Pore pressure reduction and settlements induced by deep supported excavations in soft clay

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ABSTRACT
As a part of the large research project, "LimitingDamage" (BegrensSkade), common causes of damage or unexpectedly large settlements connected to ground and foundations works have been investigated. It can be seen that drainage is a common cause for settlements when performing deep excavations, causing decrease in pore pressures and consolidation of soft soil.

The article presents monitoring data from numerous building sites, showing that there is often a substantial reduction in pore pressure levels at bedrock. The reduction in pore pressure can be observed hundreds of meters from the excavation. The general effects have been documented before, but the analysis of data in the project "LimitingDamage" shows a clear systematic reduction in pore pressures for the majority of excavation projects. The effects depend on the hydrogeological properties, as well as the extent and duration of the construction work and the mitigation efforts undertaken.

The data and observations from the case studies suggest that the risk of drainage is substantial in the conventional methods and procedures commonly used. Excavating to bedrock level, if under groundwater level, can cause substantial reductions in pore pressure. In addition, it is concluded that drilling for tie-back anchors and bored piles can increase the risk of drainage.

The risk of settlements caused by drainage and pore pressure reduction can be reduced during the early design phase of a project by undertaking the correct type of investigations and understanding the hydrogeology. Furthermore, one may select construction methods, which reduce risk of drainage. Measures may then be designed in order to mitigate the effects, followed by implementation and monitoring during the construction phase.

Keywords: Excavation, drainage, pore pressure, settlement.

1 INTRODUCTION

1.1 LimitingDamage (BegrensSkade)

Ground works such as deep excavations and foundation works performed in soft clay are known to frequently cause damage to neighboring buildings and structures. The costs related to these types of damage can be substantial and there is a large potential for reducing these costs. This is the main topic of a research project funded by the Norwegian Research Council and a wide range of consultants, clients and contractors, as well as the NGI. The project "BegrensSkade" ("LimitingDamage"), is investigating causes of damage.

The main causes of deformation connected to the performance of deep excavations in soft clay are (illustrated in Figure 1):

- Shear-induced ground movements linked to horizontal displacements of the supporting wall

- Leakage causing pore pressure reduction and consolidation settlements, when the effective stress exceeds the preconsolidation pressure
- Installation or "disturbance" effects induced by drilling for tie-back anchors or drilling for piles inside the excavation

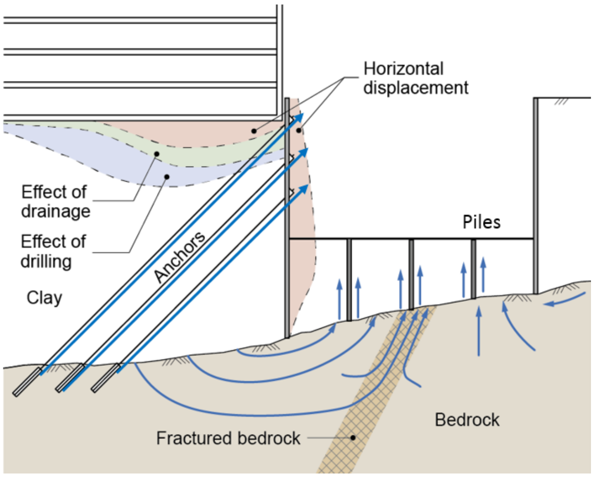

Figure 1 Illustration of the main causes of settlements connected to deep excavations in soft clay.

The settlements due to horizontal displacement of the sheet pile wall can be estimated using numerical tools or data from Peck (1969).
The settlements caused by disturbance of soil during drilling is presented in detail in reports by Lande (2015) and Veslegard et al. (2015).
This article will present results related to potential settlements caused by drainage to deep excavations given in Karlsrud et al. (2015).

1.2 Experience from leakage to tunnels

Experience from tunnels (Karlsrud et. al, 2003) and ground water pumping, shows that small amounts of leakage into a tunnel, can result in substantial decrease in pore pressures at bedrock level (at bottom of clay layer) (Figure 2). The main reason is the very limited recharge that comes through a low-permeable soft clay deposit, which makes the soil or bedrock below act as a confined aquifer. Analysis of data from numerous tunnel projects show that the leakage rate into a tunnel needs to be limited to approximately 3-8 l/m/100 m tunnel to limit pore pressure decrease to 10-30 kPa at the bedrock level (Figure 3). The data also shows that the pore pressure decrease can extend as far out as 200-400 m from the tunnel (Figure 4).

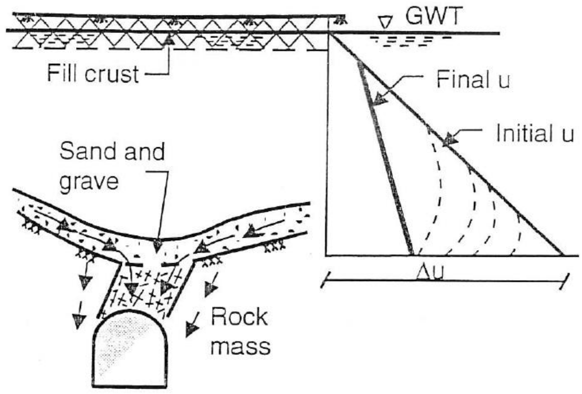

Figure 2 Leakage to bedrock tunnels overlain by clay deposits (from Karlsrud et al., 2003).

Based on the fact that the hydrogeological conditions are the same for excavations, these results implies that for an excavation of dimensions 100 m × 100 m significant pore pressure reduction can occur at the base of the clay outside the excavation, if the leakage exceeds about 5-10 l/min in total. However, the precise magnitude of pore pressure reduction, and the lateral extent of the area subjected to a reduced pressure is difficult to predict and dependant on the local hydrogeological conditions.

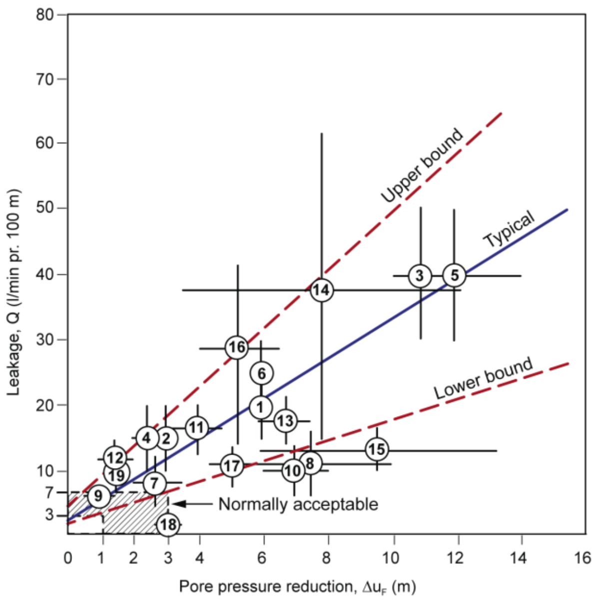

Figure 3 Measured rate of leakage to tunnels plotted against monitored pore pressure reduction at bedrock (from Karlsrud et al., 2003).

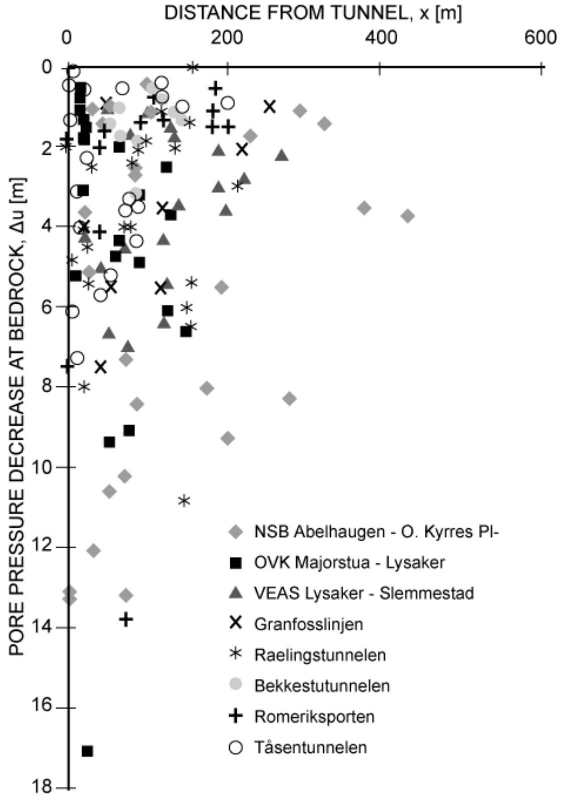

Figure 4 Measured pore pressure decrease at bedrock plotted with distance from excavation (from Karlsrud et al., 2003).

2 DRAINAGE TO EXCAVATIONS

The causes of drainage to an excavation can be many and complex. In addition, varying hydrogeological conditions will govern the effect on the pore pressures. However, the main leakage scenarios for an excavation in soft clay, as illustrated in Figure 5 are:

- Leakage through the sheet pile wall
- Leakage through gaps between the toe of the sheet pile wall and the bedrock
- Leakage through cracked bedrock
- Leakage during drilling for tieback anchors or piles (through the casing or the gap between soil and casing)

Leakage through the sheet pile wall mainly occurs during the cutting of holes for drilling of tie-back anchors. In addition, leakage can occur through unsealed or poorly sealed locks between the individual pile sections.
If the depth of the excavation reaches the bedrock level, resulting in an uncovered bedrock surface, there is a large potential for leakage through fractures. Uncovering the toe of the sheet pile wall also cause a large potential for leakage, especially if the bedrock surface is steep and there is a permeable soil layer on top of the bedrock.
Drilling for installation of piles and tie-back anchors has a potential for leakage when performed from a level below the ground water level or under artesian conditions. The leakage can occur through the gap between the installed steel casing or through the casing itself.

3 MITIGATING MEASURES

The risk of obtaining pore pressure decrease due to leakage into an excavation can be reduced by mitigating measures. The most

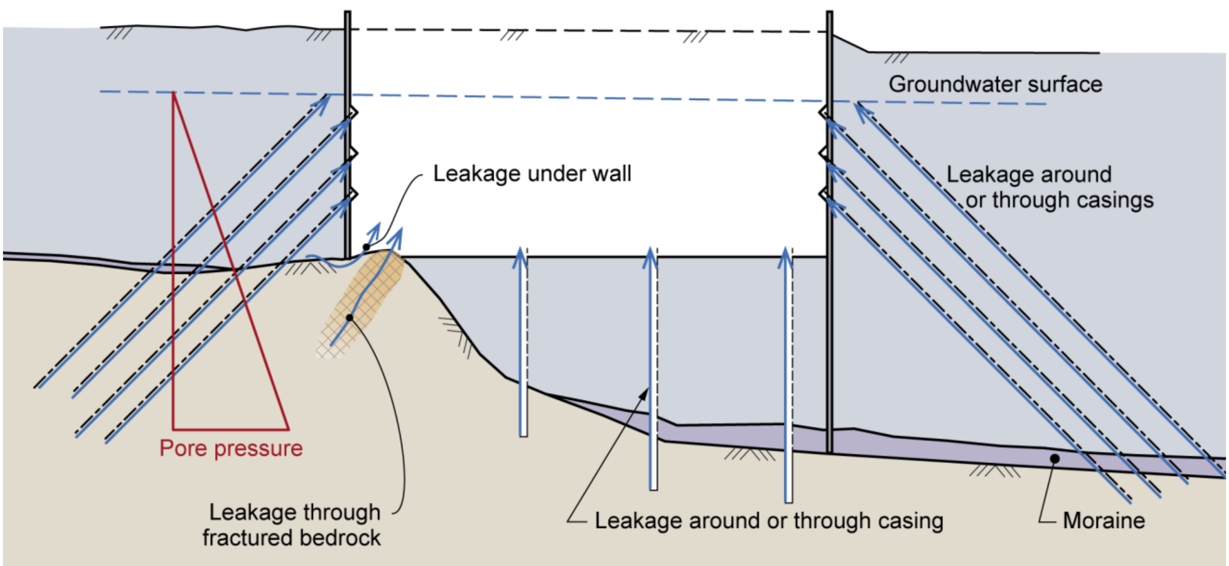

Figure 5 Illustration of possible leakage situations for a deep excavation is soft clay.

common methods for excavations in soft soils over bedrock are:

- sealing the interlocks in the sheet pile wall (with filler materials, polyurethane, polymers, bitumen)
- welding the locks after excavation
- welded double piles, combined with sealing
- mending holes in the wall
- using temporary packers in casings for tie-back anchors or drilled piles
- casting a reinforced concrete beam along the toe of the sheet pile wall cover and seal the gap between the the wall and bedrock surface
- Jet-grouting around and beneath the toe of the sheet pile wall
- rock grouting in the bedrock beneath the sheet pile wall and in the anchor boreholes
- water infiltration into the bedrock

4 CASE STUDIES

As a part of the LimitingDamage-project an extensive number of case studies have been analysed to investigate the most common causes for extensive settlements (Karlsrud et al., 2015). All projects are deep sheet pile wall supported excavations, carried out in normally consolidated soft clays. In this article five case studies are presented, with the aim to illustrate the effects of leakage and pore pressure reduction.

4.1 Case study 1

This case study was the excavation for a new railway tunnel south of Sandvika, Norway. The excavation consisted of a more than 400 m long cut-and-cover tunnel, to a depth of 17 m (15 m below the ground water level). The excavation was supported by up to 4 levels of tie-back anchors installed to bedrock. In total more than 1000 anchors were installed. The soil conditions consisted of soft normally consolidated quick clay, underlain by moraine on top of bedrock. The structure was partly founded on bedrock at the level of the excavation, in addition to drilled steel core piles.

The results from the case study has previously been reported in Braaten et al. (2004). As the excavation proceeded and drilling for anchors was undertaken, considerable pore pressure decrease, amounting to almost 10 m pressure head, at bedrock was observed. Monitored pore pressure levels over time are shown in Figure 6. Infiltration wells were installed, which resulted in stabilisation of the pore pressure levels. However, as the drilling for steel core piles started, the pore pressures decreased further.

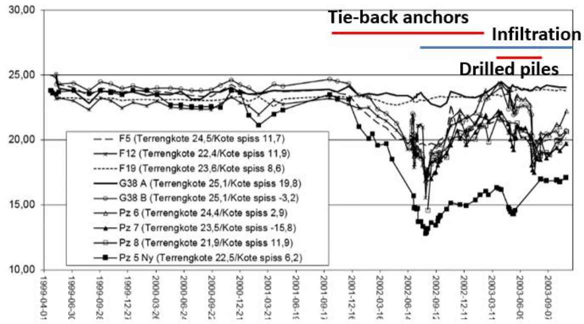

Figure 6 Monitored pore pressure levels and type of construction activities (Braaten et al., 2004).

Significant leakage was observed between the casing for the tie-back anchors and the sheet pile wall, as well as on the outside of the casings for the steel-core piles (Figure 7). The leakage through the casings was stopped by injection of cement in the bedrock. The leakage around the casings were difficult to manage. It increased rapidly and eroded fines material. The leakage decreased after several rounds of grouting with cement suspension and polyurethane grout.
Considerable leakage was also observed at the toe of the sheet pile wall. This was managed by casting a toe beam. Little or no leakage was observed through the bedrock itself.

Figure 7. Observed leakage around drilled casing for steel core piles (Jernbaneverket, Jong-Asker).

4.2 Case study 2

The second case study for a cut and cover road tunnel built in Oslo. The tunnel had a complex geometry due to exit ramps and the excavation was divided in two sections. The main excavation was about 80 m x 80 m and performed to a depth of 16 m, 14 m below the sea level. In the first section, the excavation pit was supported with up to 5 levels of tie-back anchors drilled to bedrock. In the second section, internal struts were used as a support. The main pit was open 2006 until 2010. The second pit endured from 2008 until closing in 2012.
Parts of the tunnel was founded on drilled steel core piles.

The soil conditions consisted of old harbour constructions, rock fill and deposits from excavations during numerous years, over a thin layer of normally consolidated soft clay. A permeable and stiff moraine was underlying the clay, the bedrock was detected assumed at 20-24 m depth.
Due to the moraine and rock fill the depths to bedrock were larger than assumed, and several leakage points were registered beneath the toe of the sheet pile wall. The leakage was stopped by jet-grouting with a centre spacing of 0,8 m. In addition, after the excavation was performed, visible leakage through the interlocks of the sheet pile wall were grouted with a polyurethane mix.

Results of monitored pore pressures at bedrock level in the main section are presented in Figure 8. Pore pressure measurements indicate that pressures at bedrock level corresponded to level 0 to -0,5 before the excavation was started. The pore pressure at bedrock decreased with 1 m during the excavation and the installation of tie-back anchors. It decreased further to a level of -7 m during the period for installation of steel core piles. The work was performed in combination with considerable pumping, to keep the pit dry. The pore pressure increased as the base slab and walls were cast and material was backfilled.

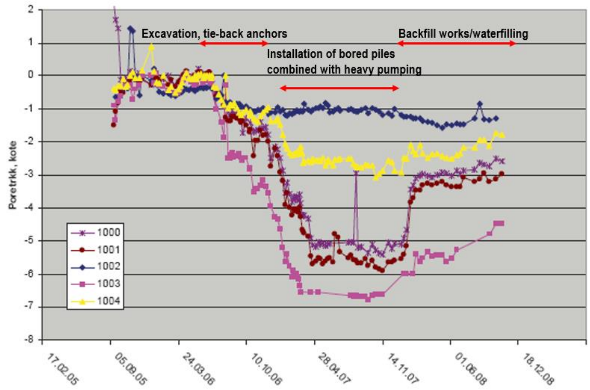

Figure 8 Observed pore pressure levels for first section in case study 2. (Modified after Johansen et. al., 2008 and vegvesen.no).

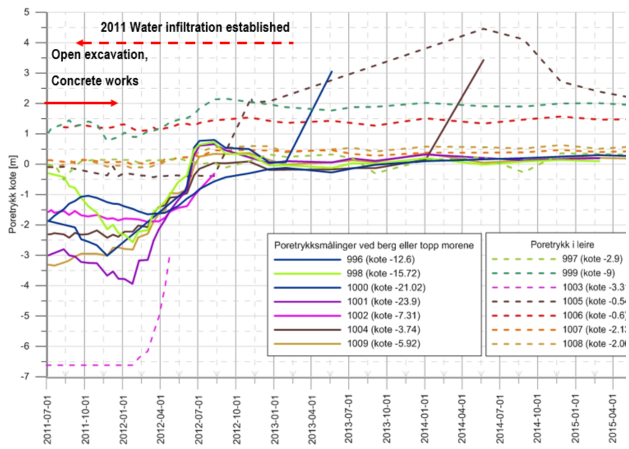

Figure 9 Observed pore pressure levels at the end of phase 2 in case study 2. (Modified after Hauser, 2015 and vegvesen.no). Water infiltration into the bedrock was started in 2011.

The second section of the excavation started in 2008. In 2011 the concrete works were performed and the backfill started, but the pore pressure did not rise to the in-situ level of 0. Therefore, it was decided to install wells for water infiltration to reduce the risk of settlements on the surrounding areas and buildings. Figure 9 show the pore pressure levels at bedrock at the end of the excavation, as well as the effects of water infiltration into the bedrock. The figure also shows that the pore pressure in the clay is not yet affected by the drainage except for one piezometer.

4.3 Case study 3

This was an extensive excavation in Oslo over an area of about 100 m × 100 m. The excavation was performed to a depth of about 10 m, 8 m below the ground water level. The excavation was supported by a sheet pile wall installed to bedrock, and supported by 1 to 5 levels of tie-back anchors to bedrock. The foundation of the building consists partly of shallow foundations on the bedrock and partly of drilled steel core piles. A typical cross-section of the excavation is shown in Figure 10.

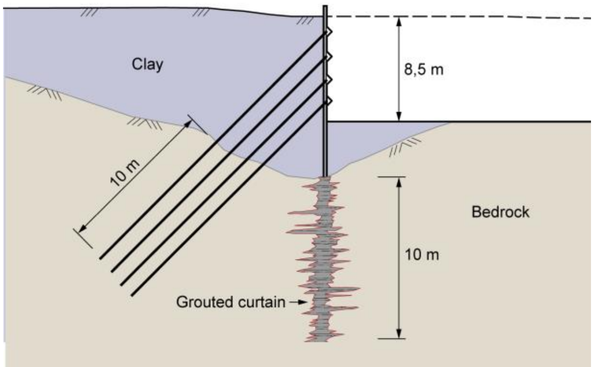

Figure 10 Cross section of case study 3.

The soil conditions consisted of fill over normally consolidated soft clay to bedrock at 2-30 m depth. A permeable layer of silty, sandy material was underlying the clay in one part of the excavation.

Due to the risk of settlements on adjacent buildings and infrastructure, measures were undertaken to reduce the risk of reduction of pore pressures. A cement curtain was grouted in the bedrock, to a depth of 10 m below the toe of the sheet pile wall. In addition, three infiltration wells were installed, tested and running before the excavation started.

Some results of monitored pore pressures at bedrock level and infiltration pressures are shown in Figure 11. Pore pressure measurements indicate pressures at bedrock level corresponding to level +1 to -1 before the excavation was started. The monitoring data shows that the pore pressures at bedrock level started decreasing during drilling of anchor level 3 and 4. During drilling for the anchors leakage was observed, especially between the sheet pile wall and the casing for the anchors, but also through the casing itself. This has been the main cause of pore pressure lowering. An example is shown in Figure 12.

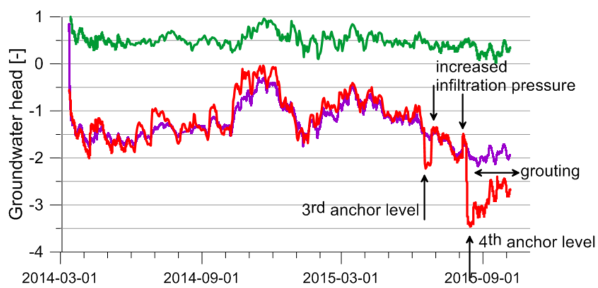

Figure 11. Monitored pore pressure levels and infiltration

Figure 12. Example observed leakage in connection with installing tie-back anchors.

To increase the pore pressure levels at bed-rock the infiltration pressure was increased. This had some effect, at the same time efforts were undertaken to stop visual sources of leakage by grouting and welding. The pore pressure decrease was limited to about 1 m.

There was no or little leakage observed through the uncovered bedrock. The grouted curtain underneath the sheet pile wall is assumed to have had the intended effect sealing water bearing fractures.

One of the key factors for limiting the pore pressure reduction is likely the extensive follow up of the work at the site and reporting sources of leakage and emphasizing the importance of also sealing small sources of leakage. In addition, the combination of grouting and infiltration has been successful.

At the time of writing piles have not yet been installed, at the bottom of the excavation and therefore the effect of drilling for piles cannot be evaluated.

4.4 Case study 4

This excavation in Oslo was performed in close vicinity of several old buildings, some founded on shallow foundations. The excavation for the basement was performed to a depth of 16 m, over an area of about 150 m × 100 m. The excavation was supported by a sheet pile wall installed to bedrock, supported by 5 levels of tie-back anchors drilled to bedrock. The project has also been presented by Eggen (2015)

The soil conditions consisted of fill over 1-2 m dry crust clay over normally consolidated soft clay to bedrock, at 10 to 30 m depth. Beneath 8 m depth, the clay was quick. The foundation consisted partly of drilled steel core piles and partly of shallow foundations on bedrock. In addition, tension anchors were installed into the bedrock to prevent uplift. A typical cross-section of the excavation is shown in Figure 13.

Drainage to existing tunnels in the area had caused decrease of pore pressures at bedrock of 10 - 35 kPa. As a result, ongoing settle-ment of 20 mm/year were registered at time of construction.

Measures were planned and undertaken to reduce the risk of drainage. The bedrock beneath the sheet pile wall was grouted to a depth of 10 - 15 m below the bedrock surface. The rock grouting was drilled vertical from the terrain level. Six infiltration wells were installed before the excavation started. The pore pressure was monitored at bedrock and in the clay with several piezometers.

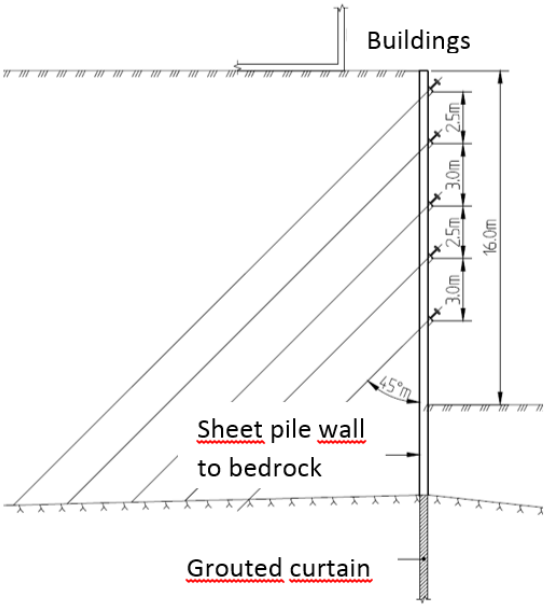

Figure 13 Typical cross section case study 4.

Pore pressure levels decreased as the excavation reached the bedrock. Infiltration wells were then activated, to mitigate the drop in pore pressure. However, the effect of the wells was smaller than expected. Therefore, additional rock grouting of the bedrock was performed, by drilling holes from the excavation pit and normal to the rock foliation resulting in more efficient sealing than the vertical grouting.

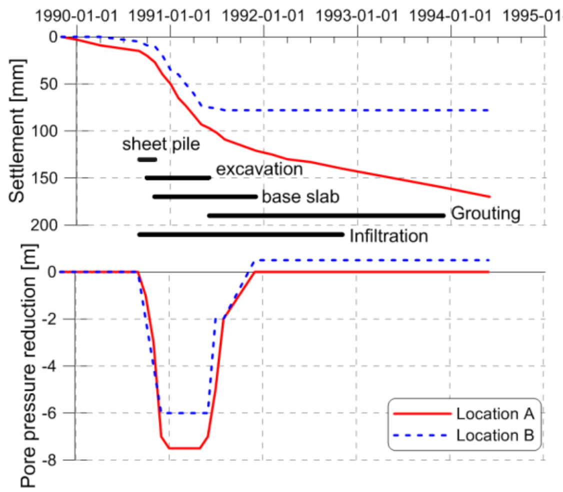

Figure 14 Monitored pore pressures and settlements at two locations.

Some results of monitored pore pressures at bedrock level and settlements are shown in Figure 14. Pore pressure measurements indicate that the grouting and infiltration was effective measurements. The pore pressures recovered and the settlement rate was decreased to the same levels as before the excavation started. Other important measurements were consistent use of packers in every borehole, where leakage was observed, both for drilled anchors and drilled piles. Furthermore, additional infiltration wells were installed trough the sheet pile wall.

4.5 Case study 5

This excavation in Oslo was an approximately 10 m deep and measuring 90 m × 50 m. The excavation was supported by three levels of tie-back anchors. The sheet pile wall was partly installed to bedrock, partly by installing every third nail to bedrock and using stabilisation with lime-cement columns. The soil conditions consisted of 2 m of fill over normally consolidated clay, with a depth of 15-45 m to bedrock. There were 120 steel core piles installed from the bottom of the excavation.

To ensure safety against bottom heave, it was necessary to lower the water pressure by 6 m inside the excavation using a system of relief wells. The water pressures were monitored outside the excavation and four infiltration wells were installed to mitigate pore pressure decrease.
Before the excavation was started, pore pressure levels in the area had already been lowered by neighbouring excavations. However, the excavation process including the use of relief wells, installation of tie-back anchors, and drilling for steel core piles have resulted in a pore pressure lowering of about 30-40 kPa over a period of about 6 months. The infiltration wells were stopped during a short period to evaluate their effect, showing that their contribution for infiltration corresponded to approximately 20 kPa. After the base slab was casted, the pore pressure levels slowly recovered to the initial levels.

5 ANALYSIS OF DATA

To better understand the effects of drainage to excavations in soft clays, the LimitingDamage-project has collected and interpreted data from 17 case histories, together with previously published data from Braaten et. al (2004), Johansen (1990) and Karlsrud (1990).The results are shown in Figure 15. In the plot, the measured pore pressure reduction at bedrock level, Δu, is normalized with respect to the depth of the excavation below the original ground water surface, H_{max}. The data are plotted against the horizontal distance of the piezometer from the excavation. The data from the five case studies are labelled CS1 to CS5.

The data shows a relatively large scatter, related to varying hydrogeological conditions, amount and duration of the leakage, use of different construction methods and varying mitigating measures. However, some general conclusions can be drawn by organizing the data accoring to the mitigating measures that were undertaken.

Red symbols show cases where no grouting or recharging (infiltration) of water was undertaken, green symbols show cases where some grouting at the toe of the wall and into bedrock was undertaken, and blue symbols represent cases where some grouting as well as infiltration was undertaken.

The figure suggests that even when performing systematic grouting and infiltration, the maximum pore pressure reduction close to the excavation could correspond of 20-50% of the depth of the excavation below the groundwater level. Furthermore, a reduction can be extend as far as 300-400 m laterally from the excavation. It can be concluded that it is challenging to maintain the pore pressure levels, even when mitigating measures are undertaken.

Dashed lines in the figure indicate which range pore pressure drawdown can be expected. It is important to note that the lines are rough estimates. The lower bound could be applied for cases where both infiltration and grouting is performed, and the higher bound can be taken as a worst-case scenario where no mitigating measures are undertaken.

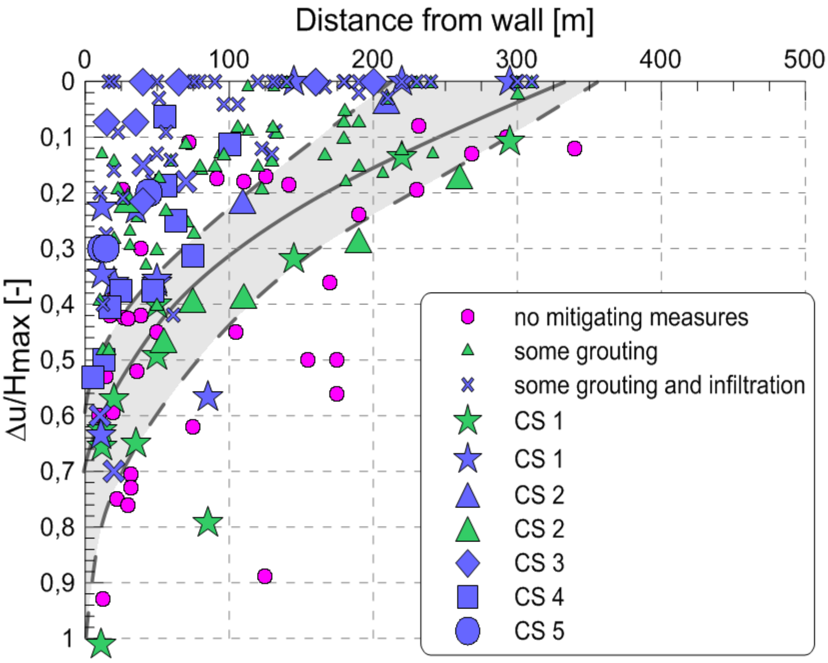

Figure 15 Observed normalized decrease in pore pressure at base of clay layer as function of distance from the excavation based on case records from Norway

However, some projects experience an even larger pressure drawdown, caused by unfavourable conditions at the specific sites.

Analysis of settlement data (Karlsrud et al., 2015) indicate that drilling for piles are associated with a greater risk of leakage than drilling for tie-back anchors. The reason is likely that piles are generally drilled from a deeper level that the anchors. In addition, systematic leakage-testing and grouting for anchors are generally performed to ensure sufficient tension capacity of the grout body. This is generally not undertaken for pile, unless designed as tension pile.

The case records CS1 and CS2 show the largest decrease in pore pressures at bedrock level. For both these projects there was a considerable layer of moraine on top of the bedrock. This is one of the reasons for the relatively large reduction in pressures, due to the fact that there was a large potential for leakage tough the permeable layer at the toe of the wall. In addition, the continuous moraine layer also resulted in a drawdown at a far distance from the wall.

6 CONCLUSIONS

The main conclusion for the analysis of data is that drainage is one of the main causes of settlements that are not accounted for in design. It is seen that measures must be taken from the early planning stage until construction is finished.

6.1 Early design phase

It is important to undertake feasibility studies and assessment of ground conditions including analysis of geotechnical (especially the over-consolidation ratio) and hydrogeological conditions (artesian pressures, sensitivity analysis to drainage), to evaluate the risk of pore pressure decrease with respect to the design depth of the excavation and the distance to the bedrock surface. Time for construction and possible duration for an open excavation pit needs to be evaluated.
At this stage, impact of previous and ongoing construction (ongoing settlements from drainage to tunnels, excavation pits, earthworks and fills, ground water lowering) need to be considered. In addition, alarm limits for pore pressure reduction and requirements for maximum allowable

settlements (including creep) should be evaluated, depending on the sensitivity to damage for buildings, structures and infrastructure surrounding the excavation. The risk for pore pressure decrease due to drilling for tie-back anchors and piles should be evaluated against alternative methods (internal struts and driven piles).

6.2 Detailed design phase

During the design phase, measures to decrease the impact from the excavation and foundation works need to be described:

- Use of temporary packers in casings, and grouting and sealing of boreholes in bedrock
- Assess and choose drilling methods considering risk of erosion, disturbance, drainage
- Request logging of data during drilling

The hydrogeological conditions should be assessed, with respect to permeable layers over bedrock or in the clay, to enable evaluation of the influence of drainage. In addition, hydrogeological tests, geological mapping of cracks and weakness zones can be valuable. Describe measures to prevent drainage into the construction pit, as well as wells for water infiltration.

6.3 Construction phase

A plan for monitoring needs to be established to document the impact of the excavation. Measurements need to start well in advance of construction, to capture seasonal variations in pore pressures, as well as ongoing settlements.

The monitoring of pore pressure should be undertaken in a zone of at least 200 – 300 m, from the excavation to capture the possible effects of drainage. It is crucial to install piezometers in the intersection between clay and bedrock and in permeable layers in the clay, to be able to capture the quick response on pressures caused by drainage.

It is necessary to undertake quality control at the construction site by geotechnical engineers or other qualified staff, including verifying the contractor's procedures and execution for drilling and sealing/waterproofing. Finally, requirements should be made to ensure that the contractors has the requested skills and expertise.

7 ACKNOWLEDGEMENTS

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