BegrensSkade/REMEDY

Risk Reduction of Groundwork Damage

Deliverable D3.4

Using hydrogeological numerical modelling to predict drainage to excavations – findings from four Norwegian case studies

Work Package 3 – Hydrogeological methods, drainage and grouting

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Summary

Urban ground work such as deep excavations performed in soft clay may cause damage to neighbouring buildings and structures as a consequence of settlements partly caused by drainage. The costs related to settlement damage can be substantial and there is a considerable potential for reducing these costs. To assess the risk of drainage caused by a particular set of construction methods, as well as the effect of various mitigation measures, it is necessary to quantify the expected groundwater drawdown in the zone of influence surrounding the groundwork site. This may be done with hydrogeological modelling.

As part of the work towards general recommendations regarding the use of hydrogeological numerical modelling to predict the pore pressure reduction caused by drainage to excavations, four modelling cases are presented and summarised. The case studies vary from being purely research-based with the purpose of assessing a model's ability to predict or replicate pore pressure reductions, to being part of consulting work with the purpose of assisting in the decision-making regarding the use of mitigation measures.

Case 1, 2 and 4 regards drainage to an excavation, while case 3 considers drainage to a tunnel. Drainage is modelled through bedrock in case 2-4, and through moraine in case 1. The two most important factors influencing the results seems to be the choice of boundary conditions and the hydraulic conductivity of the draining layer. In case 1, where a moraine layer was present, a sensitivity analysis of the layer thickness showed that it had little effect on the results compared to realistic variation of the hydraulic conductivity. The compliance of the simulated results with measured/expected values of the pore pressure reduction, varied from case to case.

The performed modelling work does not lead to an unambiguous conclusion as to what extent hydrogeological modelling should be used in construction projects. The model’s ability to predict the influence of various construction methods and mitigation measures on the pore pressure, depends on how well the local ground conditions are mapped. There will however always remain uncertainties, partly due to the simplifications that are made in a model, and partly due to the gaps in the knowledge of the ground conditions. The modeller and those who make decisions based on the results must be cautious of these regardless of what the model is to be used for.

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Review and reference page

Introduction

Urban ground work such as deep excavations performed in soft clay may cause damage to neighbouring buildings and structures. Drainage causes pore pressure lowering, followed by consolidation settlements. The costs related to settlement damage can be substantial and there is a considerable potential for reducing these costs.

To assess the surrounding building and structural settlement damage risk it is necessary to quantify the expected groundwater drawdown in the zone of influence surrounding the ground work site. In typical Norwegian ground conditions, due to the nature of confined aquifer systems and limited recharge levels, even small amounts of leakage (e.g. from a single pile casing) can result in substantial decrease in pore pressures at bedrock level.

Figure 1 illustrates ideally how the groundwater level in the surrounding soil is lowered as the construction work in an excavation proceeds, and how the groundwater level may be restored after construction has been finalized.

The risk of drainage and pore pressure reduction may be reduced by adjusting the construction design and/or implementing mitigation measures. The need for such adjustments and measures should be exposed in the early design phase of a project. Necessary investigations should be undertaken to understand the hydrogeological and geotechnical conditions at the site, before being used in analyses of the problem. Analyses may be performed analytically or numerically. For construction projects, there are often made hydrogeological numerical models to predict the influence that the ground works will have on the pore pressure reduction at various distances from the excavation at various time-steps. There is some disagreement in the industry as to how reliable such models may become and for what purpose they should be used.

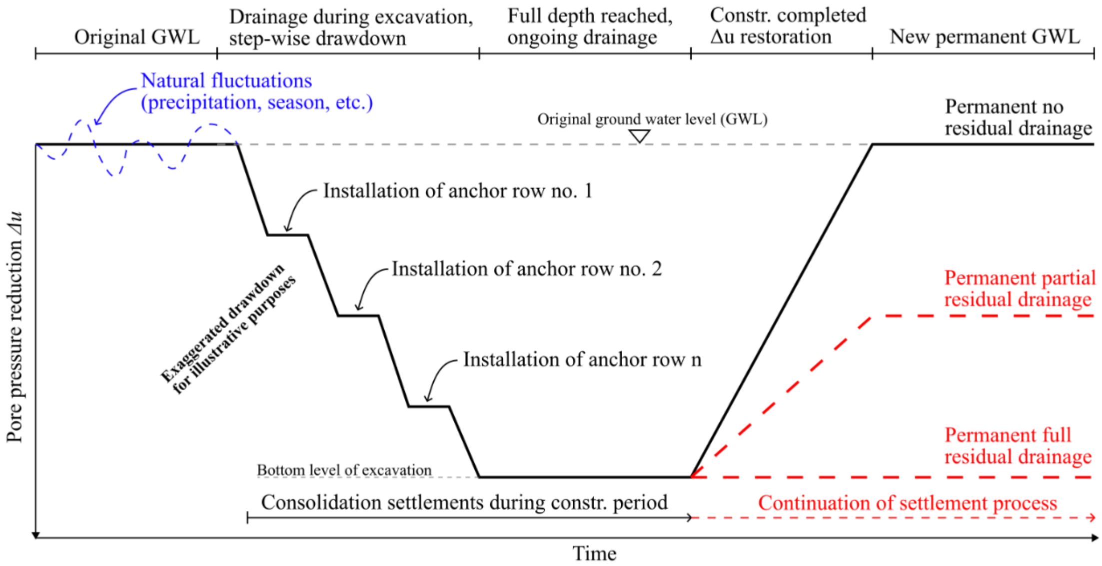


Figure 1: Illustration of pore pressure reduction Δu from construction of a deep excavation and the onset of primary consolidation in the surrounding clay with scenarios for settlement development after construction is completed, based on the degree of restoration of pore pressures.

Case studies

Hydrogeological numerical modelling was performed within the REMEDY project on four selected case studies with the aim of providing answer to the following questions:

What value and benefit did the numerical model provide to the project?
Did the available ground information allow for an accurate prediction of the pore pressure reduction Δu, using numerical computation, caused by ingress of groundwater into the excavation?
What were the uncertainties associated with conceptualization, modelling and numerical output for each case-study?

Case 1 features a typical cut-and-cover culvert deep excavation in Oslo, **Case 2** is a large footprint deep excavation in Oslo, **Case 3** is a from tunnel project in Drammen and **Case 4** is a future deep excavation planned in Oslo.

Common for all four case studies was that hydrogeological numerical modelling was applied to quantify the amount of pore pressure drawdown due to leakage into the excavation or tunnel.

Each case presented their own unique challenges related to conceptualization of the hydrogeological conditions, set-up of the numerical model and interpretation of the results with associated uncertainty.

Hydrogeological modelling - Case 1

Author(s)	Stav, Helene (NMBU)
Objective	Assess and compare with field data the pore-pressure reduction Δu around a cut-and-cover deep excavation and calculate the associated vertical clay settlements
Modelling details	**2D model** | ArcGIS Pro | Leapfrog Works | Modelmuse | FeFlow | Seep/W
Further reading	Report D3.2 *(master's thesis)* (REMEDY, 2022b)

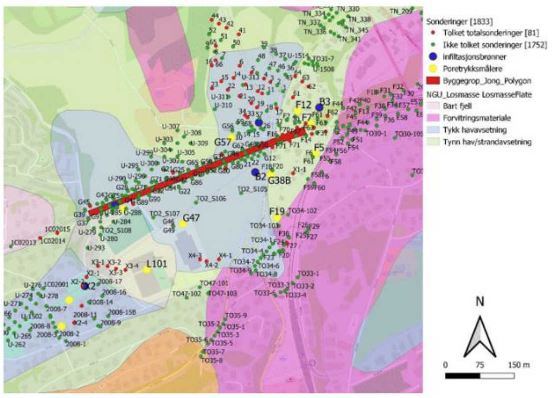
Description of project

In this thesis the uncertainty in a groundwater model has been studied, and the value of using models as a tool to evaluate the risk of draining the area surrounding a deep excavation is discussed.

The approach to this issue was to start mapping the geology and the hydrogeology, based on former ground investigation. The investigation was visualized in QGIS and a numeric visualizing program, Leapfrog Work. Based on this mapping, the groundwater model was defined. The model is a simplified 2D model of Jong, where different parameters, boundary conditions and geometry were studied.

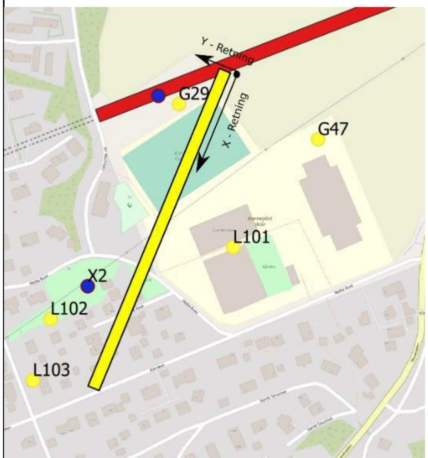
Conceptual model

There was significant amount of geotechnical investigations and pore-pressure measurements for the soil, but no site-specific bedrock information.



Numerical model

The modelled cross section (yellow line) with 400m width, with its upper end-point at the deep excavation (red line).



Most significant results & limitations

This study is showing that an equivalent groundwater model can be a good tool to evaluate the risk of a drainage. The results will not be accurate, but it will contribute with a good understanding of the aquifers response, time perspective and how big the affected area can be.

The baseline model yielded acceptable values of Δu and predictions of clay settlement when compared with actual field measurements

However, the moraine was the lower boundary. Hence, any effects from groundwater flow through bedrock was not considered. Also, No site-specific data available for hydraulic conductivity of the moraine layer. High uncertainty here (orders of magnitude).

Hydrogeological modelling - Case 2

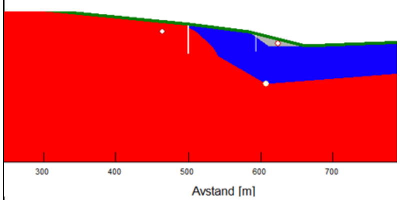
Author(s)	Tuttle, Kevin J. (Norconsult)
Objective	Assess groundwater drainage and porewater pressure reduction surrounding excavation site. Simulate and suggest remedy actions to limit pore pressure decline
Modelling details	2D model | SEEP/W
Further reading	Project reports (not openly available)

Description of project

The modelling was done in connection with a construction project, with field data consisting of geotechnical soundings, piezometers, boreholes in bedrock with down-the-hole logging, groundwater total head and Lugeon measurements. Construction pit excavated in the northern end through marine clays into bedrock, while southern end in marine clay. Lime-cement grouting in upper 5m of clay, sheet piling surrounding pit and steal-core piles through clays. Excavation 6-10m below groundwater level. Open pit modelled for 1,5-2 yrs. before groundwater fills between watertight construction and sheet piling.

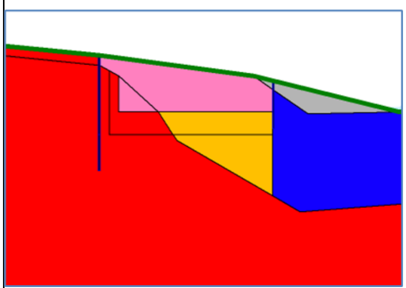
Conceptual model

1.4 km 2-D profile consists of fractured bedrock below marine clays but rise to the surface upstream of the construction pit. Water budget includes recharge to the profile surface and groundwater flux in and out of profile. In the area of the construction site, permeable anthropogenic fill overly the marine clays. Hydraulic conductivity of the bedrock and deposits were estimated, then adjusted during calibration. Lugeon measurements in bedrock confirm order of magnitude for K in bedrock.



Numerical model

1.4 km 2-D vertical model simulation pre-construction conditions, excavated pit, open excavated pit with steal-core piles, groundwater rebound within sheet piling over a period of three years. Various scenarios with grouted vertical curtains below sheet piling, grouted bedrock floor, groundwater drainage past steal-core piles.



Most significant results & limitations

Modelling aided in giving a holistic understanding of the hydrogeologic conditions in the field. Depth of vertical grouted bedrock beneath sheet piling was also informative, limiting the depth which gave significant decrease in drawdown. Simulated drawdown was within 0.7m of measured drawdown after 2 years of excavation, showing that the results gave a good estimate of groundwater drawdown, although not exact.

The modelling of the drainage along steel-core piles was not sufficient, simulated as a general higher hydraulic conductivity of the perforated clays. Drainage was much more instantaneous than simulated.

A 2-D model is not sufficient for modelling the effects of infiltration boreholes, as they are spread in a more 3-D fashion.

Hydrogeological modelling - Case 3

Author(s)	Langford, Jenny (NGI) & Tuttle, Kevin J (Norconsult)
Objective	Assess pore pressure reduction Δu due to water ingress to bedrock tunnel
Modelling details	2D model | SEEP/W
Further reading	Project reports (not openly available)

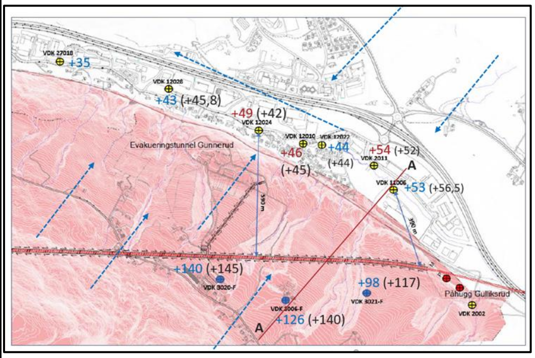
Description of project

A bedrock tunnel for railway is constructed on the Vestfoldbane, south of Drammen. Water ingress limits to the tunnel are strict due to sensitive nature areas overlying the tunnel (down to 3-5 l/min/100m), and deep depressions with soft clay in the Kobbervikdalen.

Two independent SEEP/W calculations have been carried out to predict the pore pressure decrease in the deep depression at Kobbervikdalen, at 450 m distance from the tunnel.

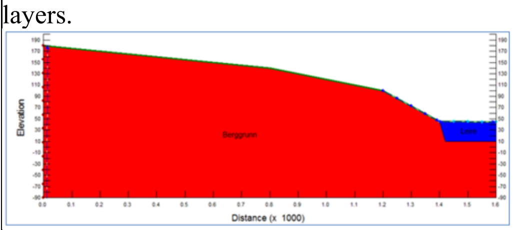
Conceptual model

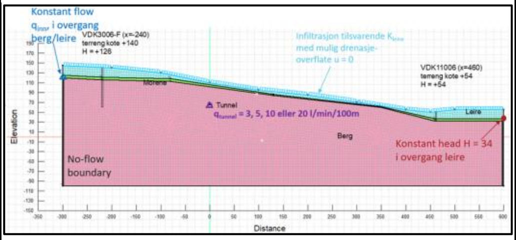
The conceptual model is primarily based on observations on groundwater levels in bedrock overlying the tunnel, and pore pressure levels in the deep depression at Kobbervikdalen.



Numerical model

Two independent models are set up in SEEP/W, with varying size, distance to the deep depression and boundary conditions. In addition, in one of the model a sensitivity analysis is performed by varying the hydraulic conductivity in the bedrock, clay and moraine layers.





Most significant results & limitations

The main conclusions from the model are:

The calculated ground water head reduction over the tunnel centre line is similar in the two models.

The predicted pore pressure decrease in the Kobbervikdalen valley differs in the two models. The difference is in the range of 1-4 m, enough to have a large impact on expected settlements due to the pore pressure reduction.

The sensitivity analysis shows that the effect of varying the hydraulic conductivity the bedrock within reasonable values results in a range of predicted pore pressure reduction in Kobbervikdalen. This gives some implications of the precision of the calculation results. From this follows that it is challenging to predict pore pressure reduction.

The flow pattern in the area is difficult to represent by a 2D-model.

Hydrogeological modelling - Case 4

Author(s)	Wiik Ånes, Eivind (NGI)
Objective	Assess the applicability of numerical 2D modelling to predict the influence of an excavation, piling and a cut-off wall on the pore pressure reduction at bedrock
Modelling details	2D Model | SEEP/W | ArcGIS Pro | Leapfrog Works
Further reading	Report D3.3 REMEDY (2022c)

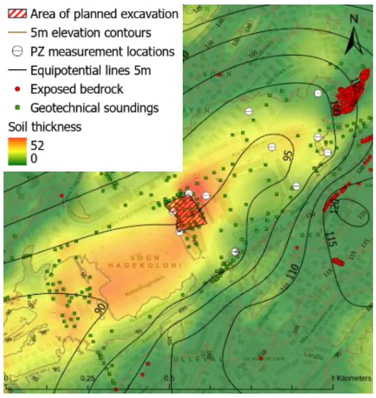
Description of project

In particular, the project investigates the ability of hydrogeological modelling to predict the pore pressure reduction at bedrock at various distances from the excavation, as well as the mitigating effect of cut-off walls.

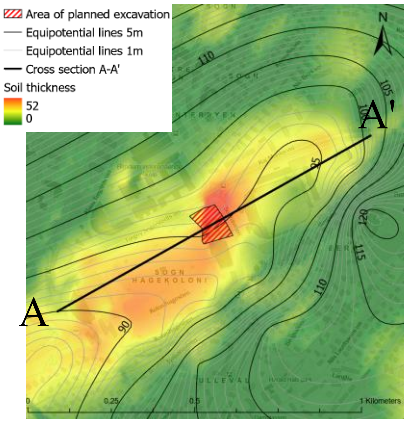
The planned excavation for NGIs new office building was used as the example case. The study began with mapping the geology and hydrogeology, based on former ground investigations. Maps of the depth-to-bedrock and the hydraulic equipotential was made using Leapfrog Works and ArcGIS Pro. The case is simplified in a 2D-cross section along the direction of predicted highest flow.

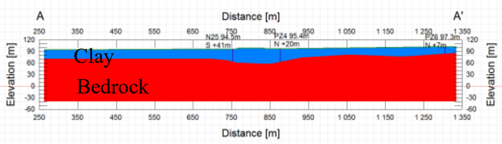
Conceptual model

The conceptual model was based on site-specific data with respect to the soil and groundwater flow, and information from nearby projects for the bedrock.



Numerical model





Most significant results & limitations

The study indicates that both choices of upstream hydraulic boundaries (constant head and constant flux) have their drawbacks for this type of problem. The modelling results themselves were in this case deemed unreliable and would not have offered help with design considerations. However, the work with the conceptual model was useful in the general problem visualization.

Main limitations regarded the hydraulic boundaries as well as the bedrock conductivity. The modelling of bedrock conductivity did not consider the anisotropy ($k_z \neq k_x$), its possible reduction with depth and the likely discontinuous nature of some of the water-bearing fractures. Deviance from empirical data regarding the influence area and the effect of the cut-off wall, is considered to be explained in part by the disregard of these aspects.

Conclusions

The following section provides conclusions made from performing hydrogeological numerical analysis on the four case studies.

Value and benefit of numerical hydrogeological modelling

As described in REMEDY (2022a) hydrogeological numerical modelling is the art of compiling data regarding the hydrology and geology of a selected field site, visualizing the three-dimensional problem, then representing this conceptual model in a simplified manor with numerical terms that still reproduces the field data during varying conditions.

Development of the conceptual model is arguably the most essential task undertaken by the modeler. It is also perhaps the most challenging one, since availability of site-specific data is generally sparse. As highlighted by Gupta et al. (2012) conceptualization is related to the fundamentals of the problem definition and is considered one of the major sources of uncertainty in numerical groundwater modelling.

Enemark (2019) the consensus model approach and (ii) the multi-model approach. For all case-studies in this report, a consensus model approach is adopted where all available observations and knowledge is integrated into a single conceptual model.

In **Case 1**, the simplified 2D numerical model contributed was determined to provide a feasible understanding of the system behaviour. Performing a 3D simulation was investigated, however it was concluded that extending the model to 3 dimensions would introduce significant model uncertainty.

Soil conditions had been extensively investigated for **Case 1**, and there were ground water monitoring data as well as infiltration well data available for developing the conceptual model and perform model calibration. The use of numerical modelling uncovered that the hydraulic conductivity yielded the highest uncertainty whereas specific storativity S as well as the moraine layer thickness had less impact on the overall results. The study shows that obtaining site-specific characterization of the moraine layer above bedrock is important for the numerical model.

In **Case 2,** simulating the 2-D profile of an excavation pit along flow lines gave valuable results regarding the depth of grout curtain below sheet piling walls to reduce groundwater ingress. It also illustrated the effects of the untreated excavated bedrock floor of the pit to groundwater ingress. Simulated porewater pressure reduction was also valuable to the project in those scenarios where ingress of groundwater was simulated along steel-core piles into the pit since that became the actual result at the construction site. Attempts and tests were performed to find ways to stop or reduce ingress along steel-core piles from bedrock into the excavation pit.

In **Case 3**, two independent models were established at approximately the same vertical profile of a bedrock hill slope which went over to a marine clay-filled valley floor. A railroad tunnel was to be constructed in the bedrock hill, and the models were to simulate various grouting intensities around the tunnel to evaluate to which degree grouting was needed to limit clay subsidence due to a drop in porewater pressure caused by groundwater ingress to the tunnel. The two models had different boundary conditions, the one focusing on groundwater flow from the hill to the valley with groundwater spring outflow, while the other model focused on both groundwater flow from the hill to the valley and also a drainage of this groundwater in a valley floor-parallel flow in an anticipated permeable sone.

The simplified models in **Case 4** were of little practical use as they were considered to not represent the actual groundwater flow in a sufficient way. There were several improvements that could have been made to make the model more realistic. Some could have been made based on the available data, but to argue for the implementation of others, there would have to be acquired additional data about the ground conditions, in particular the bedrock conductivity.

Prediction of pore pressure reduction *Δu*

Results for **Case 1** calibrated against historical data fit approximately with the projects having *partial grouting* in the Begrens Skade database for deep excavations (BegrensSkade, 2016). The modelling results also show a high sensitivity towards a change in net addition of groundwater to the model, e.g. the effect of variations in effective precipitation. Hence, predicting an accurate pore pressure reduction Δu is subject to influence of the current weather during project execution.

Case 2 was simulated prior to the excavation of the pit, so that calibration was done with static groundwater levels from a few monitoring wells and borehole data. The modelling results were used to consider various tasks to limit groundwater ingress into the pit, and to illustrate the consequences of lowered porewater pressures. Geotechnical analyses had indicated acceptance criteria for porewater pressure reduction with regards to soil subsidence, based on soil samples and tests. Since the groundwater simulations were time dependent, modelling results were also used to consider how long a lowered porewater pressure could be held before pressures needed to be regained in order to stay within subsidence acceptance criteria. Results from the simulations which follow a modelled construction scenario compared to the porewater pressure reduction registered at monitoring points show that at 3 of 4 points, the modelled porewater pressure reduction was within 0.6 meters of field measurements. These results are considered to show significant accuracy in the modelled scenario.

The results from **Case 4** deviated substantially from the empirical data in the Begrens Skade database for all scenarios which included leakage from bedrock. Both the influence area and the development of pore pressure reduction with distance from excavation, were unrealistic. Altering the geometry upstream of the excavation would have resulted in better compliance with respect to the influence area. Such a change in geometry could have been argued for, but at the same time it makes the results totally dependent on the boundary conditions, which is something that ought to be avoided. The pore pressure reduction with distance from excavation could possibly have been made more realistic by reducing the k_z/k_x ratio and/or dividing the bedrock into sections both horizontally and vertically with different conductivities. However, especially the latter change would have to be substantiated by site-specific data which are both costly and difficult to provide.

Uncertainties associated with the modelling process and results

The main uncertainties associated with **Case 1** were found to be (i) hydraulic conductivity of moraine layer, (ii) not accounting for the influence of groundwater flow through the bedrock and (iii) accurately modelling the boundary condition for the groundwater leakage (model outtake) into the deep excavation.

The main uncertainties in **Case 2** were the spatial variation in hydraulic conductivity of the bedrock not included in the model, as well as the assumption that drainage along steel-core pilings were less than open channels. The marine clay with steel-core pilings was modelled with 4 orders of magnitude higher hydraulic conductivity compared to initial clay conditions, but not high enough to correctly simulate the instantaneous draining of groundwater pressure which occurred in the field. The reason why modelling results were so good despite the poor simulation of drainage along pilings was that the drainage from the exposed excavated bedrock floor of the pit accounted for much of the total groundwater ingress.

The main uncertainties associated with **Case 4** are (i) the upstream hydraulic boundary condition and (ii) the simplified modelling of the groundwater flow in the fractured bedrock. There is also a significant uncertainty related to the conductivity of the pile leakage, but this uncertainty is not considered to have noteworthy effects on the results.

Further work

Case 1 identified that obtaining measurements on actual leakage rates to a deep excavation from various sources (e.g. around the casing of steel core piles, holes in sheet pile, from exposed bedrock) could eliminate some uncertainties regarding flow rates. In addition, extending the model to also include flow through bedrock would be more realistic, yet also introduce more sources of uncertainty.

Case 2 illustrated the need to include better representation of the drainage along piles and boreholes that are established in artesian pressure, also noted in Case 1. Simulating these conditions will vary from case to case, and it will be difficult to estimate a correct rate. Hopefully, future work will find methods to eliminate groundwater drainage along these structures.

Case 4 emphasizes the need to represent the conductivity in the draining layer as realistically as possible. It presents a couple of modelling tasks with the aim to investigate the effect of certain modelling options that take the difference between soil and bedrock conductivity into account:

Make a 2D model where the fractured bedrock is modelled as distinct materials laterally, with different conductivities. The conductivities should decrease away from the excavation in order to consider discontinuous fractures which contributes to the measured conductivity in a nearby borehole, but not necessarily to the "experienced" conductivity for a leakage point further away. This is expected to result in a more realistic development of the pore pressure reduction with distance from the excavation.

Make a 2D model where the fractured bedrock is modelled as distinct materials horizontally, with different conductivities. The conductivities should decrease downwards to consider the possible decrease of fractures and their aperture with depth in the bedrock, a feature indicated by literature (Dagestad et al., 2003; Welch & Allen, 2014). The same model should also be simulated with a scenario where the vertical conductivity is lower than the horizontal. This feature is also indicated by literature (Welch & Allen, 2014). Both adjustments are expected to result in a more realistic (but less conservative) effect of the cut-off wall.

It must be emphasized that to use the results from such models for decision-making in a construction project, the options to differentiate the conductivity would need to be substantiated by data, preferentially gathered locally.

ions to differentiate the conductivity would need to be substantiated by data, preferentially gathered locally.

References

BegrensSkade. (2016). *Begrensning av skader som følge av grunnarbeider - Sluttrapport*.

Dagestad, A., Hansen, L., & Braathen, A. (2003). *Hydrauliske egenskaper i løsmasser og fjell sett i sammenheng med EU-direktivet for deponering av avfall*.

Enemark, T., Peeters, L. J. M., Mallants, D., & Batelaan, O. (2019). Hydrogeological conceptual model building and testing: A review. *Journal of Hydrogeology*, *569*, 310–329. https://doi.org/j.jhydrol.2018.12.007

Gupta, H. V., Clark, M. P., Vrugt, J. A., Abramowitz, G., & Ye, M. (2012). Towards a comprehensive assessment of model structural adequacy. *Water Resour. Res.*, *48*, 1–16. https://doi.org/10.1029/2011WR011044

REMEDY. (2022a). *D3.1 - Drainage to excavations - State-of-Art report*.

REMEDY. (2022b). *D3.2 - Grunnvannsmodellering som et verktøy for å estimere setninger rundt byggegroper*.

REMEDY. (2022c). *D3.3 - Numerical hydrogeological modelling of drainage to an excavation*.

Welch, L. A., & Allen, D. M. (2014). Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow. *Hydrogeology Journal*, *22*(5), 1003–1026. https://doi.org/10.1007/s10040-014-1121-5

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