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The influence of parameter variability on subsidence

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ABSTRACT: Leakage into rock tunnels covered by thick soft clay deposits may cause a pore water pressure drop over large areas through underdrainage, resulting in settlement problems and potential damage to structures. In urban areas, heterogeneity in soil properties can be substantial. In this paper, a case study with a systematic sensitivity analysis combined with coupled hydro-mechanical finite element analyses was performed for three key parameters (overconsolidation ratio, vertical hydraulic conductivity and hydraulic anisotropy) considering one scenario of underdrainage. The results show that both the magnitude and uncertainty of settlements are strongly stratigraphy-dependent. The overconsolidation ratio contributed the most to the settlement uncertainty and the effect of vertical hydraulic conductivity was also found to be significant, while the changes in hydraulic anisotropy had negligible influence.

Keywords: Subsidence; Soft clay; Sensitivity analysis; Underdrainage

1 INTRODUCTION

Underground construction affecting pore water pressures in confined aquifers represents a challenge in soft marine clays, often encountered in Scandinavia. Even small rates of leakage to a tunnel, or excavation, can cause a pore pressure drop over large areas in the underlaying layer of highly permeable frictional material, affecting slowly the clay layers above, thus leading to problems of time-dependent subsidence and potential damage to structures. Typically, this engineering problem is known as underdrainage, where the rock plus a frictional layer (glacial till) at the clay-rock interface constitute a lower (confined) aquifer that functions as a draining boundary, whereas the upper (unconfined) aquifer remains at least initially practically unaffected by the pressure drop.

The compressibility of soft marine clays in Scandinavia is affected by their relatively young geological and anthropological history. Uncertainty in defining a representative soil stiffness is partially attributed to sample disturbance (Karlsson et al. 2016; Lunne et al., 2006). Retrieving undisturbed samples from greater depths is not trivial. Because of that, choosing representative values and trends for the model parameters to represent the profile can be challenging. Stress history, and its consequent effect on the compressibility and creep of soft natural clays, is site-specific and can vary drastically due to the anthropological history.

The mechanical behaviour of soft clays is best modelled using advanced constitutive models, such as Creep-SCLAY1S (Gras et al. 2017; 2018; Sivasithamparam et al., 2015) that enables modelling the complex hydro-mechanically coupled rate-dependent response of natural soft clays. Sensitivity studies have shown that such models are more sensitive to the variability in some model parameters than others (Tahershamsi and Dijkstra, 2021; 2022). One of the most important parameters is the overconsolidation ratio, *OCR*, given in some rate-dependent models, e.g. Creep-SCLAY1S, *OCR* not only influences the emerging compressibility, but also affects the predicted creep rates.

Hydraulic conductivity is one of the key parameters governing the rate of consolidation, and is therefore another important property in studying time-dependent settlements. Hydraulic anisotropy is used to describe the relationship between the components (Olson and Daniel, 1981) of the hydraulic conductivity. The sensitivity on the vertical hydraulic conductivity has previously been studied by Huang et al. (2010), demonstrating its significance on (elastic) consolidation. However, the sensitivity of the horizontal hydraulic conductivity on the predicted vertical consolidation in an environment with greatly varying clay thickness is less well known. Often the horizontal hydraulic conductivity is estimated, rather than measured, and furthermore, the predictions of subsidence often assume purely one-dimensional flow and consolidation, while the reality is 3D. To accurately predict subsidence in soft clay areas with greatly varying clay thickness, the multi-dimensionality of flow may become important.

Thus, it is important to account for the uncertainties in the preconsolidation pressure and hydraulic conductivity. When using advanced models, however, it is not straight-forward to use Monte Carlo analyses, because they become computationally inefficient. Hence, there is a call for more efficient methods which can result in appropriate levels of uncertainty.

The aim of this numerical study is to understand the sensitivity of important model parameters of a typical underdrainage problem in a natural soft clay environment with varying soft clay thickness. The problem is modelled using 2D coupled Hydro-Mechanical (HM) Finite Element analyses. The confined lower aquifer was exposed to an instantaneous uniform pore pressure drop, emulating leakage to an underlaying rock tunnel. To account for the background creep settlements, an advanced rate-dependent model is adopted to simulate the natural clay response. A systematic sensitivity study is carried out with varying sets of layer-dependent values for the model parameters; *OCR*, vertical hydraulic conductivity (k_v) and hydraulic anisotropy (r_k).

2 DATA AND METHODS

2.1 Site description

The site considered is situated in central Gothenburg (Figure 1), where a new railway tunnel is being built. The geology consists of a typical stratigraphy found in Scandinavia, consisting of a thick layer of glacial/post-glacial clay, covering 2-3 m layer of glacial till (frictional material) on top of crystalline bedrock. The uppermost part of the clay has been heavily altered due to land reclamation using dredged materials from the nearby canal. Effects of this can be noted in the vertical displacement rates from InSAR, with the largest settlements occurring closest to the canal (Figure 1). Cross-section BB displays the typical stratigraphy derived from boreholes using a geostatistical method presented in Sundell et al. (2016) (Figures 1 and 2). Groundwater levels for both the upper (unconfined) aquifer and the lower (confined) aquifer are also presented in Figure 2.

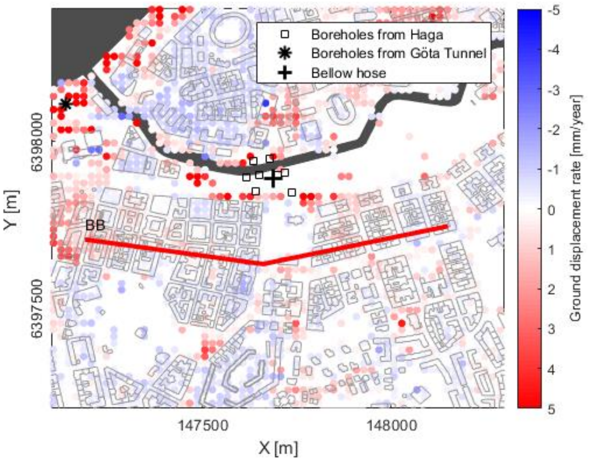


Figure 1. Study area. Ground displacement rate measurements from InSAR from TreMAPS (https://site.tre-altamira.com/insar-solutions/tremaps/) October 2022, where positive (red) values indicate on-going settlement, and negative (blue) values indicate on-going uplift.

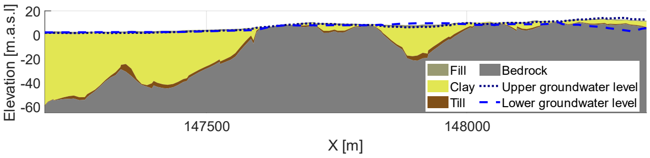
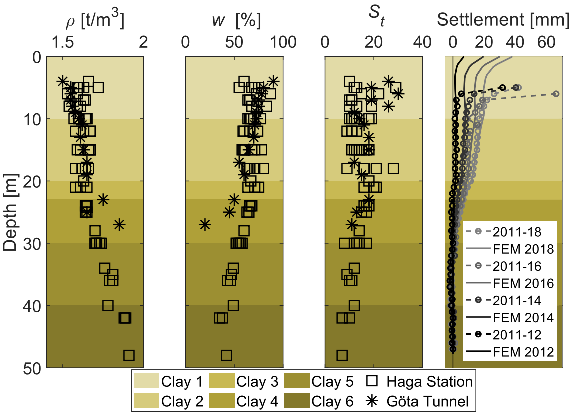


Figure 2. Hydro-stratigraphy of cross-section BB with groundwater levels for upper (unconfined) and lower (confined) aquifer.

The properties of the clay layers were derived based on 48 samples from eight boreholes around Haga (Figure 1). Figure 3(a) displays the key index properties (density, natural water content and sensitivity) derived as a function of depth. These properties are compared with the properties from the well-characterised Göta tunnel project nearby (Tornborg et al., 2021). Figure 3(a) shows that the properties from both sites are similar. The deviations in the water content at 20-30m depth is most likely due to the proximity to the frictional layer, attributed to the relatively shallow clay thickness at the Göta tunnel site. Given most model parameters are intrinsic properties, the values of Tornborg et al. (2021) were adopted (Table 1), with a site-specific value of *OCR*. Simulations by Tahershamsi and Dijkstra (2021) suggests that *OCR* is the most important model parameter for consolidation and creep.

Based on SGI (2007) sample quality assessment, all samples at Haga below the depth of 25 m were deemed of poor quality. Thus, the *OCR* values for the deeper layers had to be adjusted based on back-analyses against historic bellow hose measurements (Figure 3(b)). The measured settlements from a bellow hose (Figure 3(b)) located close to the Haga boreholes (see Figure 1) were used along with information of background creep rates from InSAR to calibrate the layering and *OCR* for the period 2011 – 2018. The top measurements diverge due to the lack of horizontal stresses acting on the bellow hose. For the deeper layers, with most sample disturbance, the *OCR* values had to be significantly increased to match the bellow hose measurements.



(a) (b)

Figure 3. a) Index properties of Haga (this study) and Göta tunnel (Tornborg et al., 2021). Layering and trends are interpreted from this study. b) Bellow hose measurements between 2011-2018 and Finite Element simulation results.

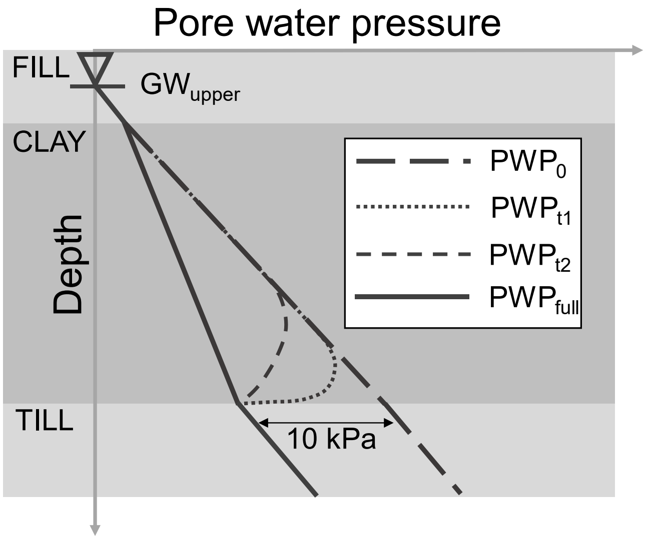


Figure 4. Pore pressure dissipation process of a typical underdrainage problem in clays bounded by an upper and a lower aquifer.

2.2 Scenario description

Construction of tunnels in hard crystalline rock leading to leakage will cause time-dependent pore water pressure (PWP) drop in clay as exemplified in Figure 4. A relatively instantaneous pore pressure drop in the lower aquifer (till) and an intact groundwater level in the upper aquifer (fill) are assumed, followed by delayed PWP drop in the clay starting at the bottom, continuing upwards until full consolidation (PWP_{full}). A scenario of a hypothetical 10 kPa pressure drop is shown in Figure 4 for times t1 and t2. If no measures are taken, in the long term, the pore pressures in the clay layer would reduce. How fast those measures need to be taken is a matter of the rate at which the pore pressures dissipate.

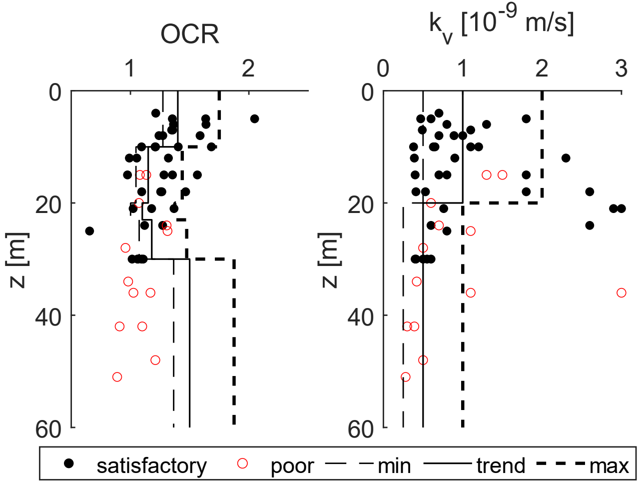
2.3 Soil properties and parameter uncertainty

To assess parameter uncertainty, it is important to understand the sources of uncertainty. Phoon and Kulhawy (1999) list four types of uncertainties: natural variability, measurement uncertainty, statistical uncertainty, and transformation uncertainty. The measurement uncertainty in this case relates to e.g. sample quality, assessed according to SGI info 3 (SGI, 2007).

Figure 5 shows the derived *OCR* and vertical hydraulic conductivity, k_v, values from constant rate of strain (CRS) tests, along with the sample quality for each sample. As discussed, the *OCR* values were calibrated using the bellow hose data from Figure 3(b). In this case *OCR* (Figure 5(a)) increases with depth, as the deeper clay layers are older, and have thereby been exposed to more creep and cementation from past diagenesis. Figure 5 further suggests that the variation is also significant at shallow depths, despite the satisfactory quality of the samples. Some values were interpreted as outliers after detailed examination of CRS curves. In addition to the general trend, two trend lines representing the minimum and maximum value in each layer were defined. To represent the uncertainty in each layer, the ratio between the minimum or maximum value and the original trending value are the same. These ratios were assumed based on the sample variation at the top 23 m of clay, where higher quality samples were recognized after removing outliers. For *OCR*, these trend ratios were chosen as 0.91 and 1.2 respectively.

Similar assumption was made for k_v, the trend ratios were selected as 0.5 and 2 (Figure 5(b)). Some samples were considered as outliers due to high silt content, given the numerous CPT tests on site indicated no evidence of continuous permeable layers.

Due to the depositional processes, the horizontal hydraulic conductivity is often larger than vertical hydraulic conductivity in the field (Tavenas et al., 1983). For this study, no tests were performed to derive the hydraulic anisotropy (r_k), the ratio between the horizontal and vertical hydraulic conductivity. However, previous studies have shown that most marine clays, have an $r_k = 1\text{–}2$ (Larsson, 1981; Leroueil et al., 1992; Olson and Daniel, 1981; Tavenas et al., 1983; Win et al., 1998). Therefore, an anisotropy range of $r_k = 1 - 2$ was chosen for this study, where $r_{k,min} = 1$, $r_{k,mid} = 1.5$ and $r_{k,max} = 2$.



(a) (b)

Figure 5. OCR (a) and vertical hydraulic conductivity (k_v) (b) assessed from Haga CRS samples vs. depth, and their chosen trends.

2.4 Soil model and FE model

A 2D plane strain Finite Element (FE) model (Figure 6) was set up using PLAXIS 2D (Plaxis, 2022). The mesh consists of 21,068 6-noded elements with 3 stress integration points by element. The lower order elements were selected to ensure the stability of the coupled flow-deformation analysis. The mesh fineness was chosen after a special sensitivity analysis to ensure mesh-independent results. The mechanical behaviour of the soft clay was simulated using an in-house implementation of Creep-SCLAY1S model (Gras et al., 2017; 2018; Sivasithamparam et al., 2015; Wheeler et al., 2003). Creep-

SCLAY1S is a rate-dependent model which accounts for creep, initial and evolving anisotropy and destructuration. This model was chosen to represent the moderately sensitive clay layers, given the evidence of ongoing background creep settlements in the area. The deposit was divided in six sub-layers based on key index properties, utilising also the results by Tornborg et al. (2021). In Creep-SCLAY1S, the rate of viscoplastic strain is calculated as:

$$\delta \varepsilon^c = \dot{\Lambda}\left(\frac{\partial f_{NCS}}{\partial \sigma'}\right) \tag{1}$$

$$\dot{\Lambda} = \frac{\mu_i^*}{\tau}\left(\frac{(1+\chi)p'_{m,i}}{p'_{eq}}\right)^{-\left(\frac{\lambda_i^*-\kappa^*}{\mu_i^*}\right)}\frac{M_c^2-\alpha_0^2}{M_c^2-\eta_0^2} \tag{2}$$

where $\partial f_{NCS}/\partial\sigma'$ is the change of the size of the normal compression surface (NCS) with effective stress (σ'), μ_i^* is the intrinsic modified creep index, τ is the reference time, p'_{eq} is the equivalent mean effective stress, χ is the amount of bonding, $p'_{m,i}$ is the size of the intrinsic compression surface (ICS) (Figure 7), λ_i^* is the intrinsic modified compression index, κ^* is the modified swelling index, M_c and M_e are the stress ratios at critical state in triaxial compression and extension, α_0 and η_0 are the initial rotation of the compression surfaces and stress ratio, respectively, at normally consolidated state.

All assumed model parameters can be found in Table 1 (after Tornborg et al. (2021)). These values were not considered in the sensitivity study as they are not as important as e.g., OCR and k_v. Additional state parameters can be found in Table 2. The material models and parameter values for the frictional layer (till) and rock can be found in Tornborg at al. (2021).

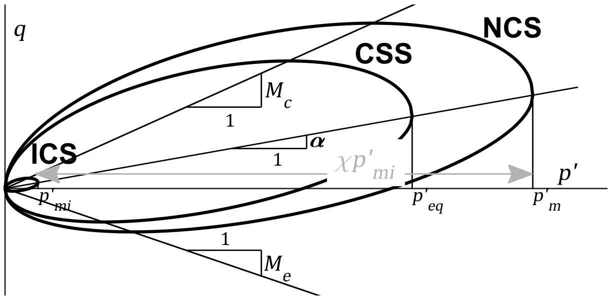


Figure 7. Current State Surface (CSS) and normal consolidation surface (NCS) in p'-q plane for Creep-SCLAY1S. Modified from Gras et al. (2017).

Table 1. Parameters of Creep-SCLAY1S for all clay layers (Tornborg et al., 2021).

Parameter	Value
Poisson's ratio, $\boldsymbol{\nu'}$	0.2
Modified swelling index, $\boldsymbol{\kappa^*}$	0.013
Modified intrinsic compression index, $\boldsymbol{\lambda_i^*}$	0.085
Stress ratio at critical state in triaxial comp., $\boldsymbol{M_c}$	1.45
Stress ratio at critical state in triaxial ext., $\boldsymbol{M_e}$	1.1
Modified intrinsic creep index, $\boldsymbol{\mu_i^*}$	0.002
Time factor (days), $\boldsymbol{\tau}$	1
Initial anisotropy, $\boldsymbol{\alpha_0}$	0.57
Rate of rotational hardening, $\boldsymbol{\omega}$	200
Rel. rate of rot. hardening due to dev. strain, $\boldsymbol{\omega_d}$	1
Initial amount of bonding, $\boldsymbol{\chi_0}$	15
Rate of destructuration, $\boldsymbol{\xi}$	8
Rate of destruct. due to deviator strain, $\boldsymbol{\xi_d}$	0.5

*Table 2. Additional model parameters. Only average values for k_v and OCR are shown. (*Approximate depth)*

Layer (depth* [m])	$\boldsymbol{\gamma}$ (kN/m^3)	$\boldsymbol{e_0}$	$\boldsymbol{k_v}$ (m/s)	OCR
Top clay	16	2.0	1E-9	1.4
Clay 1 (0-10)	16	2.0	1E-9	1.4
Clay 2 (10-20)	16	2.0	1E-9	1.15
Clay 3 (20-23)	17	1.7	5E-10	1.1
Clay 4 (23-30)	17	1.7	5E-10	1.18
Clay 5 (30-40)	18	1.2	5E-10	1.5
Clay 6 (40-70)	18	1.2	5E-10	1.5
Till	18	-	1E-6	-
Rock	20	-	1E-6	-

During the initialisation phase of the numerical analysis of cross-section BB, all layers were set as linear elastic to create the initial stress state. The seepage drainage condition was set to the horizontal boundaries. Next, a NIL step was defined where the material model was changed for the clay from linear elastic to Creep-SCLAY1S and displacements were reset at the end of this step. For these steps, an upper groundwater level was set for the top clay layer, a lower groundwater level was set for the frictional layer and rock, and in between an interpolation condition was set for all clay layers except the top clay layer. The third simulation phase included a uniform drawdown of 1m for the lower aquifer. The remaining phases were consolidation phases of 3 months, 6 months, and 1 year. In this paper, only analyses from 1 year consolidation are shown and discussed.

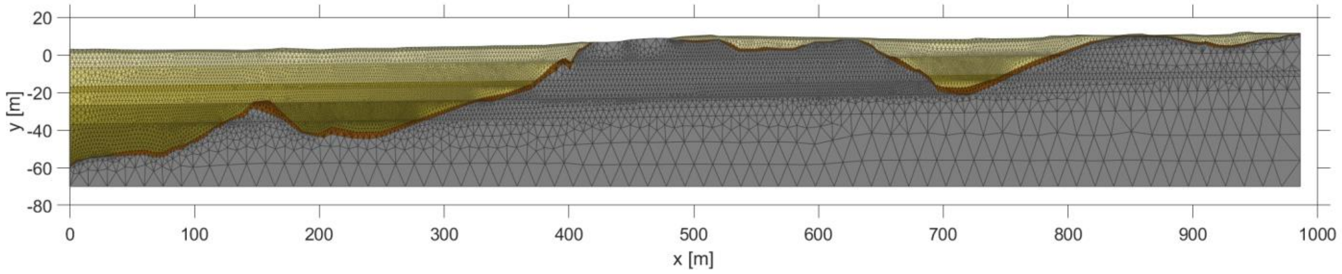


Figure 6. Mesh of cross section BB containing 21,068 elements.

2.5 *Sensitivity analyses*

The sensitivity analyses were performed by simulating unique combinations of likely minimum, trending and maximum values of the chosen parameters, where the number of simulations, N, amounts to $N=3^n$, where n is the number of parameters evaluated. The combination of minimum and maximum values is there to build a set of ranges of possible settlement uncertainty, and the trending values are there to compare for when only one parameter is chosen. This approach makes for a relatively efficient sensitivity analysis, which also likely yields a realistic range in contrast to with more demanding probabilistic methods, such as Monte Carlo analysis. Since three parameters were chosen, the number of simulations is N = 27, as shown in Appendix. The standard case is equivalent to the parameter combinations of simulation 5.

3 RESULTS

Figure 8 shows the settlement (vertical displacement u_y) results after 1m drawdown and 1 year consolidation of the sensitivity analyses for all 27 combinations (SA range). It also shows individual results of combinations of the standard case (sim. 5), where only one parameter is varied. Interestingly, Figure 8 shows that the largest settlements occur where shallow clay layer is present at the soil-rock interface. This is of course attributed to the relatively short drainage paths which result in faster consolidation in those areas, and as the effective stresses approach NCS, more creep deformations are predicted. Figure 8 also shows that the uncertainties are largest in sections with bedrock levels between 0m and -20m, whereas the smallest uncertainties are seen in sections with either deep or very shallow bedrock levels.

The largest difference between minimum and maximum trend is seen when *OCR* is varying, where *OCR* (min) contributes to the largest settlements (Figure 8(a)), followed by k_v (Figure 8(b)). Interestingly, varying r_k (Figure 8(c)) yielded insignificant differences in results, despite clear variation in bedrock levels. The insignificance of r_k can be explained by the assumptions of low varving and uniform drawdown, but also by the drainage paths being mostly vertical.

The simulation results, based on different timelines and drawdown scenarios, are fed into a 3D metamodel. The metamodel is an efficient surrogate model that combines 3D stratigraphic information with 2D numerical analyses to make 3D settlement predictions. This model allows us to analyse the time-dependent drawdown of a larger area and link it to a building damage model. The building damage model uses these settlements to estimate damage on buildings, either through empirical or semi-empirical methods.

4 CONCLUSIONS

The aim of this study was to analyse the sensitivity of important model parameters in coupled 2D settlement analyses for a typical underdrainage problem by varying *OCR*, k_v and r_k in a scenario of 1m instant uniform drawdown for 1 year consolidation time. The following conclusions were made from this study:

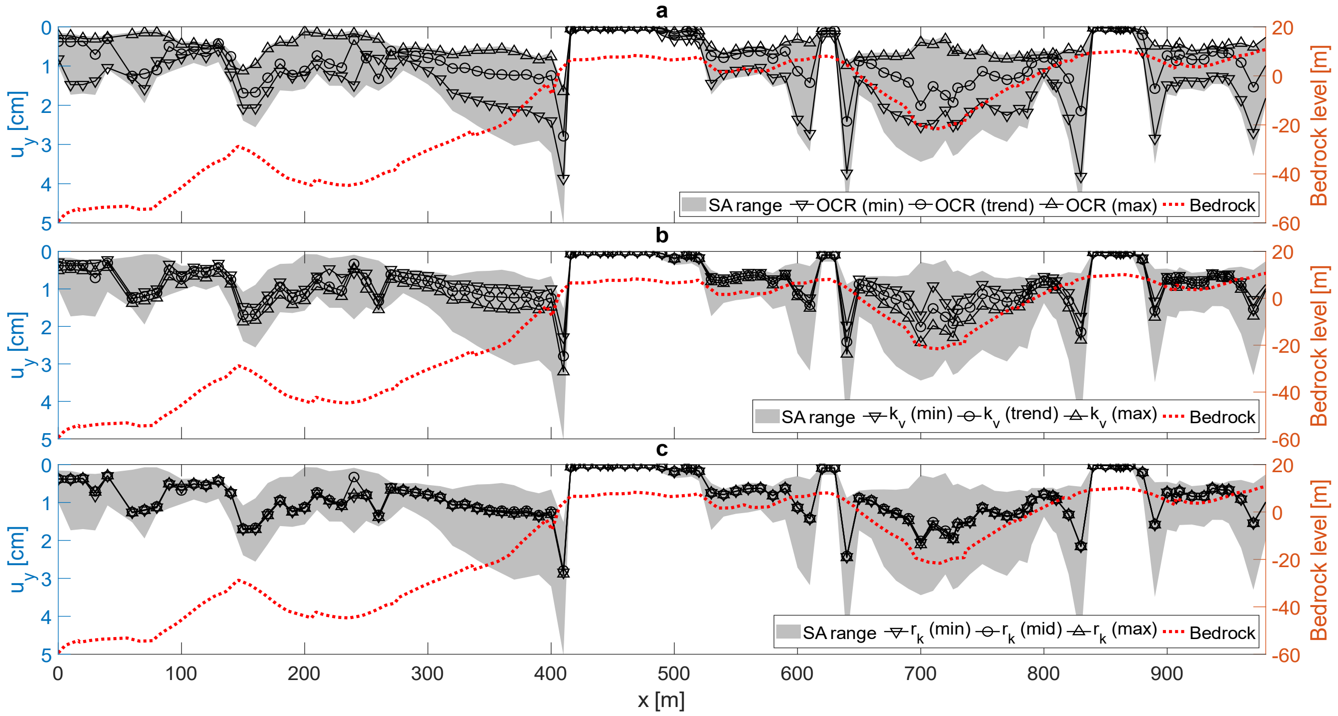


Figure 8. Displacement results from 1m drawdown, 1 year consolidation. Results of the entire sensitivity analysis (SA) range (a-c) and varying OCR (a), k_v (b) and r_k (c).

1) *OCR* clearly influenced the settlement results the most, followed by vertical hydraulic conductivity, 2) Changing hydraulic anisotropy had practically no impact on the predicted settlement results despite clear stratigraphic variation.

The predicted settlements are largest at the soil-rock boundary where the clay is shallow. This could have an impact on the structures built in these areas. As these may have different foundation types (depending on the depth to bearing stratum), it would be worthwhile investigating these areas further, while also including the effects of the foundation type.

5 ACKNOWLEDGEMENTS

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6 APPENDIX A

Table A1. All parameter combinations for the sensitivity analysis. $r_k = k_h/k_v$ is the hydraulic anisotropy ratio.

Sim.	**OCR**	$\boldsymbol{k_v}$	$\boldsymbol{r_k}$
1	Min	Min	Min
2	Trend	Min	Min
3	Max	Min	Min
4	Min	Trend	Min
5	Trend	Trend	Min
6	Max	Trend	Min
7	min	Max	Min
8	Trend	Max	Min
9	Max	Max	Min
10	Min	Min	Mid
11	Trend	Min	Mid
12	Max	Min	Mid
13	Min	Trend	Mid
14	Trend	Trend	Mid
15	Max	Trend	Mid
16	Min	Max	Mid
17	Trend	Max	Mid
18	Max	Max	Mid
19	Min	Min	Max
20	Trend	Min	Max
21	Max	Min	Max
22	Min	Trend	Max
23	Trend	Trend	Max
24	Max	Trend	Max
25	Min	Max	Max
26	Trend	Max	Max
27	Max	Max	Max

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