Evaluating effects of geological conceptualization on simulated pore pressure reduction from groundwater leakage to excavation

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Evaluating effects of geological conceptualization on simulated pore pressure reduction from groundwater leakage to excavation

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ABSTRACT: Underground construction such as tunneling or deep excavations in saturated soil or rock can lead to groundwater leakage, resulting in lowered groundwater pressure and subsequent time-dependent consolidation in subsidence-sensitive soils. In Sweden, permeable sand layers within clay deposits, formed during fluctuating sea levels during sedimentation, can significantly affect the hydraulic conductivity of these sequences but are often neglected in site characterization for groundwater modeling. This study aims to assess the impact of geological uncertainty on pore pressure reduction due to groundwater leakage. Numerical groundwater models simulated pore pressure changes for two geological scenarios: homogeneous clay and clay with interbedded sand. Sand distribution was modeled using Multiple Point Statistics (MPS), and groundwater flow models were developed in MODFLOW-NWT. The results showed substantial differences in pore pressure behavior between the two scenarios, highlighting the critical role of sand layers in influencing pore pressure dynamics and subsidence risks.

1 INTRODUCTION

1.1 *Background*

Construction in saturated rock or soil poses a risk of groundwater leaking into the structure, necessitating its drainage to maintain a dry working environment (Cashman & Preene, 2001). This can lead to a lowering of groundwater levels in the area, which may cause settlements in subsidence-sensitive soils, such as clay, due to reduced pore pressure and thus increased effective stress. In clay, which has low hydraulic conductivity, groundwater lowering occurs slowly, while in more permeable soils, changes can happen quickly, making the settlements strongly time-dependent (Terzaghi, 1943). Therefore, it is crucial to understand how leakage of groundwater can affect groundwater levels without the risk of consolidation in order to plan preventive measures.

For a reliable risk analysis of pore pressure changes and consolidation due to groundwater lowering, models that can predict changes in groundwater levels are required. Numerical groundwater modeling is an effective tool for this, as it can simulate flows and pressure changes in aquifers around underground structures. However, a significant source of uncertainty in these models is the geological conceptualization (Bredehoeft, 2005, Højberg & Refsgaard, 2005, Refsgaard et al., 2012, Troldborg et al., 2007). Therefore, a valid representation of geology is crucial for the model's ability to provide representative results. Field investigations provide important information on how the hydrogeological system functions, but they are expensive and time-consuming to conduct. Knowledge of the area's geological history can therefore be a valuable complement to field investigations (Jørgensen et al., 2010).

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Sweden's soil types are mainly of Quaternary origin, shaped by glacial melting and coastal shifts caused by land uplift and sea level changes (Lundqvist, 1983; Lagerlund & Housmark-Nielsen, 1993). The general stratigraphy in clay-filled valleys below the highest coastline after the last glaciation is thus a result of coastal shifts in combination with varying sedimentary and climatic conditions due to variations in glacial meltwater quantities and the distance to the ice margin (Miller & Robertsson, 1988). This means that wave-washed sediments and sand originating from wave-affected moraines can be found both above and within the clay sequence. Depending on their interconnection, permeable units like sand lenses can influence the bulk hydraulic conductivity of the clay sequence, thereby influencing groundwater flow in the system (Kessler et al., 2013, Knudby & Carrera, 2005). Failure to consider these permeable units can lead to underestimating both the extent and the rate of groundwater lowering, as well as the reduction in pore pressure in subsidence-sensitive soils.

1.2 *Aim*

This study aims to assess how permeable sand lenses within clay deposits influence the magnitude and rate of pore pressure reduction in clay resulting from groundwater leakage into deep excavations. This is done comparing simulated groundwater levels derived from numerical models based on varying geological conceptualizations of the stratigraphy. The study is performed using real-world data from the construction site of a new railway tunnel station at *Korsvägen* in Gothenburg, Sweden.

2 METHOD

2.1 *Case-study area*

The case-study area is located in the central part of Gothenburg, Sweden (Figure 1a). The topography of the area is varied, with higher mountains in the east and southwest, which together form two valleys (*Korsvägen* and *Mölndalsån* valleys). In the northern part of the model area, the ground is relatively flat. The hydrogeology of the area is characterized by bedrock outcrops in the higher areas and clay-filled valleys. In the valleys, the stratigraphy consists of, from bottom to top, crystalline bedrock, frictional material (glacial till/glaciofluvial deposits), glaciomarine clay with occasional wave-washed sand lenses, and filling material. The top layer on the ground surface generally has higher permeability, allowing higher water flows compared to the underlying clay sequence. In this study, this will be referred to as an unconfined aquifer. In the areas of bedrock outcrops, the upper aquifer is in contact with the till below the clay, which forms a confined lower aquifer. The sand layers, which are found in places within the clay sequence, form intermediate aquifers, which in some cases are in contact with the upper and lower reservoirs at the peripheral zones. Groundwater recharge in the area is complex since large parts of the area are highly urbanized and covered by relatively impermeable materials such as pavement. Leaking drinking water pipes contribute to groundwater recharge, while stormwater management contributes to drainage. Groundwater recharge to the confined aquifers and bedrock generally occurs in elevated areas and at the bedrock outcrops.

2.2 *General approach*

To assess changes in pore water pressure due to groundwater leakage into the shaft, four different geological models have been developed based on borehole data and domain knowledge of the stratigraphy at the study site. The first model features a simplified stratigraphy, consisting of crystalline bedrock overlain by frictional material (glacial till/glaciofluvial deposits), glaciomarine clay, and anthropogenic filling material. The remaining three models have the same stratigraphy, with the addition of wave-washed sand lenses within the clay sequence. All models are based on the same borehole data from the area. These geological models are then

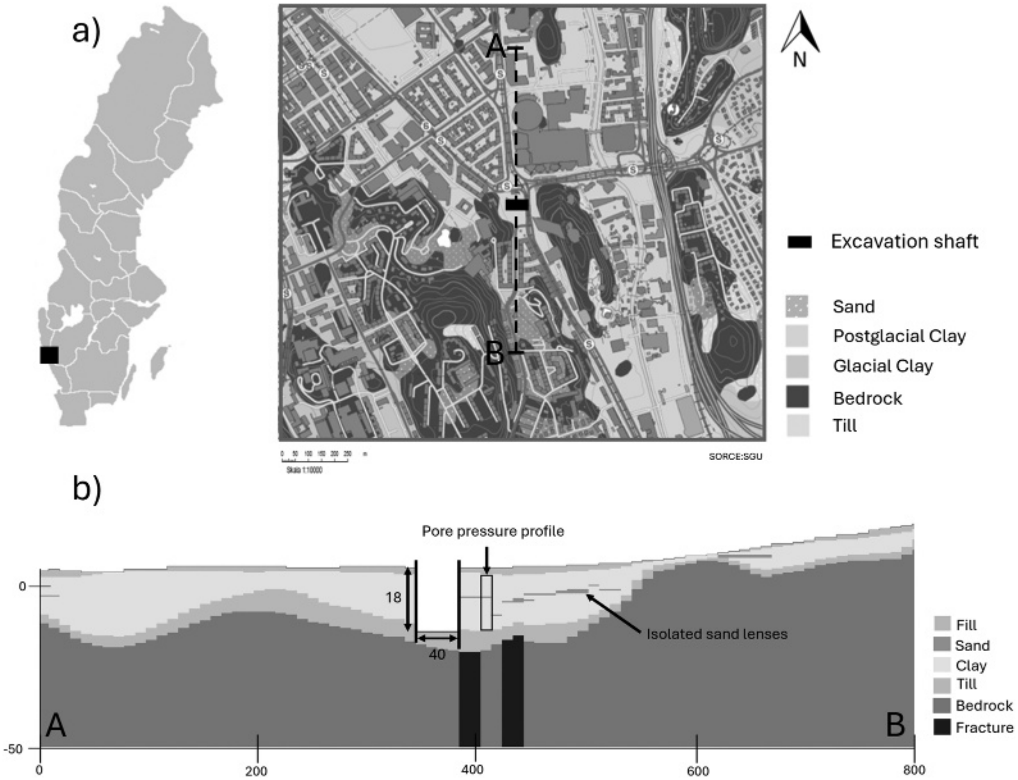

Figure 1. a) Location of the case-study area, the excavation shaft and cross section AB. b) Stratigraphical model section (cross section AB), with the placement and depth of the excavation shaft. Units in meters.

used as input data for the groundwater flow models. A deep shaft was placed at *Korsvägen* with permeable walls intended to represent a leaking retaining wall. The impact on groundwater levels in the lower confined aquifer and pore pressure changes in the clay due to inflow into the shaft is evaluated through transient groundwater modeling with multiple time steps. The approach of transient groundwater modeling was chosen to evaluate the difference in the magnitude of groundwater lowering at different times, enabling an analysis of the variation in speed for the different geological conceptualizations.

2.3 *Borehole data*

The dataset from the model area and the examined clay sequence comprises 1,495 unique boreholes. These were sampled at 0.5-meter intervals, yielding 32,362 data points with indicator values of 0 or 1, where 0 denotes clay and 1 denotes sand. Of these points, 333 correspond to sand (indicator 1), while the remainder represent clay (indicator 0). These data points served as conditioning data for the simulation of sand lens distributions in the models containing sand.

2.4 *Geological model*

The first geological model, is a continuous layer model detailed in Trafikverket (2016). This model represents a simplified stratigraphy consisting of bedrock, a lower aquifer in friction material, clay, and an upper aquifer.

The models that include sand, and thus a more complex stratigraphy, are based on this continuous layer model, but with the clay sequence also incorporating sand in the form of layers or lenses. The location and distribution of the sand lenses were simulated using the geostatistical method Multiple Point Statistics (MPS). The primary function of MPS is to capture and reproduce complex spatial patterns and relationships observed in a given dataset. Unlike traditional geostatistical methods, which focus on pairs of points (bivariate statistics), MPS considers multiple points simultaneously, accounting for their spatial arrangement within a defined area.

MPS also relies on a "training image," a reference image that represents the desired spatial patterns. This image guides the simulation process and ensures that the generated models capture the key spatial features and patterns observed in the training image. As MPS is a stochastic simulation method, it can generate multiple realizations of the geology. In this study, three different but equally probable realizations of the sand layer distribution were used in the geological models containing sand lenses. For a more detailed description of the MPS method, the reader is referred to Liu (2006), Strebelle and Journel (2001), Strebelle (2002), or Hu and Chugunova (2008).

2.5 *Numerical models*

To evaluate the impact of pore pressure change, when including thin local sand layers in the geological model structure in numerical modelling, four groundwater flow models have been developed. Steady-state and transient groundwater flow models using MODFLOW-NWT (Niswonger et al., 2011) were constructed within the open-source Python framework FloPy (Bakker et al., 2016).

The numerical models were developed using the voxel approach, where the geological structure is represented by a three-dimensional grid of volumetric pixels (voxels). Each voxel corresponds to an indicator (stratigraphic unit) assigned specific properties, such as hydraulic conductivity and storativity. The model's resolution was set to 10 x 10 meters with a layer thickness of 0.5 meters, resulting in 158 rows, 173 columns, and 295 layers.

Model validation was performed through manual calibration against observed groundwater levels in both upper and lower aquifers from 156 boreholes. The calibration was considered satisfactory when the levels in all boreholes fell within the range of minimum and maximum measured values, and the root mean square error (RMSE) for the median groundwater level did not exceed 1 meter. The calibrated steady-state groundwater levels were then used as initial conditions for the transient models. For further validation of the transient models, manual calibration was also conducted based on a pumping test at *Korsvägen*. The hypothetical shaft was placed at the test site, as this is the area where the model validation was performed.

2.6 *Evaluation of pore pressure change*

The differences in pore pressure changes between the models containing sand and the model without sand have been evaluated by identifying areas where the reduction differs. Based on this, pore pressure reduction profiles for the clay were selected and presented in Section 3, where the sand lenses have varying effects depending on their connectivity to other permeable materials. The effects on pressure changes in the clay due to leakage into the shaft were analyzed through transient groundwater modeling with three time steps. The time steps were set to 1 week, 1 year, and 30 years to allow for an evaluation of pore pressure changes both in the short and long term.

3 RESULT AND DISCUSSION

Pore pressure reduction profiles have been chosen to illustrate the effects of the sand layers and their connectivity within and to other permeable layer, as well as to the retaining walls of the excavation. The results are divided into two cases: Case 1 refers to sand layers connected to the lower confined aquifer, while Case 2 refers to sand layers with no connection to other permeable materials.

3.1 *Case 1 - Connection to the lower aquifer*

Figure 2 illustrates the pore pressure reduction profile for the clay layer in two models: one without sand lenses and one containing sand lenses in the clay sequence. The dashed line represents the reduction for the models including sand lenses (GWM2-Sand and GWM3-Sand). The solid line represents the reduction for the model without sand, referred to as GWM1-Clay. The pore pressure reduction is shown at three time-steps: 1 week, 1 year, and 30 years. A grey horizontal line marks the sand layer, indicating its depth. In this figure, the sand layer is connected to the lower aquifer.

Figure 2a shows that the reduction is consistently higher for GWM1-Clay at all time steps, suggesting that the sand layer serves as an extended flow path, allowing water from the lower aquifer to reach the excavation shaft. However, because water continues to flow from the lower aquifer, the reduction in pore pressure within the clay is less pronounced for GWM2-Sand.

Figure 2b shows the pore pressure reduction for GWM1-Clay and GWM3-Sand. The sand layer in this profile is connected to the lower aquifer but is located approximately 300 meters away from the excavation shaft, meaning it has no connection to the retaining walls of the shaft. It can be observed that GWM3-Sand experiences a higher pore pressure reduction compared to GWM1-Clay long-term. After one week, the differences between the two models are negligible; however, over the long term, the sand layer behaves similarly to the lower aquifer, which contributes to the faster and more significant propagation of pore pressure reduction in the clay.

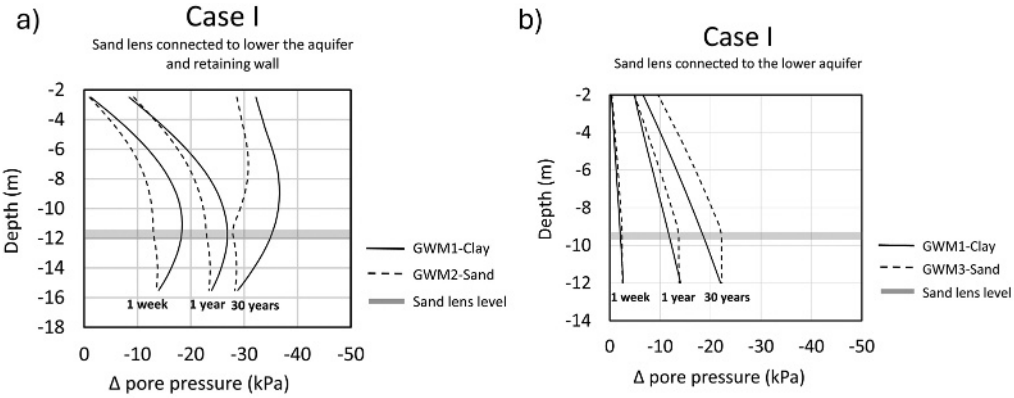

Figure 2. a) Pore pressure reduction profile for GWM1-Clay and GWM2-Sand. The sand lens in GWM2-Sand is connected to both the lower aquifer and the excavation shaft b) Pore pressure reduction profile for GWM1-Clay and GWM2-Sand. The sand lens in GWM1 is connected to the lower aquifer.

The comparison between the models for Case 1, where the sand layer is connected to the lower aquifer, shows that the pore pressure reduction depends on whether the sand layer is connected to the excavation shaft. When there is no connection to the excavation, the models containing sand exhibit a higher pore pressure reduction. This suggests that not considering the sand layer may underestimate the pore pressure reduction in the clay, potentially leading to settlement issues.

3.2 *Case 2 – Isolated sand lens*

Figure 3a shows the pore pressure reduction profile for GWM1-Clay and GWM4-Sand for a sand layer that has no connection to other permeable deposits but is connected to the retaining walls of the excavation shaft. The reduction for GWM4–Sand is much higher compared to GWM1-Clay. The sand layer, located at a depth of nine meters, acts as a drainage path for the water in the clay, resulting in a significantly higher pore pressure reduction in the clay sequence.

Figure 3b shows the pore pressure reduction for GWM1-Clay and GWM2-Sand for a sand layer with no connection to either other permeable materials or the excavation. Here, the sand acts as an intermediate aquifer but has no significant effect on the pore pressure reduction in the clay sequence.

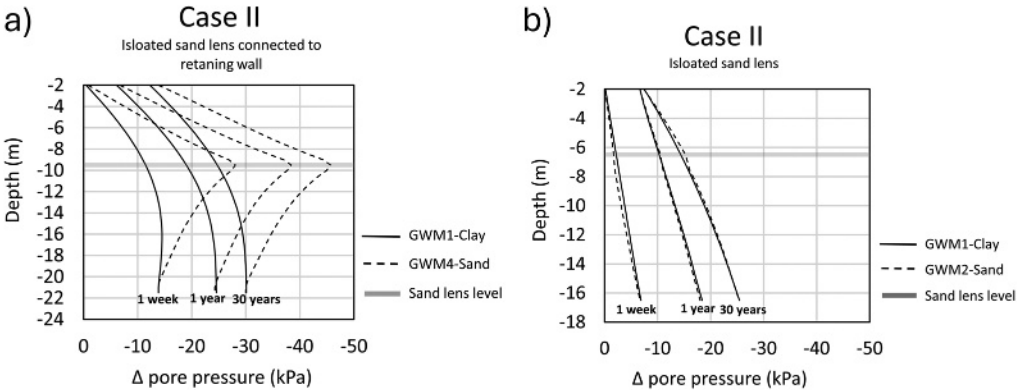

Figure 3. Pore pressure reduction profile for GWM1-Clay and GWM2-Sand. The sand lens in GWM2-Sand is connected to both the lower aquifer and the excavation shaft b) Pore pressure reduction profile for GWM1-Clay and GWM2-Sand. The sand lens in GWM1 is connected to the lower aquifer.

4 CONCLUSION

The results from the simulated pore pressures reveal significant differences in both the rate and magnitude of pore pressure changes when including local and permeable sand lenses in the groundwater model. Isolated sand lenses, without direct connection to other permeable deposits, have little impact if they are not connected to the leaking shaft. When connected to the shaft, the sand layers act as drainage and significantly increase both the magnitude and rate of pore pressure reduction in the surrounding clay. This means that in urban environments, where subsidence-sensitive buildings may be close to the shaft, excluding these sand lenses can lead to an underestimation of settlement risks. A similar draining effect can be seen for sand layers connected to both the shaft and the lower aquifer if the pressure level is below the sand layer's level. However, these sand layers can also act as a buffer that reduces the pore pressure reduction in the surrounding clay, which can decrease the risk of settlements around the shaft. Also, at greater distances from the shaft, the sand layers can have a significant impact. Sand layers connected to the lower aquifer act as an extension of this aquifer and respond to pressure changes in a similar way. Excluding these sand layers risks underestimating the pore pressure reduction in the surrounding clay, as these sand layers allow for a greater and faster pore pressure reduction, which in turn can lead to an underestimation of settlement risks.

These findings underscore the critical role of thorough ground investigations and site characterization in assessing risks associated with underground excavations. The inclusion of sand lenses in groundwater models highlights the complexity and variability of ground conditions and their significant influence on settlement risk assessments. The location and connectivity of the sand lenses are crucial factors, and excluding these geological uncertainties could lead to settlement risks being either underestimated or overestimated. This, in turn, can result in overlooked risks that could have been anticipated and managed, leading to potential damage and unforeseen costs.

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