Permanent sheet pile walls in complex soil conditions
Surveillance, monitoring and safety

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Abstract. Kvaernerbyen field F1, also known as Kvaerndammen, is part of the Kvaerndammen project in Oslo, Norway. Kvaerndammen consists of a 7-storey residential complex on an underground parking floor. The south-eastern part of the building cuts into the lower part of a steep slope, with soil conditions consisting of dry crust above firm silty clay, followed by quick clay/sensitive clay above a thin moraine layer over bedrock. Due to existing buildings and constructions further up the slope, the allowable deformations of the building pit during and post construction of Kvaerndammen had to kept within very tight thresholds. Since the summer of 2017, Cautus Geo AS and Multiconsult Norway AS have been cooperating in “research and development” (R&D) focusing on deformations of sheet pile walls (SPW) in complex ground conditions and all aspects connected to interaction between engineering, monitoring, alerting and safety. Starting with surveillance during the construction period, monitoring a permanent SPW supporting the mentioned slope at Kvaerndammen, the R&D collaboration was continued between Cautus Geo and Multiconsult with continuous surveillance of the construction for almost 2 years after completion. Throughout the project, all phases of a critical SPW-construction have been evaluated, mainly focusing on the effects of seasonal variations in a "permanent" phase. Observations and experiences made during the project with a comprehensive database derived from geotechnical instrumentation have provided an unusually detailed documentation of the development of the construction after completion. The load cells connected to anchors in two rows on the SPW show a correlation between increasing temperature and increasing anchor force in a permanent phase, most likely due to a volume expansion of the structure. This is an opposite trend to what was observed during the construction phase, where increasing force is recorded in the load cells at decreasing temperature, especially at negative degrees Celsius. The temperature in the load cells is measured to oscillate between positive and negative degrees Celsius only during the construction phase, where increasing force is recorded in the load cells at decreasing temperature, especially at negative degrees Celsius only during the construction phase. The load may tend to increase in the upper part of the SPW during heavy rainfall, but of negligible value. Based on a slight change in load and deformation during the permanent phase, the SPW is regarded as a stable and secure construction at Kvaerndammen. For future projects, it is important to be aware that load changes in anchors may be dependent on a well-functioning frost protection.

1. Introduction – Kvaerndammen field F1
Kvaerndammen field F1, also known as Kvaerndammen, is part of the Kvaerndammen project in Oslo, Norway. The Kvaerndammen project is one of Norway’s largest urban housing projects, converting a former industrial area into housing and offices [2]. Kvaerndammen consists of a 7-storey residential complex on an underground parking floor. Multiconsult worked on the project as geotechnical
consultants and engaged Cautus Geo AS as supplier of a surveillance and monitoring system to follow up and measure the development of the construction during establishment.

1.1. Topography and soil conditions
The terrain surrounding Kvaernerdammen is at about elevation +18. The south-eastern part of the building cuts into the lower part of a steep slope. A walking and cycling path (W/C-path) lies close to Kvaernerdammen at about elevation +27. A parking garage at level + 29 and a kindergarten at elevation +32 both on shallow foundations further up the slope meant that deformations of the building pit during and post construction of Kvaernerdammen must be kept to a minimum. Figure 1 shows the terrain and the placement of the W/C-path and the buildings in a cross-section.

In the bottom of the slope the soil conditions mainly consist of a 5 m thick fill layer above bedrock. The soil conditions up the slope consist of dry crust above firm silty clay, followed by quick clay/sensitive clay above a thin moraine layer over bedrock. The thickness of the layers varies along the slope. The groundwater table is about 3-4 m below the surface based on pore pressure measurements. Still, local variations in pore pressures characterize the area.

2. Surveillance and monitoring
From both a consultant’s and a contractor’s perspective, close and smooth communication was an important factor in elucidating ambiguities and ensuring that solutions and plans were discussed and mutually agreed. Start-up meetings with designers, contractors and executive subcontractors were held prior to the start of each sub-process, which was thus crucial for success, as well as regular site inspections. The need for close follow-up of the basic work during the construction phase was determined on the basis of the overall level of risk associated with the project. A comprehensive measurement program with automatic logging and notification of various elements such as deformation and anchor load were therefore established for close monitoring of the development of the building pit.

2.1. Surveillance installations
To monitor and follow up during the construction phase, the following measurement systems were established (see Figure 2):

- 3 inclinometers along the SPW (SAAF500 Model 3).
- 2 load cells, one in each anchor row (Geosense VWLC-5000).
- 6 electrical piezometers (Geosafe PVT) and 4 hydraulic piezometers.
- 2 vibrational instruments in soils.
- Measurement of settlements on neighboring buildings.
3. Establishment of SPW structure
The workflow for the permanent SPW was as follows [1]:
- Establishment of a working platform/counter fill in the bottom of the slope.
- Installation of the SPW to bedrock with rock bolts.
- Lime cement stabilization (LCC) of the soil inside of the SPW inside the building pit.
- Sectional excavation along the SPW with excavation at three levels.
- Installation of anchors anchored in bedrock at two levels.
- Establishment of sealing lid on top of the SPW.

Figure 3 shows a drawn cross-section of the SPW after completion.

4. Surveillance, follow-ups and observations in a permanent phase
With a satisfactory follow-up through the establishment of the SPW, a R&D project between Multiconsult and Cautus Geo was formed. The focus was set on documenting and observing how external forces such as temperature variations and precipitation during different seasons would affect the construction after completion. After successful dialogues with the project management team, contractor and residents of the residential complex Kvaerneramme, it was agreed that surveillance and monitoring of the construction should continue indefinitely, after a cosmetic improvement. The R&D project was evaluated as a positive commitment by all parties – a verification of the designed construction for the contractor and a security measure for the residents of Kvaerneramme. Remote logging of deformation and anchor load (including temperature gauges) is still ongoing, while about 3
electric piezometers with manual reading are operation. In the phase following the establishment of the SPW, Multiconsult and Cautus Geo have had meetings on a regular basis to study measurements and record observations with possible causes. Collection and quality control of pore pressure data, as well as further development of the functionality in the Cautus Geo web-portal for presenting data, has been ongoing during this period. In total, measurement data has been collected for almost 2 years to present date after completion of the SPW, with more than 250,000 automatically collected measurements from the various sensors.

4.1. Anchor load

Figure 4 presents anchor load cell data from June 2018 to present from both load cells. The upper load cell has recorded a variation of approx. 65 kN, while the lower load cell has approx. 40 kN based on seasonal variations. The figure shows that the anchor loads display the same pattern as the year before.

Figure 5.
Measured loads with internal temperature readings for both load cells from June 2018 to present. Orange and green line shows temperature of upper and lower load cell.

The upper load cell in Figure 5 shows a variation in temperature of approx. 19 °C, with the lowest temperature at approx. 1 °C. The lower load cell shows a variation in temperature of approx. 12 °C, with
the lowest temperature at approx. 5°C. This suggests that the upper anchor row is more sensitive to changes in temperature than the lower anchor row. The upper anchor row is closer to the surface and will be more affected by changes in atmospheric temperature. Changes in both temperature and load are greater in the upper anchor row. Figure 6 shows a good correlation between change in load and change in temperature.

Figure 6.
Measured load with internal temperature reading for upper load cell in July 2019.

It is observed in the permanent phase that the load in both load cells increase as temperature increases, hence causing a volume increase in the construction (see Figure 6 above). Looking closer at load and temperature readings during days with large variations in temperature between day and night in the permanent phase, a clear correlation between temperature increase and load increase is observed (Figure 7).

Figure 7.
Measured load for top load cell with internal temperature reading combined with atmospheric temperature in March 2019.

Figure 7 shows a delay of the temperature reading in the upper load cell compared to the measured temperature in the atmosphere. In addition to an isolated and frost protected SPW, the upper load cell is approx. 2.5 m below the surface, which causes a delay in the load cell’s internal temperature following
changes in atmospheric temperature. As rising temperatures correlate well with load increase, the question of structural expanding within the measurement instrument itself arises. This effect is taken account for in the calibration band and should not be a source of error.

In looking back to periods in the construction phase where temperature changes significantly between day and night, an opposite effect is observed – the loads in the cells increase as temperature decreases (Figure 8). It is important to note that, during the construction phase, the temperature in the load cells fluctuated between positive and negative degrees Celsius, which is something that is not observed in the permanent phase. This can imply that the SPW is affected by volume increase in the soils behind the SPW, which creates an increase in earth pressure during cold periods.

Figure 8. Measured load for upper load cell with internal temperature reading in September 2017 (construction phase).

Figure 9 shows that the temperature has not gone below 0 ºC in both load cells during the permanent phase. The loads seem to be mainly affected by structural expansion as the loads increase with rising temperature (steel expands with increase in temperature). Volume expansion of the SPW will take place in several elements, from the wall itself to other components such as walers and anchors. Based on the load cells, it is observed that there has been no frost in the construction since the lid was completed in June 2018, which again indicates that the permanent frost protection works as planned.

Figure 9. Measured loads with internal temperature readings for both load cells from September 2017 to present. Orange and green line shows temperature of upper and lower load cell.
The two large peaks in temperature (Figure 9) during the construction phase seems to match the time when the casting of walers was performed in each anchor row (heating from the curing process). Registered data shows no obvious correlation between anchor load and precipitation (Figure 10). Specific cases where it appears that large rainfall levels may have increased the load are also characterized by a rise in temperature.

There is still observed a small increase in the upper load cell in specific cases right after large rainfall levels occurs, and before the temperature increase is registered (Figure 11). The lower load cell also seems to be affected by the events, getting a small decrease in anchor load. During periods of heavy rainfall, a temporary increase of the groundwater table occurs, which is assumed to affect the upper part of the SPW and cause an increase in force in the upper anchor row. With an increase in pressure against the top of the SPW, the lower part of the structure will react by possibly bending inwards against the slope, away from the building pit. This may result in a decrease observed in the lower load cell as demonstrated in Figure 11.

This effect is not observed when the load increases only as a result of an increase in temperature. As the change in temperature occurs in the construction in its entirety, a volume expansion or reduction will affect both anchor rows similarly, thereby causing the same load change at both locations.
4.2. Pore pressure

To confirm the temporary increase in pore pressures during large rainfall levels, a study of the data collected from the piezometers was performed. The pore pressures were logged automatically during the establishment of the SPW. Several electrical piezometers were eventually missing data, which may have resulted from tampering by random passersby. Pore pressure measurements in the permanent phase have been regularly collected through manual readings following completion in June 2018. A correction of the pore pressures against atmospheric pressure has been made by automatically obtaining observations from the Meteorological institute’s (MET) measuring station at Blindern, Oslo. The correction provides even more defined plotted results and makes it easier to locate other external influences such as interventions or periods of large rainfall levels. Figure 12 shows the pore pressure in the piezometer located at the W/C-path, closest to the SPW, plotted against precipitation.

![Figure 12. Measured pore pressure for PZ W/C (7.6 m) with precipitation from June 2018 to present.](image)

Clear responses appear in pore pressure at the piezometer close to W/C-path when large rainfall levels occur. The pore pressure stabilizes over a relatively longer period after instances of relatively heavy rainfall, as the piezometer is most likely located in the clay layer. A slight increase in anchor load may occur during these pore pressure increases as previously mentioned, but not of significant value.

4.3. Deformation of sheet pile wall

![Figure 13. Measured sheet pile deformation on inclinometer 3 from June 2018 to present.](image)

From Figure 13 above, the SPW appears as a stable construction, with a maximum deformation of 4 mm in the permanent phase from June 2018 to present. The three installed inclinometers show very minor displacements, and it is difficult to extract special events where, for example, there have been temperature changes or precipitation periods during the permanent phase, due to the small deformation values and no obvious deformation pattern.
By looking at the segment positions along the instrument for inclinometer 3 (Figure 13), it is still possible that the small changes in deformation are related to seasonal changes and behavior of the sheet pile wall. Overall, measured deformations show that the SPW behaves as desired with minimal deformation in the permanent phase.

Looking at the deformation plots including internal temperature from the inclinometers, it appears that the temperature variations throughout the seasons are small at the bottom of the SPW and increase towards the top. Periods of negative temperatures in the upper part of the inclinometer have been observed during the permanent phase. The negative temperature measured in the upper part of the inclinometer may be due to transport of cold air down the channel, thereby affecting the measurement nodes mounted above the top point and some distance down into the inclinometer channel. This effect is clearly seen in individual occurrences where there are large variations in temperature between night and day (Figure 14).

![Figure 14. Deformation of the SPW plotted against temperature with depth for inclinometer 2 from March 1st to March 2nd 2019.](image)

Figure 14 shows that the variations in temperature for 24 hours (March 2019) are increasing up the inclinometer channel, but rather small down the profile. No obvious change in deformation is recorded in relation to change in temperature. The internal temperature recorded in the load cells corresponds well to the internal temperature recorded in the inclinometer channels at the load cell positions.

5. Communication, performance and presentation

In order to maintain safe conditions and avoid delays on the project, there was a mutual understanding of the importance of planning and establishment of the geotechnical monitoring system as early as possible. At the same time, a fundamental factor in all disciplines of geotechnical monitoring is to have continuous control over the natural variations before initiating measures or interventions. Establishing the instruments in time often proves to be a decisive factor in getting a database of good quality measurements and a thorough understanding of the environment. Therefore, those who install and process measuring equipment and measurement data should be involved at an early stage to contribute their expertise to develop a customized sensor and installation solution best suited for the given site conditions. It is crucial that all geotechnical instruments are installed with optimal practical performance to minimize the risk of disruptions and conflicts with construction work during the construction phase.

The potential development of communication between the different parties in this project has been an ongoing dialogue throughout this R&D collaboration. Improved and simplified communication between the developer, consultant and contractor in terms of geotechnical monitoring will result in increased safety for personnel at the facility and quicker reaction time in the event of unexpected
situations. There is a potential need to develop new functionality integrated into the handling of measurement data, where all users and executives can easily insert “topic snags” into the measurement data timeline, or comment on measurement data for specific events. This will help to document when the various sub-processes are performed and creates the possibility to quickly determine any possible connection between implemented measures and the results in the gathered data.

5.1. Presentation of geotechnical measurements
In parallel with the R&D project, Cautus Geo has worked on developing a new version of the web portal Cautus Web. The new service has been further developed from the current version of the web portal and comes with a number of new functionalities, based on feedback from this project and input from other users. Through the R&D project, the need to provide users with all the necessary analysis and compilation of measurement data across measurement technologies has been present, in order to find concurrent trends without the extensive use of traditional tools such as Excel. The purpose of the development is to be able to offer a web portal that gives the developer, consultant and contractor a simple but powerful tool for processing and analyzing measurement data at the same time. A 3D view of borehole deformations has already been developed, and further work is being done to create a function that can change between different plot styles - color selection, stripped line and icons. A new functionality for implementing future weather and climate forecasts is under development, which can notify future potential changes in conditions for structures being monitored.

6. Conclusion
The load cells show a correlation between increasing temperature and increasing anchor force in the permanent phase, which is most likely based on a volume expansion of the structure at increasing temperature. This is an opposite trend to what has been observed during the construction phase, where the force of the load cells increases at decreasing temperature, especially at negative degrees Celsius. This effect is probably due to volume expansion in the soils behind the SPW, adding earth pressure to the structure. It is important to mention that the temperature in the load cells has been measured to oscillate between positive and negative degrees Celsius during the construction phase. No negative temperatures are recorded in the load cells in the permanent phase, while the measured temperature in the inclinometers occasionally show negative temperatures in the top of the SPW. The SPW is still demonstrated to be a frost-proof construction in the permanent phase. During heavy rainfall, the load may tend to increase in the upper part of the structure, although the temperature also often increases when heavy rainfall occurs. Based on a slight change in load and deformation (a few millimetres in the permanent phase), the SPW is regarded as a stable, secure and reliable construction.

In connection with the change in rainfall and seasonal temperature changes of approx. 19°C, measurements show that anchor load can vary by approx. ± 3% in the permanent phase. Values of this magnitude in the permanent phase can be neglected in connection with the reference project at Kvaernerdammen, but with regard to future projects, it is important to be aware that load changes in anchors may be dependent on a well-functioning frost protection.

References
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