MONITORING REQUIREMENTS FOR LARGE SCALE EXCAVATIONS IN GOTHENBURG

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KEYWORDS

Accuracy, Deep Excavation, Jet Grouting, Monitoring, Railway, Retaining Walls, Soil Movements, Surveying

ABSTRACT

The excavation and foundation work of Västlänken lot E05 Korsvägen is performed in conditions characterized by varying geology, neighboring buildings and public infrastructure along the alignment. The deep excavation pits do not only need to meet structural requirements but often also require watertightness. Several different special foundation methods are used to address the respective technical and economic constraints, e.g. drilled and driven steel piles, secant bored piles, diaphragm walls and sheet piling. In general, the very soft clay within the excavations needs to be stabilized to enable foundation works and the subsequent excavation of the naturally highly thixotropic soil.

To prevent critical settlements and movements in adjacent buildings and infrastructure that remain in operation throughout the construction period, strut systems are used for bracing the excavations. Wall deflections and settlements are monitored in an extensive control program using levelling and surveying stations. In addition, multiple inclinometers, distance meters and extensometers are monitored. For load monitoring in struts, different sets of strain gauges are used. With a system of wells, the ground water level is monitored, evaluated, and controlled by infiltration. Monitoring results are presented together with a discussion on accuracy and relevance in requirements, in relation to expectations of different actors, based on experiences from the project.

1. INTRODUCTION

For the development of the public transport infrastructure of West Sweden, the Swedish Transport Authority Trafikverket builds an 8 km long double lined railway track in the city of Gothenburg. The southernmost 3.2 km of the

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alignment are executed in the lot “E05 Korsvägen” by the Joint Venture “WLC – West Link Contractors” consisting of the Swedish contractor NCC and the German contractor Wayss & Freytag.

As part of the lot “E05 Korsvägen” the excavation pit of Almedal is located within the vicinity of an existing live railway on one side and the highway E6 on the other side connecting Gothenburg with Malmö/Copenhagen (Figure 1). Due to the sensitivity of the existing infrastructure a robust retaining structure along with extensive ground movement monitoring is required. Besides a brief display of the given soil conditions and chosen retaining structures, predicted deformations and ground movements are to be discussed in comparison with the monitored movements and stresses. Along with this comparison, challenges connected to the operation of monitoring systems within the construction field and the interpretation of the retrieved monitoring data are examined.

Figure 1: Live railway next to the strut supported deep excavation for the Västlänken-tunnel.

2. DESIGN BASE: HYDROGEOLOGY AND BOUNDARY CONDITIONS

The soil stratigraphy in the Almedal tunnel area mainly consists of soft clays and an underlaying frictional material laying on bedrock. The clay is mostly sensitive, or even quick, to varying depths between 7 m to 20 m. The frictional material consists of grain sizes from fine sands up to coarse boulders, located in a layer of up to 5 m thickness on top of the bedrock (Figure 2).

The hydrology is mainly characterized by two aquifers, one close underneath ground level and the other one confined underneath the clay layer. Due to the sensitivity of the neighboring infrastructure and buildings and the immediate impact of ground water level changes related to the foundation and excavation works, strict tolerances are to be maintained.

The design is based on finite element modelling in Plaxis 2D. The untreated clay on the active side is modelled with the NGI-ADP material model. The input for the undrained shear strength s_u^{DSS} is 16 kPa and the stiffness E ~ 10 MPa, both increasing by depth. The clay stabilized with lime cement columns (LCC) on passive side, and the frictional soils in fill and bottom layers, are modelled as Mohr-Coulomb material. The input for the LCC's undrained shear strength c_u is 100 kPa and the stiffness E ~ 40 MPa, both constant by depth and time [1].

The connection of the sheet pile to the bedrock through rock dowels is modelled as a fixed point at top of rock, with no moment restraint [2].

Figure 2: Illustration of the soil stratigraphy in Almedal

3. EXECUTION OF GROUND AND FOUNDATION WORKS

Prior to the foundation and excavation works and related utility relocation in Almedal, three railway tracks are to be demolished and two of them are rebuilt next to the planned work site.

The retaining structure of the discussed excavation pit in Almedal consists of sheet pile walls AZ42-700 driven to bed rock supported by dowels embedded into bedrock at the wall's toe, see Figure 3.

To enable a sealed excavation pit the transition zone between sheet pile toe and top of bedrock is treated with jet grouting. Further, a curtain of rock grouting is installed underneath the sheet pile wall. To mitigate groundwater drawdowns caused by residual water seepage into the pit, several infiltration wells are installed and operated around the work site.

Before the start of excavation works, the clay inside the later pit is stabilized using dry deep soil mixing (DDSM) installed in a pattern of side be side lime cement columns (LCC) bringing a coverage rate of almost 100%. Stabilizing the soil makes the soft clays solid with strengths of approximately 100 to 500 kPa, and therefore facilitate excavatable material, without liquification of the clay. Besides the practical effect for excavation, the stabilized clay block is utilized to reduce the horizontal deflections of the retaining walls during excavation.

The excavation to final level is performed in stages along with the installation of up to three strut layers including double HEB-steel waling beams. Each level of the strutting system ranges for the waling beams from double HEB 600 up to double HEB 1000; the steel pipe struts are varying from diameter 600 mm up to 1220 mm with wall thicknesses from 22 mm up to 32 mm. The struts are installed with a center to center spacing of 7.0 m in longitudinal direction.

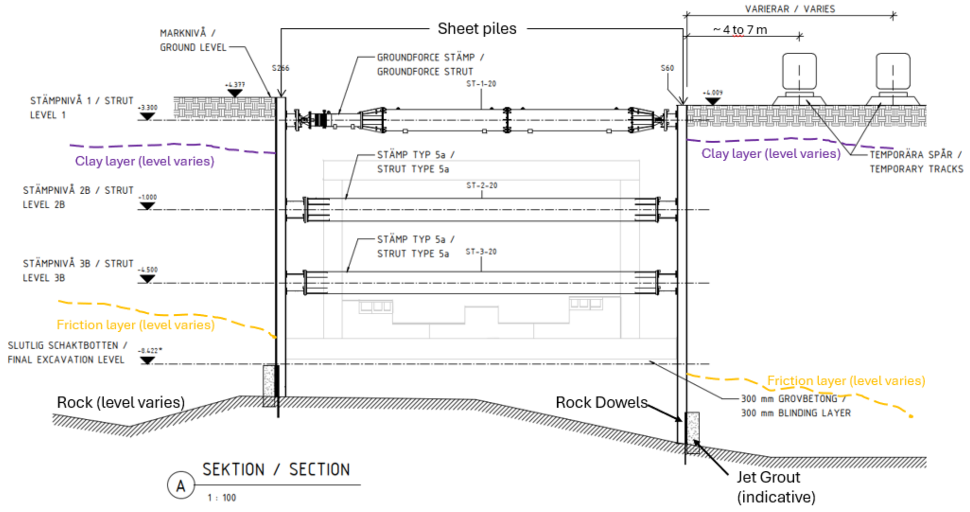

Figure 3: Cross section of excavation pit next to relocated railway tracks

After the final excavation level is reached, the concrete tunnel for the later railway is built in the bottom-up method. In between the different casting sections of the tunnel elements, struts and waling beams are removed in stages. The lowest strutting layer is removed after the tunnel bottom slab is installed, middle and upper most strutting layers are removed in connection with the installation of the tunnel walls and roof slab, while the gap between the tunnel walls and the sheet pile walls is backfilled with heavy concrete to counteract uplift and to enable load transfer from outside earth and water pressure into the tunnel's bottom slab.

4. MONITORING

Monitoring of buildings and infrastructure

The working site area has been rigidly monitored in purpose to verify the response in the installed supporting structures during construction as well as to monitor surrounding ground and structures, e.g buildings, highway, railway and bridges, to prevent exposure to harmful or unexpected deformations.

The surrounding structures and ground surface are monitored by using total stations, digital levels, monitoring prisms, level markers etc. Railway curvature and relative distance between the tracks is verified from daily performed wheeled "crab"-monitoring results. In addition, satellite monitoring is also available to discover ground level movements in random points and general pattern of settlements and heave.

Total stations, Leica Nova TM60, are used for monitoring of the prisms. The monitoring accuracy of the total stations is stated by the manufacturer to be 0,6 mm +0.0001 %. This applies for ideal conditions, however at the working site it is clearly seen that the practical accuracy is in the range of ±2-3 mm at the best. Most monitoring noise is evaluated to be caused from uncertainty in the reference monitoring net and from refraction caused by heat flow e.g. around vehicles or simply from sun or rain. As most of this monitoring is performed around-the-clock, trends and systematic behavior can be concluded, e.g. thermal response on daily or yearly basis. Monitoring during night hours is found to have less monitoring noise than during daytime, which is likely related to the reduced impact of the sun and construction activities during daytime. The total stations deliver more accurate monitoring results in length than transversally, which is caused by the geometrical difficulty of projecting angle measurements over distance. A variety of different prisms is used, depending mainly on flexibility needs and risk of damaging from production. For example considering the requirement of replacing prisms due to unforeseen impacts from the activities with heavy machinery, more economical prisms with less accuracy are used on the retaining structure.

Digital levels, e.g. Leica LS15, are used for levelling of markers, sheet pile top, railway tracks and other objects in the vicinity of the pit. The product data sheet of the digital levels state monitoring results with the accuracy of parts of a millimeter. Measurements within the working site confirm this accuracy with a high reliability.

Due to the complexity of predicting ground movements caused by the execution of foundation works, also in the project in Almedal, only deformation limits related to the excavation process are considered in the design. Movements caused by e.g. the forces, pressures and vibrations from sheet piling or jet grouting are to be handled during the execution phase on site. The most demanding limits are in this case connected to the adjacent railway tracks, allowing only deformations of up to 12 mm over 6 m length equaling (1/500). The maximum limit values for vertical ground movements in the vicinity of the excavation pit retrieved from the design calculations range between 10 – 20 mm. As preventive measure the foundation works along the railway are performed during night times with certain hours of line closure. Due to the very sensitive clay underneath the railway tracks ground works are challenging to execute safely, especially jet grouting works, where pressures of more than 400 bars are induced into the soil. Depending on grain size and thickness of the frictional layer sudden heaves of up to 100 mm within minutes have to be controlled (see Figure 4). Besides the extensive surveying, various mitigation measures are in place, such as a tamping machine, to secure safe railway tracks after the line closure.

Figure 4: Risk zone of 50 m, 100 m and 150 m distance from the location of groundwork execution. During installation of jet grouting heave may appear fast and with significant impact.

Monitoring of retaining structure

Horizontal displacements in supporting structures are monitored by using prisms and inclinometers mounted on the sheet pile walls. Loading effects in the steel struts from different steps of loading and unloading during excavation and constructions works are monitored by using loading cells and strain gauges mounted on the struts.

Inclinometer sensors are MEMS Digital In-Place Inclinometer System from RST instruments. The data is handled by a digital logger LS-G6 in a wireless monitoring system from Worldsensing. The accuracy of each sensor is stated as 0.003 mm/m in the manufacturer´s data sheet. The sensors are installed with internal distance of 1.0 m in depth. As the sensors are installed in a chain, there is likely an error propagation by depth of one or a couple of millimeters. However, in practice the main interest is in relative deflection and consequently impact of error propagation may be neglected.

Comparing the FEM-calculated deflections of the sheet pile walls with the actual field measurements of the inclinometers a general qualitative consensus is noted. However, evaluating deflections in a specific cross section of the excavation box in a three-layer braced section with one inclinometer on each side, differences in absolute values can observed, see Figure 5. While on one side the predicted values are exceeded (IM S49), the corresponding opposite stays below the expected values (IM S277). This may be related to locally varying soil properties and taken assumptions during design phase.

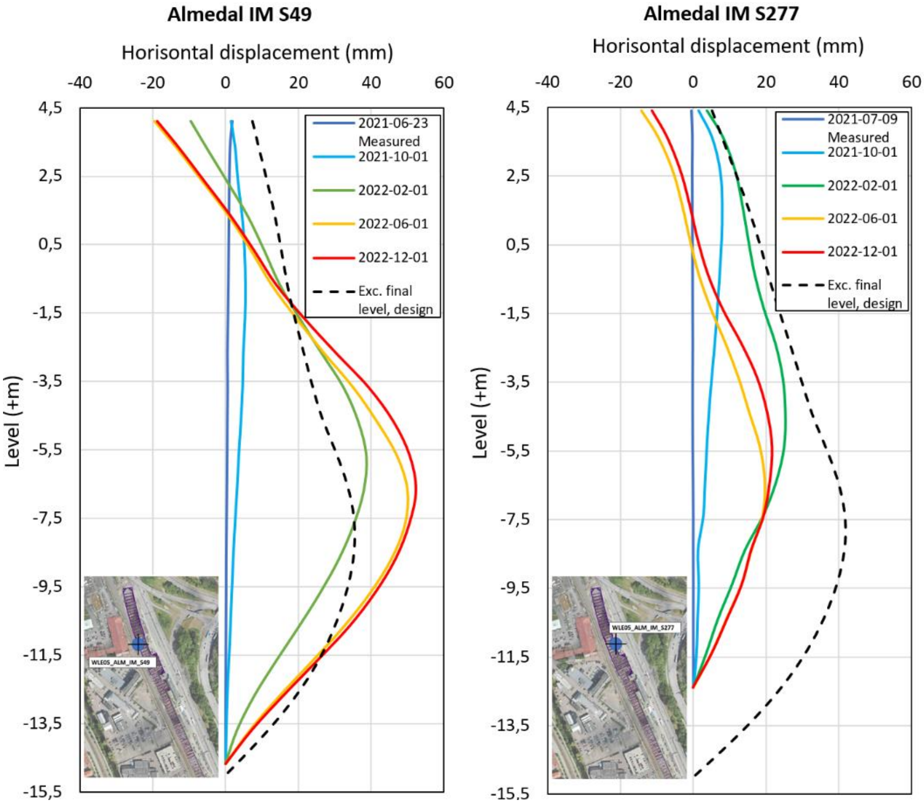

Figure 5: Inclinometer monitoring result from sensor installation to final excavation and installing of all supporting steel. Calculated deflection at full excavation is indicated in black dashed line.

Strut loading is monitored by using strain gauges fixed to the steel struts in fours positions in each monitoring section. The strain gauges are VWSG-A sensors from RST instruments. The monitoring accuracy of the strain gauges is stated as 0.05 %, indicating < ±25 kN for a loading of 5000 kN. In a few positions at site, the sensor layout has been calibrated with acceptable accuracy when pre-stressing the strut, however this has not been verified in the struts presented in this text. In sections with struts provided from Ground Force, the loading is monitored in a loading cell in the end joint of the strut.

The large amount of data monitored provides the engineering opportunity to evaluate behavior both on a local and on a global level. For example, the strain gauges setup provides data in different positions around the steel strut tube; top, bottom and both sides. The mean value of these sensors is used in the general strut evaluation to fulfil the Control plan requirements. However, from the monitoring results of the individual sensors the stresses may vary significantly. This is evaluated to be from bending moment but also from the fact that the contact surface between the large size strut tubes and the waler beams will never be perfectly performed, resulting in eccentricity. Another observation from the extensive monitoring is the response on temperature. Depending on the stiffness and depth of the supporting sheet pile wall, the thermal expansion of the struts induces loads and deflection in the wall differently. Further, the loading response from temperature also seems to vary more extensive on short term basis (daily) than on long term (seasonal), see Figure 6.

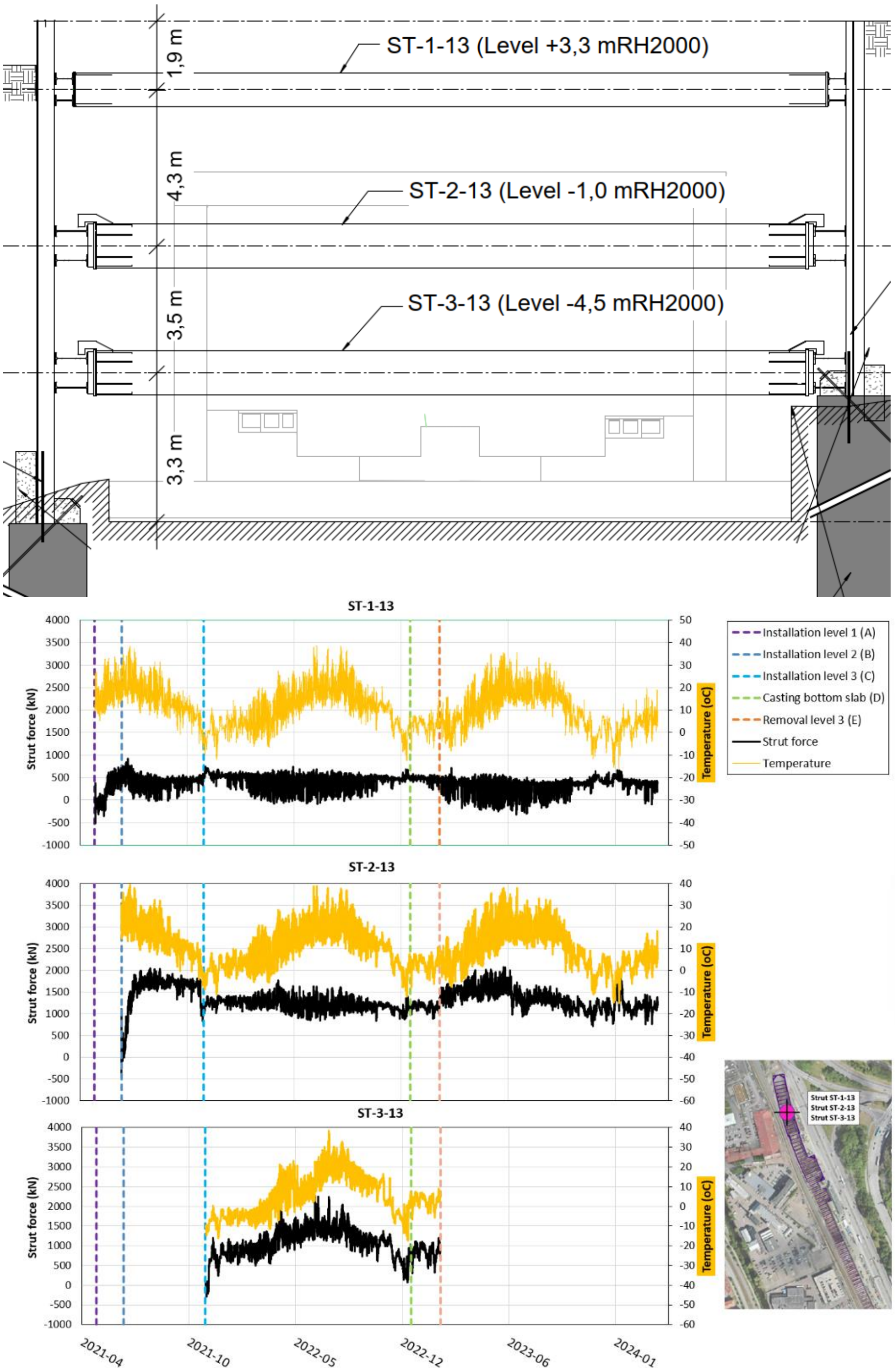

Figure 6: Section of the excavation, and plot on strut force and temperature vs time. The strut forces as per design is in the range of 4000 to 9000 kN.

5. LESSONS LEARNED

To monitor is to know! Properly used, the monitoring results can be used to verify design assumptions, optimize or adjust working sequences or quantify deformations. Monitoring brings information to evaluate and make knowledge-based decisions. Yet it is crucial to understand what to monitor, why, and not least how.

Noting that the accuracy of monitoring instrumentation is most often less in field conditions than in laboratory environment or in data sheets. Considering the accuracy limits of surveying and the impacts of the construction site, a sort of critical approach on produced monitoring data is recommended.

Digital levels are found to deliver monitoring results with very high accuracy, <1.0 mm. Automatic total stations with prisms delivers regularly continuous monitoring results, that are useful for evaluation of trends and general behavior, but with a lot of monitoring noise and less accurate results. To increase the accuracy the automatic monitoring requires daily hands-on service.

A sensor always delivers monitoring data if it is not broken. A full understanding of the way a sensor is installed and responding to its zero measurement is essential. For example, strain gauges are applied in groups of four around a steel strut; damage of one of the four sensors may lead to reporting of faulty mean values.

Sensors are most often sensitive to temperature and water, and in practice the sensors and connecting cables can be broken by construction machinery or simply being moved because they conflict with other works. Maintaining monitoring points on ground surface in working site environment is extremely difficult and shall be considered during the design phase.

An extensive monitoring system including a huge number of monitoring points also generates an enormous amount of data. To use the potential of this data, the project requires proper staffing and competence to evaluate data and distinguish between relevant movements and monitoring noise. Also, it is essential to understand potential consequences, while holding the mandate to act in short notice if required.

Monitoring can be used with the purpose to detect the development of settlements or rapid phenomena like the failure in a retaining wall. Inclinometers are accurate enough to detect both long term and short-term phenomena. Inclinometers are found to be less affected by monitoring noise than automatic total stations and therefore being preferred for the detection of rapid failures.

Installation of LCC and jet grouting often generates heave and soil movements, still this is regularly not modelled in FEM-based designs. This is likely because the behavior is extremely complicated to predict as it depends on a range of parameters such as soil structure and installation methods. The movements of the installation works are often in the size of centimeters or even decimeters. Thorough risk assessments with effective mitigation measures are therefore vital to handle occurring movements and deformations during the execution phase.

Proper and relevant monitoring increases the understanding of the supporting structures and it gives an opportunity to evaluate behavior and detect danger and risks. To achieve these relevant aims, it is necessary that the measurements and the Control program have the trust of the organization. Communication between different actors is a key factor for success. There is occasionally a believe that monitoring, additional monitoring points or very specific and narrow limit levels is a straight and easy fix to make a design more robust or the construction works safer. However, experience proofs differently: Oversized monitoring creates unmanageable amount of data, likely connected to a lot of monitoring noise and the subsequent loss in confidence from the working site. Proper monitoring is difficult and comes with a high cost. The cost benefit must be analyzed in relation to other actions creating a robust working site. Non-specific, too generous, limit levels make the control monitoring irrelevant or even dangerous, but too narrow limits force focus to problem in monitoring accuracy rather than on verifying design or worse, not discovering the unexpected incidents that occur when there are humans working in a complex environment.

ACKNOWLEDGEMENT

Thanks to Yanling Li for assistance with figures and technical support on modelling.

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