Influence of permeability on creep development: A comparative study of oedometer test and field-scale berm

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Abstract. The estimation of settlements in soil that exhibits creep is a challenging task. This paper first numerically replicates oedometric-like tests in PLAXIS for a 1 m thick layer of soil. These simulations investigate the effects of permeability values and consolidation time on the development of the creep displacements. The results show that in the simulations, the part of settlements related to creep is affected by the permeability values at the beginning, and that the differences are large; however, the displacements obtained from the constitutive models considering creep gradually converge after approximately 60 years in the case of the oedometric test simulation. Subsequently, the paper shows that those initial discrepancies are similar in the case of settlement of a real-scale underwater berm. However, a convergence to a single settlement value is not observed in the simulations of the berm.

1 Introduction

Predicting long-term settlement in soft, structured clay is one of the challenging issues in geotechnical engineering. Traditionally, the settlement process in consolidation analysis is divided into two phases: primary consolidation, governed by the dissipation of excess pore water pressure [1], and secondary consolidation (creep), defined as a time-dependent deformation of the soil under constant effective stress [2]. Ladd et al. (1977) defined Hypotheses A and B based on whether creep occurs during primary consolidation. Hypothesis A assumes that creep happens after primary consolidation ends; Hypothesis B assumes that creep appears immediately, at the beginning of primary consolidation [3]. Some researchers, such as Mesri and Godlewski [4], Choi [5], Feng [6], Mesri and Vardhanabhuti [7], and Mesri [8] supported Hypothesis A. while, Bjerrum [9], Stolle et al. [10], Vermeer and Neher [2], Nash and Ryde [11], Yin et al. [12], Leroueil [13], Leoni et al. [14], Karim et al. [15], Nash and Brown [16] supported Hypothesis B.

Field observations of thick clay deposits sometimes show settlement exceeding theoretical predictions [17]. One potential reason for that is that we fail to consider the creep correctly.

Bjerrum (1967) was one of the first to argue that the creep starts at the beginning. He observed that many buildings on the soft clay continued to settle more than predicted. Hence, he introduced the concept of delayed compression and argued that soil behaves visco-elastically as soon as the load is applied, even while the water is being squeezed out [9]. Yin and Graham (1989) proposed a concept based on equivalent time that shows total strain rate is a function of the current state of the soil and the equivalent time when loading started. This implies that creep is an intrinsic part of the consolidation process and starts at the beginning, even before pore pressure dissipation [18]. Kelln et. al. (2009) used the same logic for finite element analysis of an embankment on a soft estuarine deposit in Northern Ireland [19]. In addition, Leroueil (2001) mentioned that the viscous behaviour of the soil exists throughout the entire loading period; however, in the thick clay layers, the slow dissipation of water due to low permeability makes the creep behaviour during the early stages of settlement less visible [20].

This paper employs PLAXIS 2D analysis with two constitutive models considering creep: Soft Soil Creep (SSC) and Creep-SCLAY1 to investigate how the variation of permeability influences the visibility and rate of creep.

2 Material and method

2.1 General description of seabed soil

The simulation uses seabed soil data from the Tahkoluoto site in Finland, which mainly consists of soft clays. Soil samples were taken by the Geological Survey of Finland’s (GTK) research vessel Geomari with a Kullenberg piston. The samples were taken from sediment cores, up to 5 m long. The samples were taken from the seabed, approximately 50 m below sea level [21, 22]. To determine soil properties, we conducted extensive laboratory tests on the samples, including hydrometer tests, fall cone tests, oedometric tests and triaxial tests.

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2.2 Constitutive models

The Finite Element Method numerical analyses are conducted with PLAXIS 2D software. We computed the settlements with 4 different sets of permeabilities (see Table 1) using the Soft Soil, Soft Soil Creep (SSC), SCLAY1, and the Creep-SCLAY1 constitutive models. The Soft Soil and Soft Soil Creep model parameters are the same as previously established for this soil [21-25] and shown in Table 2, while parameters for the SCLAY1 and Creep-SCLAY1 models are given in Table 3.

Table 1. Sets of permeability values.

Considered permeabilities				
Calculation case *i*	Case *1*	Case *2*	Case *3*	Case *4*
$k_{x,i}$ (m/s)	10^{-8}	10^{-9}	10^{-10}	10^{-11}
$k_{y,i}$ (m/s)	10^{-9}	10^{-10}	10^{-11}	10^{-12}

Table 2. Soft Soil Creep material parameters.

Parameters of Soft Soil (Creep)	
Saturated unit weight, γ_{sat} (kN/m^3)	14.5
Modified compression index, λ^* $(-)$	0.169
Modified swelling index, κ^* $(-)$	0.025
Modified creep index, μ^* $(-)$	0.03

Table 3. Creep-SCLAY1S material parameters.

Parameters	
Absolute rate of destructuration, ξ	0
Relative rate of destructuration, ξ_d	0
Initial anisotropy, α_{K0}	0.46
Intrinsic modified compression index, λ_i^* $(-)$	0.169
Intrinsic modified creep index, μ_i^* $(-)$	0.03
Absolute rate of rotation, ω	0.76
Relative rate of rotation, ω_d	17.23
Slope of the critical state line, (M_c)	1.2
Bonding, (χ_0)	0
OCR	1

For the SCLAY1 family of models, the scalar value α_{K0} corresponding to in-situ K0 condition can be theoretically derived based on Equation (1):

$$\alpha_{K0} = \frac{\eta_{K0}^2 + 3\eta_{K0} - M_c^2}{3} \tag{1}$$

Where $\eta_{K0} = 3(1 - K_0^{NC})/1 + 2K_0^{NC}$.

In addition, the relative rate of rotation (ω), and the absolute rate of rotation (ω_d) are calculated based on Equations (2) and (3):

$$\omega_d = \frac{3}{8}\frac{4M_c^2 - 4\eta_{K0}^2 - 3\eta_{K0}}{\eta_{K0}^2 - M_c^2 + 2\eta_{K0}} \tag{2}$$

$$\omega = \frac{1}{\lambda_i^*}\frac{10M_c^2 - 2\alpha_0\omega_d}{M_c^2 - 2\alpha_0\omega_d} \tag{3}$$

Where λ_i^* is the intrinsic modified compression index.

In these models, the parameters for destructuration and bonding are set to zero. Moreover, the values of intrinsic modified compression and creep indices are kept consistent with the Soft Soil and Soft Soil Creep models. These changes ensure that any observed differences in long-term settlement can be attributed specifically to the permeability effect.

2.3 Oedometric test simulation

We modelled a large-scale 1D oedometric test in PLAXIS, assuming an axisymmetric model with sample diameter and height both 1 m. The boundary conditions at the bottom are fixed, while on the left and right sides, they are only fixed in the x-direction. Drainage can occur at the top and bottom parts of the sample. The sample originates from a depth of 5 m. Therefore, in the first step, we defined a 5m high sample, then we removed the top 4 m of the soil, and finally we applied an incremental load in the consolidation phase. We considered a long consolidation time (100 years) to be sure that we are at the end of consolidation. Further details can be seen in [26].

2.4 Simulation of an underwater berm

The other simulation investigated how different values of permeability may influence the amount of settlements related to creep of an underwater berm. The Mohr-Coulomb model is chosen for backfill and Berm, and for clay, Soft Soil Creep, Soft Soil, Creep-SCLAY1, and SCLAY1 models are employed to consider the effect of permeability on the creep. The geometry of the model is demonstrated in Fig. 1.

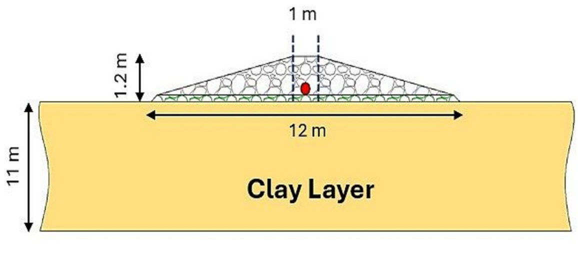

Fig. 1. Model geometry of underwater berm.

The above sketch shows a subsea cable protected by an underwater berm. The berm is made of loose sand, with the unit weight of 18 kN/m^3. Between the cable and the clay layer, we have a 20 cm thermal backfill as a cooler layer to better dissipate energy. The diameter of the cable is 20 cm. The simulation and further details about the geometry and constitutive models can be found in [26].

3 Results and discussions

3.1 1D oedometric simulation

This section compares the settlement results for Soft Soil vs. Soft Soil Creep (SSC) model, SCLAY1 vs. Creep-SCLAY1, Soft Soil vs. SCLAY1, and Soft Soil Creep (SSC) vs. Creep-SCLAY1 models. The results are assembled in Fig. 2.

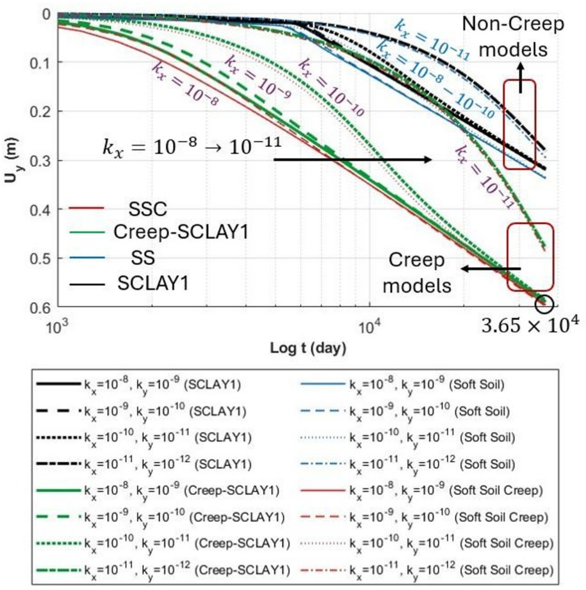

Fig. 2. Parametric study evaluating the impact of permeability on the long-term settlement behavior over time using different constitutive models. The analysis compares non-creep models: SCLAY1 and Soft Soil (SS) against their creep-enabled counterparts: Creep-SCLAY1 (green curves) and Soft Soil Creep (SSC). The upper cluster is comprised of the non-creep models (SS and SCLAY1), where settlements stabilise early, and the lower cluster is comprised of the creep models (SSC and Creep-SCLAY1), where secondary compression continues to drive settlement.

In Fig. 2, the creep models (Soft Soil Creep and Creep-SCLAY1) show larger settlement due to the inclusion of secondary compression. When permeability decreases from $k_x = 10^{-8}, k_y = 10^{-9}\ m/s$ to $k_x = 10^{-11}, k_y = 10^{-12}\ m/s$, the start of the major settlement is delayed, shifting the curve to the right on the logarithmic time scale.

In addition, for the lowest permeability case ($k_x = 10^{-11}, k_y = 10^{-12}\ m/s$), both clusters (creep and non-creep models) show a steep slope, which highlights that low permeability not only delays pore pressure dissipation but also extends the period over which creep significantly contributes to the total settlement.

Furthermore, the trends between the Soft Soil and SCLAY1 families are quite similar, as we aimed to keep the key parameters for settlements (compression index, swelling index) for those models the same. However, there is still a small difference in the outcomes, perhaps due to differences in the formulation of the constitutive models.

In both clusters, for the first three sets of permeability, the final value of settlement is almost converged; however, for the case with smaller permeability ($k_x = 10^{-11}, k_y = 10^{-12}\ m/s$), it seems it would require more time than the simulated 100 years.

3.2 Effect of permeability on creep

In the following Tables (Tables 4 and 5), the secondary settlement (Creep) is demonstrated for different sets of permeability as the difference in settlement between the creep and non-creep models.

Table 4. Difference in settlements between creep and non-creep models for different sets of permeability (Soft Soil and Soft Soil Creep models).

	S	S_{creep}	$S_{creep} - S$
k_{x_1}, k_{y_1}	0.3376	0.5991	0.2615
k_{x_2}, k_{y_2}	0.3375	0.5989	0.2614
k_{x_3}, k_{y_3}	0.3357	0.5958	0.2601
k_{x_4}, k_{y_4}	0.2955	0.4889	0.1934

Table 5. Difference in settlements between creep and non-creep models for different sets of permeability (SCLAY1 and Creep-SCLAY1 models).

	S	S_{creep}	$S_{creep} - S$
k_{x_1}, k_{y_1}	0.3195	0.5897	0.2702
k_{x_2}, k_{y_2}	0.3194	0.5894	0.27
k_{x_3}, k_{y_3}	0.3177	0.5860	0.2683
k_{x_4}, k_{y_4}	0.2812	0.4798	0.1986

In the above Tables, S is the primary settlement and is derived based on the Soft Soil and SCLAY1 models. S_{creep} is the total settlement and is derived based on the Soft Soil Creep and Creep-SCLAY1 models. $S_{creep} - S$ gives the settlements due to creep for the four cases with different permeability, see Table 1. The evolution of the difference in settlements between creep and non-creep models is shown in Fig. 3.

In Fig. 3, curves for both Soft Soil and SCLAY1 families of models exhibit a similar trend. For permeability cases 1-3, the settlements related to creep seem to converge in 100 years. For Case 4, it seems to show nearly linear progression and has only reached about 0.19 m in 100 years. Furthermore, in an oedometric situation, since the boundaries are restricted, the evolution of anisotropy should not have an effect.

3.3 Settlement results of the underwater berm

In the case of the underwater berm, the comparison between creep and non-creep models was made for the Soft Soil and Soft Soil Creep models. For the two different consolidation times, 50 years and 500 years, we derived the settlement and the difference between settlements obtained from the Soft Soil Creep and Soft Soil models. The results are shown in Figs. 4 and 5. In Fig. 4, black lines represent the results of the Soft Soil model, and gray lines represent the results of the Soft Soil Creep model.

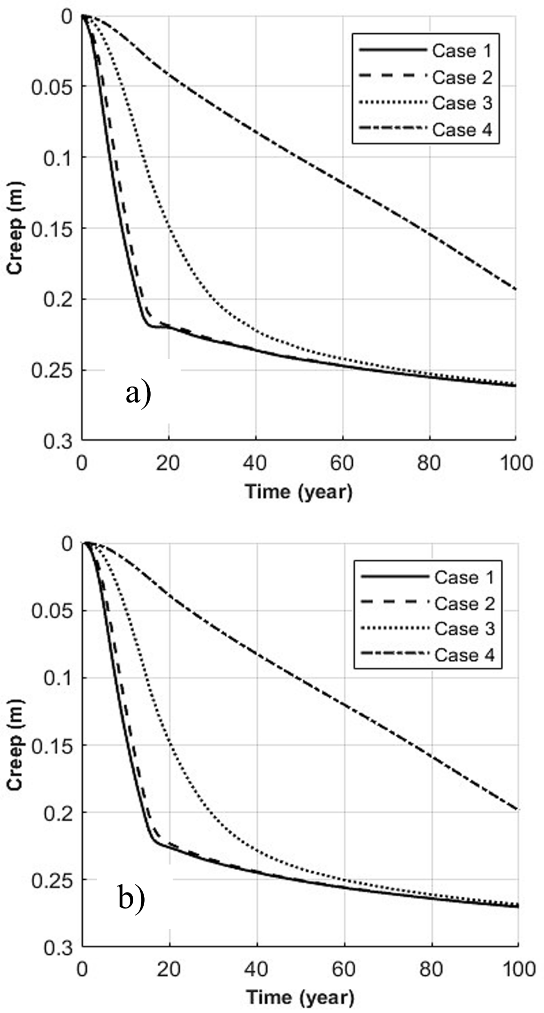

Fig. 3. Difference in settlements between creep and non-creep models: a) derived from the Soft Soil and Soft Soil Creep models; b) derived from the SCLAY1 and Creep-SCLAY1 models.

For cases with the sets of permeabilities $k_x = 10^{-10}, k_y = 10^{-11}\ m/s$; and $k_x = 10^{-11}, k_y = 10^{-12}\ m/s$; the evolution of creep is smaller. However, for the case with $k_x = 10^{-9}, k_y = 10^{-10}\ m/s$, we have large differences. This can also be concluded from Fig. 4, since the final settlement related to the larger permeability is much larger than the other cases.

The numerical results further indicate that, unlike the 1D oedometric simulation, which converges within 60 years, the 2D berm settlements do not converge for the investigated permeability range over 500 years. In the lower-permeability cases, the dissipation of excess pore water pressure is slow, meaning these models may remain in the primary consolidation phase for most of the simulation.

Despite efforts, we cannot offer a well-validated theory explaining the differences between the creep and non-creep for the berm simulation, and we have decided not to speculate on the reason for the observed behaviour.

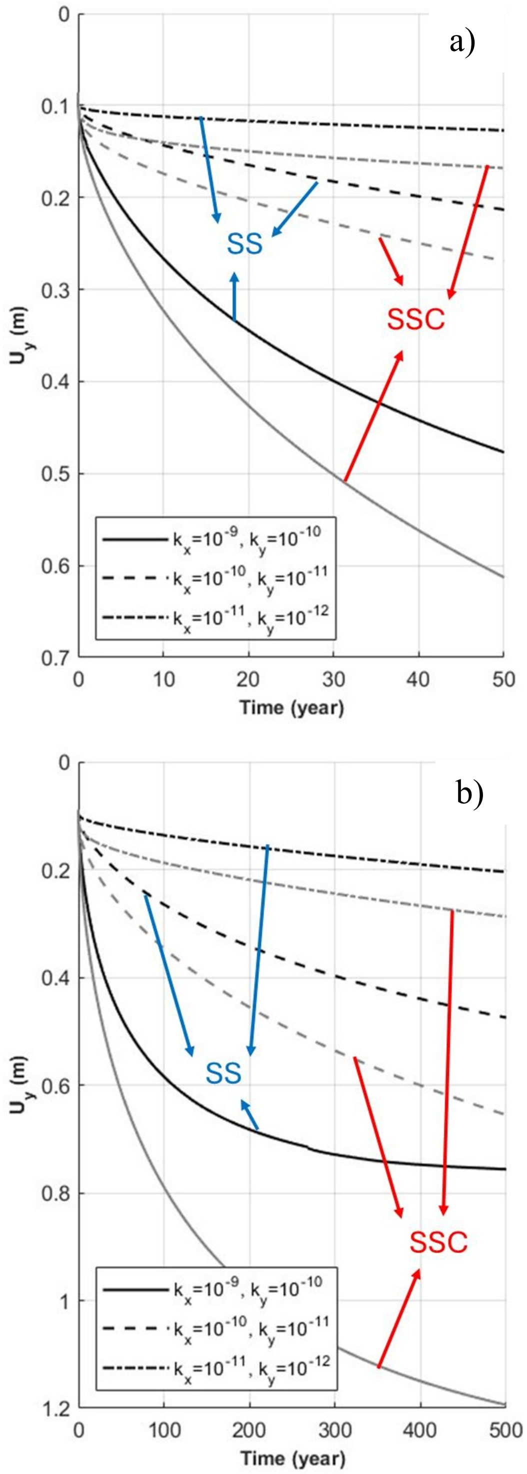

Fig. 4. Settlement results of embankment: a) after 50 years; b) after 500 years. Black lines represent results obtained using the Soft Soil model, while gray lines represent results obtained using the Soft Soil Creep model.

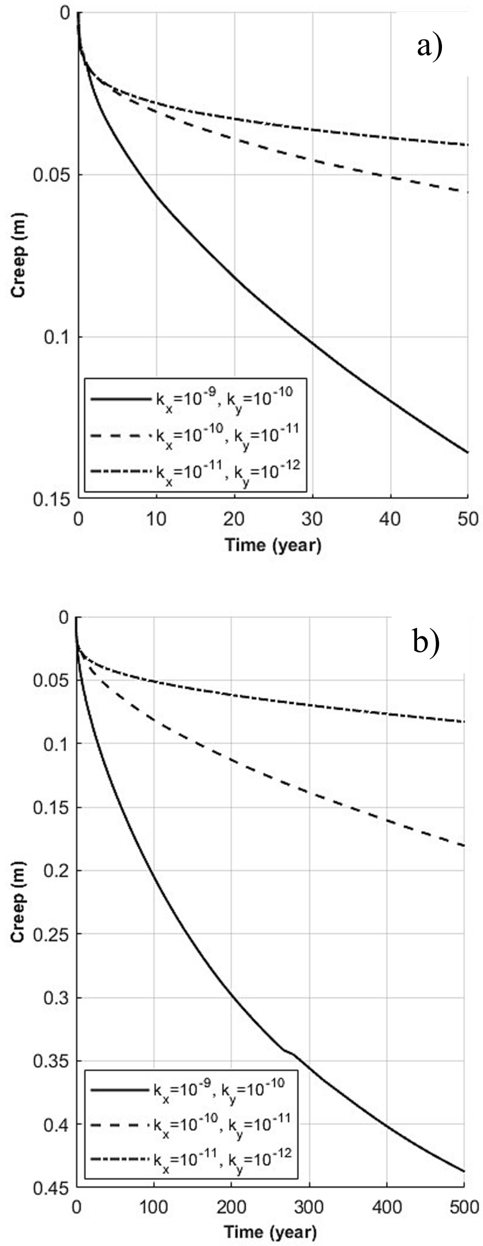

Fig. 5. Evolution of the difference in settlements between creep and non-creep models: curves a) after 50 years; b) after 500 years.

4 Conclusions

Numerical simulation of creep evolution reveals a fundamental scaling effect between 1D oedometric simulation and the 2D field berm. While the 1D oedometric simulation shows that creep curves converge for three cases after about 60 years, there is no convergence in the underwater berm case even after 500 years. Moreover, for a subsea berm on a thick clay layer, permeability is a dominant parameter for estimating the final settlement. The creep settlements are not only defined by the modified creep index, but also by permeability values.

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The PLAXIS files that support the findings of this study are openly available at Zenodo at: https://doi.org/10.5281/zenodo.20431039

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