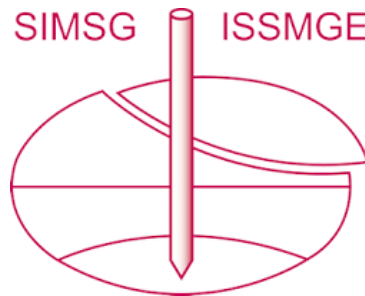


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Permanent sheet pile walls in complex soil conditions – surveillance, monitoring and safety

Palplanches permanentes dans des conditions de sol complexes – surveillance, contrôle et sécurité

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ABSTRACT: Kvaernerdammen located in Oslo, Norway, consists of a 7-storey residential complex on an underground parking floor cutting into the lower part of a steep slope. Soil conditions consist of dry crust above silty clay, followed by sensitive clay and moraine over bedrock. The deformation of the building pit during and post construction of Kvaernerdammen had to be kept within tight thresholds, due to existing constructions up the slope. Cautus Geo and Multiconsult have been part of a R&D-project focusing on behavior of sheet pile walls (SPW) in complex soil conditions and the aspects related to interaction between engineering, monitoring and safety. Surveillance of the mentioned SPW has been continued for over 3 years after completion. The focus has been on the effects of seasonal variations in a "permanent" phase. A comprehensive database has provided detailed documentation of the development after completion. Measured anchor load in two rows on the SPW show a correlation between increasing temperature and anchor load in a permanent phase. A recent NTNU master thesis (2020) developed a model calculating change in anchor load due to change in temperature, where combining thermal strain in the SPW and the soil proved to correlate to the measured forces.

RÉSUMÉ : Kvaernerdammen localisée à Oslo en Norvège se compose d'une résidence complexe de 7 étages. La résidence se situe sur un parking souterrain coupant la partie inférieure d'une pente raide. Le sol est constitué d'une croûte sèche à sa base, d'argiles silteuses suivie d'argiles sensibles et de moraines sur un substrat rocheux. La déformation de la fosse de construction pendant et après la construction de Kvaernerdammen a dû être maintenue dans des seuils stricts en raison de constructions existantes en haut de la pente. Cautus Geo et Multiconsult ont fait partie d'un projet de recherche et développement axé sur le comportement des palplanches (SPW) dans des conditions de sols complexes mais également sur les aspects reliés aux interactions entre l'ingénierie, le contrôle et la sécurité. La surveillance de ces SPW s'est poursuivie pendant plus de 3 ans après la fin de la construction. Un focus particulier a été mis sur les effets des variations saisonnières durant la phase « permanente ». Une base de données complète a fourni une documentation détaillée du développement après la fin de la construction. La charge d'ancrage mesurée sur deux rangées de SPW montre une corrélation entre l'augmentation de la température et la force d'ancrage au cours de la phase « permanente ». Un récent mémoire de fin d'étude a développé un modèle calculant le changement de force d'ancrage dû aux changements de températures, où la combinaison de contraintes thermique dans les SPW et le sol sont corrélées aux forces mesurées.

KEYWORDS: surveillance, deformation, load, SPW, seasonal variations.

1 INTRODUCTION

Kvaernerbyen field F1, also known as Kvaernerdammen, is part of the Kvaernerbyen project in Oslo, Norway. The Kvaernerbyen project is one of Norway's largest urban housing projects, converting a former industrial area into housing and offices (Obos 2019). Kvaernerdammen 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 and post establishment.

1.1 Topography and soil conditions

The south-eastern part of the Kvaernerdammen building cuts into the lower part of a steep slope. A walking and cycling path (W/C-path) lies close to Kvaernerdammen just up the slope. A parking garage and a kindergarten 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.

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 m below the surface based on pore pressure measurements. Still, the area is characterized by local variations in pore pressure.

1.2 Surveillance and monitoring

From the perspective of both consultant and contractor, close communication was an important factor in elucidating ambiguities and ensuring that solutions and plans were discussed and mutually agreeable. 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 was determined based on the overall level of risk associated with the project. A comprehensive measurement program with automatic logging and notification of various elements (ex. anchor load) was established for close monitoring of the development of the building pit. To monitor and follow up during the works, the following measurement systems were established (Multiconsult 2017):

- 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 and measurement of settlements on neighboring buildings.

Figure 1 shows a drawn cross-section of the SPW after completion. The construction exists of a SPW bolted to bedrock with 2 rows of anchors.

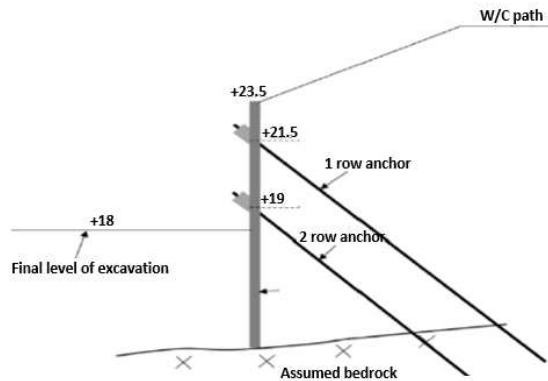


Figure 1. Cross-section of the SPW after excavation to final level.

2 OBSERVATIONS

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. It was agreed that surveillance and monitoring of the construction should continue indefinitely. 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 Kvaernerdammen. Remote logging of deformation and anchor load (including temperature gauges) is still ongoing, while 3 electric piezometers with manual reading are operational. 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 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 over 3 years after completion of the SPW, with more than 300,000 automatically collected measurements from the various sensors.

2.1 Anchor load

Figure 2 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.

The upper load cell in Figure 3 shows a variation in temperature of approx. 20°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 4 shows a good correlation between change in load and change in temperature.

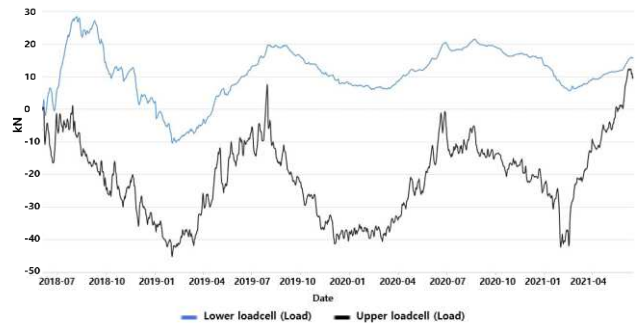


Figure 2. Measured variation of load in upper load cell (black) and bottom load cell (blue) from June 2018 to summer 2021.

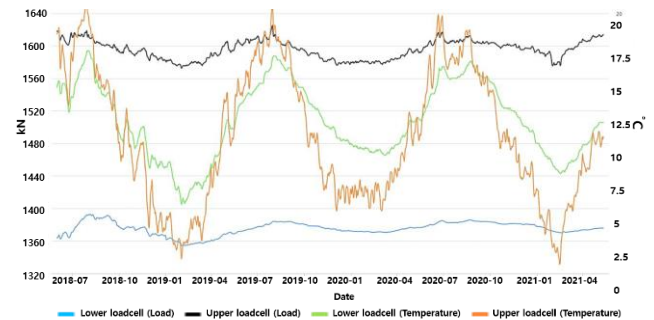


Figure 3. Measured loads with internal temperature readings for both load cells from June 2018 to summer 2021. Orange and green line shows temperature of upper and lower load cell.

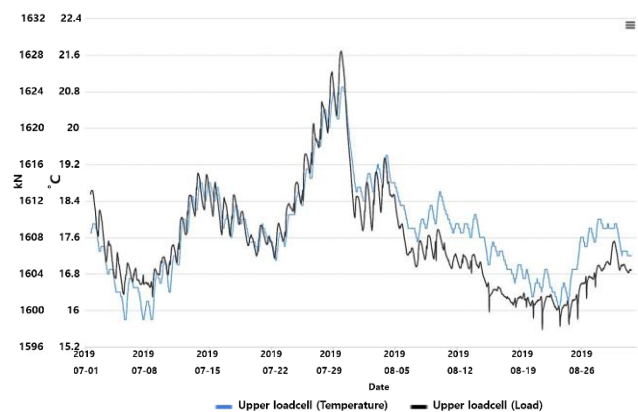


Figure 4. Measured load with internal temperature reading for upper load cell in July 2019.

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. 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 5).

Figure 5 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 considered 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 increase as temperature decreases (Figure 6). 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 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.

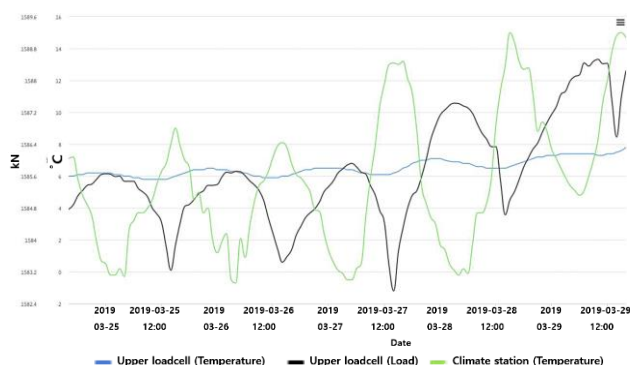


Figure 5. Measured load for top load cell with internal temperature reading combined with atmospheric temperature in March 2019.

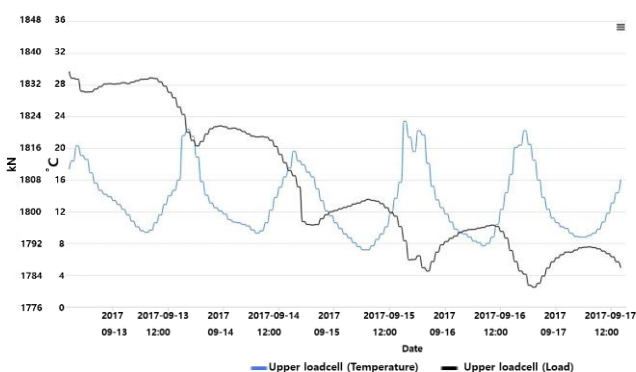


Figure 6. Measured load for upper load cell with internal temperature reading in September 2017 (construction phase).

The two large peaks in temperature (Figure 7) 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 8). Specific cases where it seems like large rainfall levels may have increased the load are also characterized by a rise in temperature.



Figure 7. Measured loads with internal temperature readings for both load cells from September 2017 to summer 2021. Orange and green line shows temperature of upper and lower load cells, respectively.

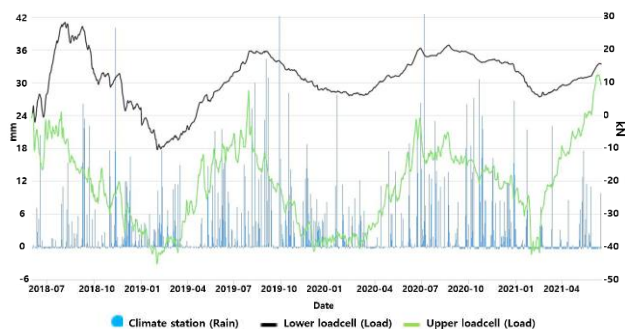


Figure 8. Measured load for upper and lower load cell with precipitation data from June 2018 to summer 2021.

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 9). 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 causes 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 9.

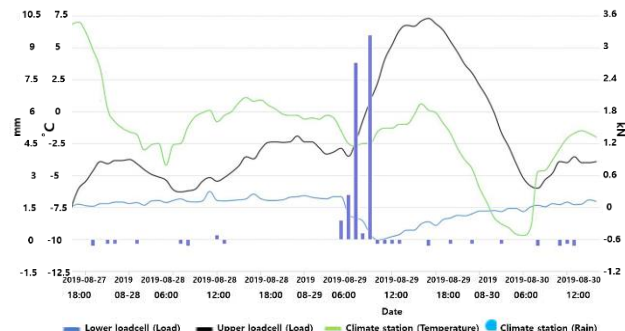


Figure 9. Measured load for upper and lower load cell combined with precipitation and atmospheric temperature in August 2019.

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.

2.2 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 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 performed 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 10 shows the pore pressure in the piezometer located closest to the SPW, plotted against precipitation.

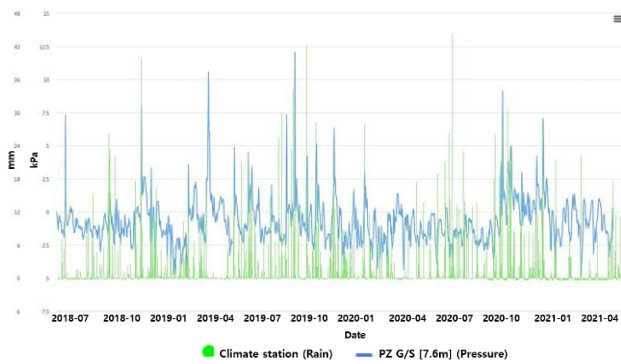


Figure 10. Measured pore pressure for PZ W/C (7.6 m) with precipitation from June 2018 to summer 2021.

Clear responses appear in pore pressure 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.

2.3 Deformation of SPW

From Figure 11 the SPW appears as a steady construction, with a maximum deformation of 4 mm in the permanent phase from June 2018 to summer 2021. The three installed inclinometers show minor displacements. 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.

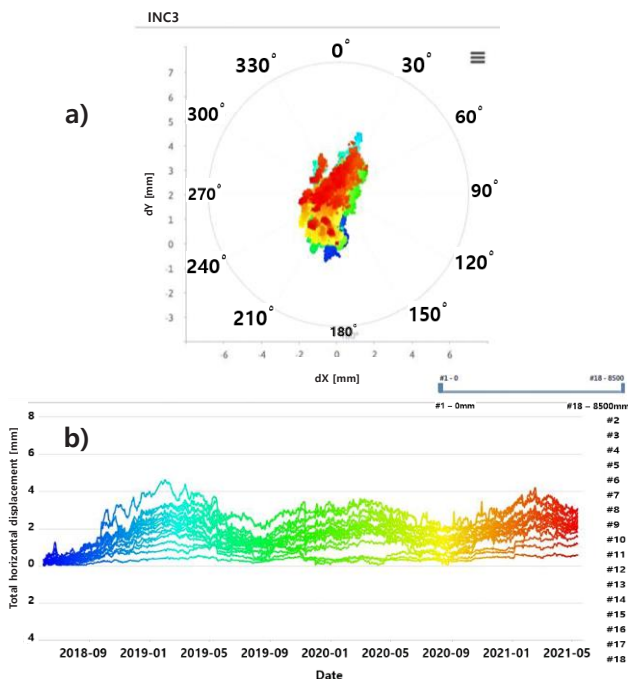


Figure 11. Measured deformation inclinometer 3 from June 2018 to summer 2021, a) shows direction and b) shows magnitude of increment.

By looking at the segment positions along the instrument for inclinometer 3 (Figure 11), it is still possible that the small changes in deformation are related to seasonal changes and behavior of the SPW. 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 down into the inclinometer channel. This effect is clearly seen in individual events where there are large variations in temperature between day and night (Figure 12).

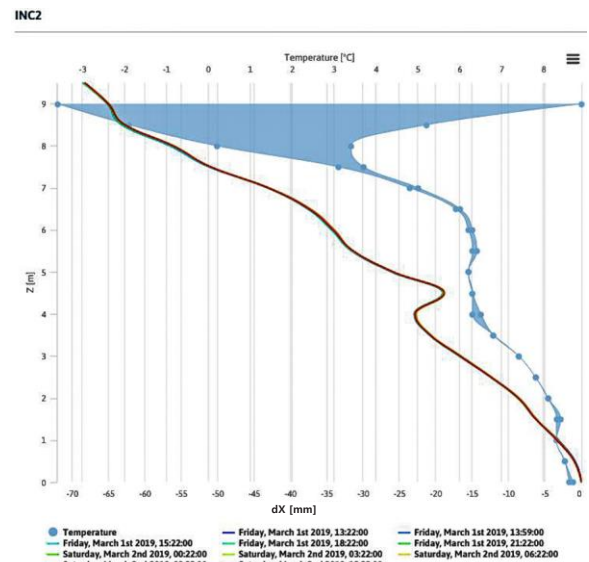


Figure 12. Deformation dX of the SPW plotted against temperature with depth for inclinometer 2 from March 1st to March 2nd, 2019.

Figure 12 shows that the variations in temperature for 24 hours (March 2019) are increasing up the inclinometer channel. 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.

3 CALCULATIONS OF CHANGE IN ANCHOR LOAD

In Sem's master thesis from 2020 (Sem 2020), calculations of changes in anchor loads were made, with Kvaernerdammen being the reference project. In the following, some of the results from the assessments and calculations presented in the thesis, will be presented and discussed. As the thesis was delivered in June 2020, supplementary calculations have been made in order to analyze data until April 2021. However, the overall assessment of the calculation model has remained.

3.1 Methodology

The calculations represented in this paper are built on the basis of two models – Model A and Model B. Model A is based on the fact that increasing temperature in a SPW causes expansion in the steel. The SPW will expand both horizontally and vertically. Model A is based on the idea that the vertical extension of the SPW will cause the SPW to pull the anchor head upwards and increase the tensile force in the anchor. The anchor load and the friction between the soil and SPW will at the same time increase the pressure-axial force in the sheet pile at depths below the attachment points of the anchors. The model uses a discrete element method to model the interaction between sheet pile, anchors and soil when a sheet pile is exposed to temperature changes.

Model B is based on laboratory studies showing volume increase observed as an effect of increase in temperature in some

clays. Assuming that the soil expands with heating, the expansion will cause a displacement of the SPW, if there is no resistance. For an anchored SPW, expansion of the soil will lead to increased pressure against the SPW and thus also an increase in force in the anchors. Both models were tested, but a model that combined the effects from both models gave the best correlation with the measurements. The calculation results presented in this paper are based on the combined model.

3.2 Input parameters

All input parameters used in the calculations presented in this article are taken from Sem's master's thesis (Sem 2020). Parameter selection is justified based on the structure's geometry, measurements, ground investigations carried out on the site and a parameter analysis. In the following, some aspects from the process of parameter determination, given in the master's thesis, are explained. A more detailed explanation is given in Sem's master's thesis (Sem 2020).

The calculations in Model A are made using a discrete element method. The 10,5 m tall SPW is divided into 21 elements measuring a height of 0,5 m each. Model A calculates the change in anchor loads based on the measured temperature change (ΔT_i) for each element i in the SPW. The temperature change for an element ΔT_i for a month is calculated as the difference between the temperature measured for the element in the current month and the temperature for June 18. The inclinometers installed along the SPW at Kvaernerdammen measure the temperature down the entire profile. This data is used as input for the calculations performed with model A. For model B, the soil layer at the depth of the anchoring points alone is considered, and therefore only the temperatures measured at these depths are used in the calculations for this model.

The inclinometer measures the temperature on the soil side of the wall. However, it is possible that the actual temperature in the SPW deviates from the measured temperature on the soil side of the SPW. The space between the SPW and the building consists of air where heat and air can circulate. During the first year of measuring, the temperature on the soil side of the wall was almost constant at the bottom of the SPW, while it had a variation of approx. 20°C at the top. At the same time, a continuous heat transfer occurs between the air particles, transporting air and heat from the surface towards the bottom of the SPW, which limits how large the difference between top and bottom can be on the air side of the wall. It can thus be argued that the temperature changes are greater on the air side of the SPW than on the soil side, where the heat transfer is slowed down by meters of soil. For the calculation with model A, which consider expansion in the steel, an adjusted value for temperature difference has therefore been used, where ΔT_i is multiplied by a factor f_{temp} . The adjusted value for a given point along the SPW is given in Eq. 1.

$$\Delta T_{i,adjusted} = f_{temp} * \Delta T_i \quad (1)$$

The models calculate the change in anchor load, ΔN , induced by a given temperature change. To find the occurring anchor load after the temperature change, the occurring anchor load before the temperature change must be added. The temperature change is calculated using the measurement recorded with timestamp 00:00:00 on June 1st, 2018 as the reference point. The reference value N_{ref} should thus have been the measured anchor load at that time exactly. However, a test calculation showed that this gave results that seemed to be shifted, compared to the measurements, especially for the upper load cell. A comparison is given in Sem's master thesis. In the Kvaernerdammen project load cells accuracy is stated to be 0.5% of full scale. At the same time, there may be some "noise" affecting the measurements from the beginning of the transition from temporary to permanent phase for the SPW. Based on this, the reference value was adjusted so that calculated values correlated better with those measured.

However, supplementary calculations have been made during the development of this paper, in order to also include data from the period June 19 to April 21. A new adjustment of the reference value for the anchor loads, has therefore been made in comparison to the master thesis. The reference value for the upper row of anchors was adjusted down from 1619 kN to 1606 kN in the calculations presented in this paper. The reference value for the lower row of anchors was adjusted up from 1369 kN to 1375 kN.

There is uncertainty associated with several of the parameters included in the calculation model (the combined model). Therefore, in Sem's master's thesis, an analysis of the various parameters was performed, to investigate how variations of these parameters affect the calculation results. Analysis performed show that changing these parameters can have a major impact on the calculations. This adds uncertainty to the calculated results.

3.3 Results and discussion

3.3.1 Deformation of SPW

The model for thermal expansion in soil suggests a context where an increase in temperature in the soil leads to an expansion of the soil, and thus increased pressure against the SPW, which would give a deformation in the positive x-direction. However, it is difficult to identify a trend for the inclinometer measurements that correlates with the temperature variations observed throughout the year. The explanation may be that the inclinometer is located between anchoring points. It may seem that the SPW bulges and dents slightly between the anchoring points, causing deformation between the anchoring points where the inclinometer is situated, which do not occur directly at the anchoring points.

3.3.2 Calculation of anchor load

The results show good agreement between measured and calculated anchor loads. Figure 13 shows a comparison of measured and calculated value. For the lower row of anchors, the difference is greatest in August 2018. Here, the difference between measured and calculated value is about 13 kN. During this month, there were also irregularities in anchor load. These irregularities did not seem to match the changes in temperature and is therefore believed to have been caused by an unknown outer influence. It is therefore not surprising that the calculated value does not match as well with measured value at the time. For the other months, the difference stays below 10 kN, mostly below 5 kN. As previously mentioned, the accuracy of the load cells is 0.5% of full scale. An accuracy of closer to 5 kN is thus considered relatively good.

The results for calculated deformation in the SPW showed deformation in the positive x-direction with temperature increase and the opposite for temperature decrease. This temperature dependence was not observed in the deformation measurements for any of the inclinometers. At the same time, the seasonal variation in deformation of the SPW, calculated with Model B, is minimal, with approx. 0.1 mm for the lower row of anchors and 0.5 mm for the upper row. With an inclinometer with a precision of 1.5 mm per 32 m length, it would therefore be difficult to document this variation. Even if the inclinometers were placed close to the anchoring points, it is thus unlikely that it would have been possible to observe a clear seasonal variation.

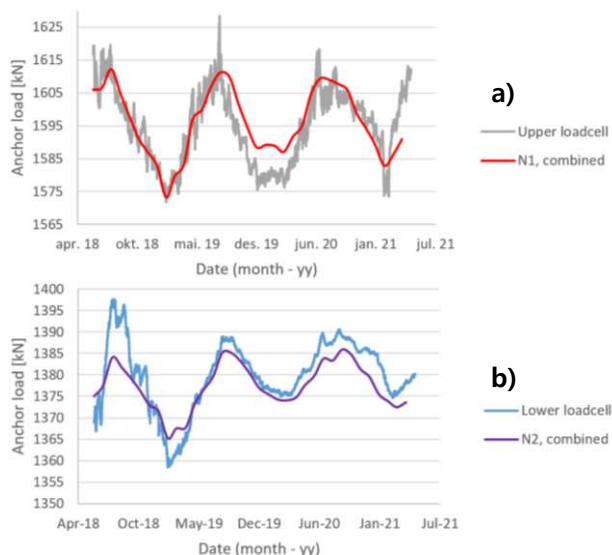


Figure 13. Calculated and measured anchor loads from June 2018 to April 2021 in a) upper load cell, and b) lower loadcell.

4 COMMUNICATION AND PERFORMANCE

In order to maintain safe conditions and avoid delays in 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 towards development of 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.

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 several 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. 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.

5 CONCLUSIONS

The load cells show a correlation between increasing temperature and increasing anchor load in the permanent phase, which is most likely based on a volume expansion of the structure at increasing temperature. The calculated changes in anchor loads show results that corresponds well with the measurements. These calculations are based on Sem’s model that considers both thermal strain in soil and thermal strain in the steel in a SPW. Though there is uncertainty associated with several of the parameters in the calculations, the strong correlation indicates that the thermal strain in soil and SPW could be a reasonable explanation to the seasonal variations in anchor load measured at Kvaernerdammen.

The increase in anchor load due to an increase in temperature 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 subfreezing temperatures are recorded in the load cells in the permanent phase, while the measured temperature in the inclinometers occasionally shows subfreezing 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, the SPW is regarded as a secure and reliable construction.

Regarding the change in rainfall and seasonal temperature changes of approx. 20°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 the reference project at Kvaernerdammen, but with regard to future projects and other types of sheet pile walls, it is important to be aware that load changes in anchors may be dependent on a well-functioning frost protection system.

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