, although challenging due to e.g. temperature compensation, as outlined in Section 4.1, provides unique new data and knowledge on the evolution of *in-situ K′*. These preliminary findings reinforce the results derived from prior laboratory and numerical studies published in literature (e.g. Schmidt 1966). Our experience is that clustered instruments, as a complement to instruments for conventional control monitoring, provide valuable additional insights on the hydro-mechanical response of soil at element level *in-situ*. This greatly aids the benchmarking of numerical simulations at boundary value level.

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