BegrensSkade II – REMEDY – Risk Reduction of Groundwork Damage: An Overview

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Abstract. Deep excavation and foundation works in soft clays can cause large settlements, resulting in damage to neighboring buildings and structures. The costs related to these types of damage can be substantial. There is significant potential for reducing such costs if the causes are better understood and the risk is assessed during planning, design and execution. The research project "BegrensSkade II" ("REMEDY") focuses on developing guidelines for the main causes of excavation-induced damage related to installation effects, drainage and pore pressure lowering, and vibration effects. In addition, tools to support risk management and decision making in the building process are developed. The project is funded by the Norwegian Research Council with participation from a wide range of consultants, contractors, clients and research institutes in Norway. This paper provides an overview of the work carried out in BegrensSkade II and highlights some initial findings.

1. Introduction
Scandinavian cities have challenging ground conditions. Typically, soft marine clays, which are susceptible to settlements, overlay hard bedrock with varying depth. Increasing population and concentration of infrastructure in urban areas in Norway has led to extensive need for underground construction. Deep excavations and foundation work for new development is carried out in areas with more challenging ground conditions than before, and close to existing buildings and structures. The required groundworks can result in deformations which can cause damage to neighbouring property.

The cost for damage caused by geotechnical works alone in Sweden and Norway is estimated at 3% of the total investment in building projects [1]. Adopting this 3% estimate, the annual costs of 'geotechnical damage' in Norway is a staggering 13 billion NOK. These costs are covered by insurance companies, property owners and project stakeholders, which often are state agencies (in other words by Norwegian society). There is an enormous potential for cost savings by reducing the number and the extent of groundwork damage.

2. Brief overview of BegrensSkade - Remedy
In the years of 2012-2015 the R&D project BegrensSkade I was executed, with the aim of reducing costs related to damage to neighboring buildings. In this project data from case studies were collected and the main causes of damage were mapped. This initial research has provided the required insight and data to develop risk management tools. The main aim of BegrensSkade II/REMEDY (2017-2022) is to integrate risk management into geotechnical projects, to reduce the risk of damage caused by
deep excavation and foundation works. Figure 2 illustrates the building process from planning to execution, the stakeholders involved and examples of decisions to be made, which affect the risk of the project. Risk management tools will aid risk informed decision-making during the building process and will support communication amongst the project stakeholders. To achieve the objective for the R&D project, practicable tools for risk management, vulnerability analysis and cost-benefit analyses are developed.

Figure 1. Illustration of the building and construction process, involved stakeholders and decisions to be made, and the impact of the research.

In this paper, the conducted research to develop tools and guidelines is discussed. This paper is structured as follows: First, installation effects caused by drilling of foundation piles and anchors are discussed. Second, field data from excavation-induced pore pressure reduction is presented. Third, a field test of blasting-induced vibrations is introduced. Fourth, work related to assessing installation effects of driven piles on slope stability is briefly described. Fifth, developed practical tools for risk assessments are presented. Finally, this paper closes with concluding remarks and an outlook of future work.

3. Focus areas

3.1. Effects of drilling of foundation piles and anchors

For the geological conditions in Scandinavia, with soft soil over hard bedrock, it is common to drill tieback anchors and foundation piles with casings through soft soils and into strong bedrock. Within the BegrensSkade I-project 24 case studies of deep excavations in soft clay supported by sheet pile walls have been analysed [2]. It was concluded that the use of drilled tieback anchors and/or foundation piles significantly increases the risk of excessive settlements in the areas surrounding the excavations. The settlements are related to both leakage of ground water along the casings for anchors and/or piles and subsequent consolidation settlements, as well as mechanical disturbance and erosion of the soil from drilling. Figure 2 show measured ground settlements ($\delta_v$) against distance ($x$) from the support wall of deep excavations in soft clay, both normalized against the depth of the excavation ($H$). The shown data was acquired approximately one year after the excavation works were finalised and thus include displacements caused by installation effects, excavation works and partly from pore pressure reductions. The figure includes more recent data from deep excavations. The different symbols refer to the used support system (e.g. drilled tieback anchors, drilled piles, internal struts and combinations). For
comparison the solid and dotted black lines represent lines for expected ground settlements for a deep excavation in soft clay, with sheet pile wall installed to bedrock or above bedrock [3]. To deepen the understanding of the impact of foundation pile and anchor drilling on induced displacements, both field and laboratory investigations were carried out which is discussed below.

Figure 2. Measured ground settlements $\delta V$ versus distance $x$ from the support wall of deep excavations in soft clay normalized against excavation depth $H$. Updated from [2]).

Monitoring data from field tests ([4] and [8]) and case studies [2] have documented that drilling with air driven hammers may cause significant pore pressure changes and settlements in the surrounding ground. The results also showed that ground settlements occurred shortly after drilling, hence indicating a loss of soil volume (i.e. cavities) around the casings when drilling through granular material above bedrock. The cavities are likely explained by the air-lift pump effect ([22] and [21]) from flushing which may induce a flow of ground water towards the drill bit and "suck" silt and sand particles into the borehole. The field tests ([4] and [8]) also showed that drilling with water driven hammer caused less settlements and excess pore pressures compared to air flushing.

A series of small-scale model tests was conducted to get further insight into the mechanisms of drilling effects on soil displacements. Figure 3 shows a 3D drawing of the experimental set up which made it possible to drill a miniature pile (diameter = 35 mm) with simultaneous penetration, rotation and water flushing. Baskarp sand No. 15 was saturated and used for the entire test series. The main objective of this research was to investigate the influence from drilling with water flushing on the surrounding ground by varying parameters such as penetration and flushing rate. The preliminary test results show that increased flow rates not only caused larger excess pore pressures and influence zone around the pile but also generated up to 2.7 times more drill cuttings than the installed pile volume. The results indicate that a careful balance between the penetration and flushing rate could notably reduce the risk of unwanted soil erosion around the pile. Further details of the conducted experimental programme and findings are reported elsewhere ([5] and [6]).
3.2. **Drainage towards excavations causing pore pressure reduction**

One of the main causes of damage related to deep excavations for Scandinavian soil conditions is leakage into excavations. The leakage causes pore pressure lowering in the underlying confined aquifer and settlements developing over time. The main leakage scenarios for an excavation in soft clay, as illustrated in Figure 4.

The problem is closely related to the subsidence caused by groundwater pumping from confined aquifers in areas with soft soil deposits (e.g. Mexico City, Bangkok, Shanghai, New Orleans etc.). However, the application to deep excavations and the complexity of the possible leakage scenarios around an excavation, especially in urban environments have not been studied sufficiently.
The BegrensSkade I-project has collected and analysed pore pressure data from 20 case studies, some from previous references [9], [10] and [11]. The results are shown in Figure 5. In the plot, the measured pore pressure reduction at bedrock level, \( \Delta u \), is normalized with respect to the depth of the excavation below the original ground water surface, \( H_{\text{max}} \). The data are plotted against the horizontal distance of the piezometer from the excavation. Circular symbols show cases where no grouting or recharging (infiltration) of water was undertaken, triangular symbols show cases where some grouting at the toe of the wall and into bedrock was undertaken, and crosses 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 water lowering close to the excavation could correspond to 20-50\% of the depth of the excavation below the groundwater level. Furthermore, a reduction can be extended as far as 300-400 m laterally from the excavation. It is concluded that it is challenging to maintain the pore pressure levels, even when mitigating measures are undertaken.

Dashed lines in the figure indicate a range of expected pore pressure drawdown. 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 upper bound can be taken as a worst-case scenario where no mitigating measures are undertaken.

Figure 5. Pore pressure reduction with respect to excavation depth under the ground water table [2].

To avoid damage caused by drainage, there is an urgent need to develop a better understanding of the vulnerability to pore pressure decrease for confined aquifers. The project aims to use analytical and numerical models to predict pore pressure change caused by drainage and to evaluate the sensitivity of the models for different parameters such as the boundary conditions, soil layering, hydraulic conductivity and groundwater recharge situation. Finally, it is envisioned to translate the new insight into guidelines to reduce damage caused by excavation-induced pore pressure reduction.

3.3. Vibrations due to construction activity

To protect neighbouring buildings from damage caused by vibrations from blasting, many countries have vibration guideline limit values in national standards. However, building damage assumed to originate from vibrations are seldom observed. This may indicate that today's limit values are overly conservative. More recent research was carried out to investigate which magnitude and frequency of
vibrations buildings can withstand without suffering from damage. For this reason, a full-scale field blast test has been executed and analyzed. The blasting test was performed in Spulsåsen rock quarry in Våler municipality in Hedmark, Norway in November 2018. Two test buildings were erected at the test site, one in cast-in-place C30/37 concrete and one made of Leca (lightweight expanded clay aggregate) blocks. The buildings were founded on an approximately 0.5 m thick compacted layer of gravel, over rock. The dimensions of the buildings were 5 x 2 x 2.4 (l x w x h) meter. The concrete building had 200 mm thick walls without reinforcement, while the Leca building was constructed from 250 mm Leca blocks with plastered outer surfaces. Both buildings had one door and one window opening. At the top of the buildings, joists were laid and filled with crushed rock to simulate the mass and ground pressure from a typical detached house on top of a basement. Each building was instrumented with eight three-axial velocity sensors (geophones) and eight dynamic strain sensors. In addition, vertical vibration on the ground and air blast pressure were measured. Figure 6 shows the test area and the instrumented Leca building.

Five blasts rounds were fired consisting of all together 143 charged holes. The total amount of explosives detonated in one blast round varied from 3 kg to 404 kg, and the explosives detonated per delay varied from 3.0 kg to 37.8 kg. The blasts were designed to give equal dynamic loading on the two test structures, and increased vibrations, starting at a low value and increasing progressively as the blasts came closer to the buildings. The buildings were visually inspected between each blast round to detect and document any damage. In addition, the results from the strain measurements were reviewed correspondingly to detect any cracks not visible to the naked eye.

The measured maximum peak particle velocity (PPV) varied from about 20 mm/s to more than 260 mm/s between the different blast rounds. Measured PPV were consistently higher in the Leca building than in the concrete building. The guideline limit value calculated according to today's Norwegian standard NS 8141:2001 [12] are 50 mm/s for both buildings. The last three blast rounds produced vibration values above this guideline limit value for both buildings. However, no visible damage was found on any of the buildings. Nevertheless, the closest blast produced a 0.05 mm wide crack above the door on the concrete building, which was not visible to the naked eye, but could be detected from the strain measurements. Both buildings were exposed to strain levels which are above the critical strain levels according to e.g. Siskind et al. [13]. This may indicate that these newly erected constructions may tolerate higher strain levels than what has been found to produce cracking in other studies. Nevertheless, the results of the test indicate that today's vibration guideline limit values include a large safety margin for buildings on rock, when considering damages to outer walls, which
this study was designed to investigate. The reduced dimensions of the test buildings compared to more common buildings may have affected the vibration response. For damage mechanisms like shearing and bending, for which the building is forced to follow the vibration motion of the ground surface, the deviation in resonance frequencies is of minor concern. However, since measurements in accordance with NS 8141:2001 shall be carried out at foundation level, building amplification may be higher in more common buildings than in the test buildings in this experiment. This may cause resonant response to become a more dominant damage mechanism in more common buildings and needs to be further considered before using the findings from this experiment to adjust the vibration limit values.

3.4. Effects of pile driving on slopes
Pile driving in soft soil cause mass displacement, disturbance and pore pressure build-up. In the vicinity of slopes, pile driving may trigger slope failure. In Norway, there is no standardized method to analyze these effects. Within the BegrensSkade-project, the effect of pile driving near slopes is being analyzed in order to propose a method to account for the reduced slope stability during pile installation. This will reduce uncertainties normally encountered in the installation process including the sequence of pile driving and can also improve methods and guidelines of pile installation practice in Norway. The aim of this research is to develop a clearer picture of the failure mechanism as well as to develop an analysis framework that can be adopted in practice.

During this work, methods which can be used to predict pore pressure generation and dissipation due to pile driving are gathered. Cavity Expansion Method and Strain Path Method are two of the recognized methods to simulate pile driving. These methods are combined with constitutive soil models to predict displacements and excess pore pressures generated in the soil as a result of pile driving. Furthermore, data from executed construction projects are compared with results from numerical simulation in order to assess predictions.

A case study has been investigated, where pile installation caused slope stability failure of a bridge foundation in Fredrikstad, Norway. Numerical simulations of this case are undertaken using the Plaxis 2D finite element code and applying the Volumetric Strain feature to replicate pile installation. The initial analysis results so far indicate that it is unlikely to capture the reduced safety factor of the slope using elastic-perfectly plastic constitutive models which do not consider strain softening of the soil. Further work on this case will include employing more advanced soil models and 3D modelling of the problem.

4. Methods for risk management
Systematic risk assessments that focus on the damage potential caused by ground works are traditionally not undertaken in building and construction projects. For projects which involve challenging ground conditions, risk management could reduce damage costs and conflict. To help the industry implement risk assessments into projects, BegrensSkade is developing tools to aid risk management and decision making. One tool is developed for risk identification and management, based on a classical risk matrix approach where the uncertainty and consequence for unwanted events is assessed semi-qualitatively. In addition, a tool is developed to assess the risk of excavation-induced damage of neighboring buildings which is implemented in ArcGIS. These tools will support decision making, communication and follow up during construction.

4.1. Risk identification and management
The excel risk management tool is developed in Excel, programmed in Visual Basic for Applications (VBA) and it works in Excel. The risk methodology used to design this tool is based on the framework described in the ISO-31000:2018. The tool is developed for geotechnical works, but is generic and can be applied to any type of project. The tool is described in a paper in this conference proceedings [14].
4.2. Vulnerability analysis

The computer program ArcGIS was used to implement a pre-construction risk mapping procedure to assess the risk of building damage due to excavation works. This is crucial for urban infrastructure projects including the excavation of tunnels or deep excavations in subsidence prone soft soils. The proposed methodology offers a systematic procedure for incorporating both the impact of excavation-induced displacements and the vulnerability of adjacent buildings with a focus on typical Scandinavian conditions. Specifically, effects due to excavation-induced pore pressure reduction combined with abrupt changes in bedrock depth are considered. In the following sections, a brief description of the main components of this risk mapping procedure is provided.

Figure 7 shows an overview of the adopted procedure. Adjacent buildings which are not directly founded on bedrock are considered. The impact assessment applies empirically derived relationships between vertical displacement and distance from the excavation wall [2] to compute short-term settlements for each building corner point (based on data in Figure 2). Consolidation settlements due to pore pressure reduction are also considered (based on data in Figure 5). These so-called long-term settlements are derived by combining a soil stratification model, field data of excavation-induced pore pressure reduction [4] and the modulus concept initially proposed by Janbu in 1963 [15]. Two continuous layers were used to conceptualise the soil stratification, which were: a layer of dry crust with a constant thickness and a clay layer above bedrock. Finally, building slope and settlement limits proposed by Rankin in 1988 [16] were adopted to derive impact categories for each building considering the sum of predicted short-term and long-term displacements. Figure 8 depicts the outcome of an impact assessment applied to a deep excavation for a railway project. Note that this method of computing building displacements neglects soil-structure interaction mechanisms and assumes that buildings respond fully flexible.

The second part of the risk mapping procedure focuses on the building vulnerability, which can be described as the building predisposition to damage due to soil deformations. Geometrical and structural building characteristics and results from a visual inspection of the building condition are considered for the definition of vulnerability classes. The obtained impact and vulnerability results are combined in a risk matrix to predict the risk of building damage caused by excavation works. This methodology is suitable to identify buildings exposed at high risk of damage that require further assessment, monitoring or mitigation measures. Further details of this methodology are provided elsewhere ([17] and [18]).
Figure 8. Impact assessment: (a) prediction results (overall impact category based on building slope) and (b) symbols used to visualise impact categories (from [17]).

5. Summary and conclusions
Underground construction in urban areas with soft soil ground conditions can cause damage to neighbouring property. The costs related to this type of damage can considerably add to the overall project costs. The main aim of the BegrensSkade-project is to reduce the risk of damage, by focusing on developing risk assessment tools to aid the industry in adopting risk informed decision making. In addition, the project focuses on the main causes of damage (installation effects, drainage and vibration) and developing new guidelines for the industry. Result are published open access on the project webpage: https://www.ngi.no/eng/Projects/BegrensSkade-II-REMEDY-Risk-Reduction-of-Groundwork-Damage/Risk-management-tools.

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