Results from a geotechnical benchmark exercise of an embankment on soft clay

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ABSTRACT: The results of a simple geotechnical benchmark problem, an embankment on soft clay, are presented and discussed. The problem has been simulated with several constitutive models: models that are commonly used for practical geotechnical engineering problems, as well as advanced models developed by SCMEP Network partners. These advanced constitutive models account for initial and induced anisotropy, destructuration and creep or combinations of these features. The comparisons highlight the effects of these features on soft clay response and demonstrate the differences between alternative constitutive modelling approaches.

1 INTRODUCTION

Building embankments and other constructions on deposits of natural soft soil is still a challenge in geotechnical engineering. Construction on soft soils becomes even more important as urban areas all over the world become more and more congested, and thus construction projects today are often on or passing through areas, which were considered to be unsuitable for construction just a couple of decades ago.

With simulations of simplified geotechnical problems, it is possible to assess how different fundamental features of natural soil behaviour, such as anisotropy, creep and destructuration, reflect on predicted soil behaviour. Thus, the implementation of new models can be tested and the predictions can be easily compared with those by established models without having to deal with the uncertainties that are common for real geotechnical problems. Simplifications of real construction problems, or artificial simple problems, can be called 'benchmark' problems.

The benchmark calculations presented in this paper follow the specifications by the SCMEP Network partners. The subsoil is modelled by using a characteristic set of parameters representing a soft Scandinavian clay determined from the same set of experimental data for all the models considered. The simulations enable to compare the soil response predicted by the advanced models to the response by models for soft soils frequently employed in practice. Additionally, some critical remarks will point out shortcomings and restrictions of the chosen benchmark specifications.

2 SPECIFICATION OF THE BENCHMARK

The benchmark embankment is simulated as a plane strain finite element problem, using a model with roughly 750 to 1500 nodes, by considering half of the geometry with a width of 60m and a

depth of 36m. A cross section of the embankment is shown in Fig. 1. It is assumed that underneath the soft clay layer there is a rigid stratum. The boundaries are horizontally restrained at lateral boundaries and fixed in both directions at bottom boundary; for consolidation the lateral boundaries are assumed to be closed, allowing drainage at the water table (assumed to be 2m below the ground surface) and the bottom boundary only. Initial stresses have been taken (assuming tension positive) as $\sigma'_v = -\gamma' \cdot h$ and $\sigma'_h = -K_0 \cdot \gamma' \cdot h = -(1-\sin\varphi') \cdot \gamma' \cdot h$, where h is the depth below surface. Additionally, vertical preconsolidation pressures of $\sigma'_{pv} = \sigma'_{v0} - 30\text{kPa}$ for the clay above the ground water table, and $\sigma'_{pv} = \sigma'_{v0} - 10\text{kPa}$ for the clay below the ground water table, have been assumed. The soil is hence assumed to be lightly overconsolidated. It is acknowledged, that the use of normally consolidated K_0 values for in-situ stress calculation together with the specified pre-consolidation pressures is not realistic, but this has been assumed for the sake of simplicity.
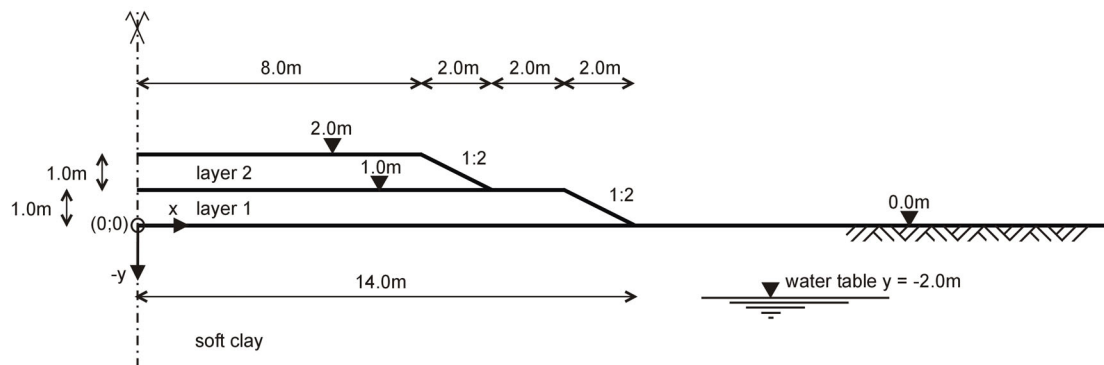

Figure 1. Geometry of the 'benchmark embankment'

Slope of normal compression line	λ	0.71
Slope of unloading-reloading line	κ	0.03
Poisson's ratio	ν'	0.2
Effective cohesion	c'	0kPa
Ultimate friction angle	φ'	30°
Dilatancy angle	ψ	0°
Initial void ratio	e_0	2.1
Slope of the critical state line	M_c	1.2
Bulk unit weight (saturated)	γ_{sat}	15kN/m³
Permeability (isotropic)	k_f	$1 \cdot 10^{-9}$m/sec

Table 1. General material parameters of the subsoil

Young's modulus	E'	40000kPa
Poisson's ratio	ν'	0.3
Cohesion	c'	1kPa
Ultimate friction angle	φ'	38°
Dilatancy angle	ψ	0°
Tensile strength	σ'_t	0kPa
Total unit weight	γ	20kN/m³
Permeability (isotropic)	k_f	1m/sec

Table 2. Material parameters for the embankment

Both layers of the embankment are applied under undrained conditions, with zero pore water pressures above the ground water level. After the undrained construction of the embankment, 100 years of consolidation is simulated. Material parameters to be used for the underlying subsoil and the embankment are listed in Tab. 1 and Tab. 2, respectively.

3 CONSTITUTIVE MODELS AND INPUT PARAMETERS

The construction of the embankment was analysed by five research groups using several different constitutive models with different complexities. In this paper, the results of the groups from Glasgow University (GU), University of Stuttgart (USTUTT) and Graz University of Technology (TUG) are shown. Eight constitutive models have been used: Modified Cam Clay (MCC), S-CLAY1 and S-CLAY1S, the Soft Soil model (SS) and the Soft Soil Creep model (SSC), as well as the Multilaminate Creep model (MLC), the Multilaminate Model with destructuration (MLD) and the Multilaminate Model for Clay (MMC).

The MCC (Roscoe & Burland 1968) and the SS model (e.g. Brinkgreve 2002) are both well-established isotropic constitutive models often used in practice and have been included for comparison. The S-CLAY1 model (Wheeler, Näätänen, Karstunen & Lojander 2003) accounts for plastic anisotropy by means of the rotation of the yield surface and the S-CLAY1S model (Koskinen, Karstunen & Wheeler 2002) incorporates additionally the degradation of bonding with plastic straining. Ultimately, these two models reduce to the isotropic MCC model if certain initial state parameters and soil constants are set to zero. The MCC, S-CLAY1 and S-CLAY1S models have been implemented into SAGE CRISP and the other models in PLAXIS. The SSC (see Brinkgreve 2002) and the MLC model account for creep, and the latter one accounts for anisotropy via the multilaminate framework (Zienkiewicz & Pande 1977, Pande & Sharma 1983). The other two multilaminate models are the anisotropic MLD model (Cudny 2003), which considers structural anisotropy and destructuration (but not creep), and the anisotropic MMC model (Wiltafsky 2003), which is a double hardening model incorporating both shear and volumetric hardening. A detailed description of the adopted advanced constitutive models is presented by Wheeler, Cudny, Neher & Wiltafsky (2003).

4 RESULTS OF THE ANALYSES

In the following the results of the simulations with the different constitutive models are presented. Fig. 2a shows the surface settlement trough immediately after construction of the embankment. All models show qualitatively a similar response. As far as maximum settlements are concerned, the models accounting for anisotropy predict higher vertical displacements than the isotropic models; the destructuration also increases slightly the magnitude of displacements (S-CLAY1 vs. SCLAY1S). MMC predicts somewhat higher vertical displacements than S-CLAY1. MLD, the model with destructuration formulated in the multilaminate framework, predicts the highest values for the settlements. At the centreline the results by the other models range from about 0.11 to 0.24m. The creep models predict the lowest settlements in the short term. The SS model and MCC model can produce very similar results, depending on whether or not the parameters for the SS model are set to approximate the MCC model. The importance of the parameter governing the behaviour of the cap in the SS model is demonstrated by varying the K_0^{nc}-value (USTUTT: $K_0^{nc} = 0.5$; TUG: $K_0^{nc} = 0.665$).

The effective horizontal stresses and the excess pore pressures are plotted in Figs. 2b and 2c, respectively, for a horizontal section at a depth of 2.5 m below the ground surface. In Fig. 2b MCC, S-CLAY1 and S-CLAY1S show significantly different distributions compared to the other models; this is due to numerical instabilities in the excess pore pressure predictions close to the water table, which is a common problem when using SAGE CRISP. There are, however, no discontinuities in the horizontal direction due to this problem (Fig. 2d). The predicted shear stresses (Fig. 2c) show the same tendency for all models with moderate differences in magnitude.
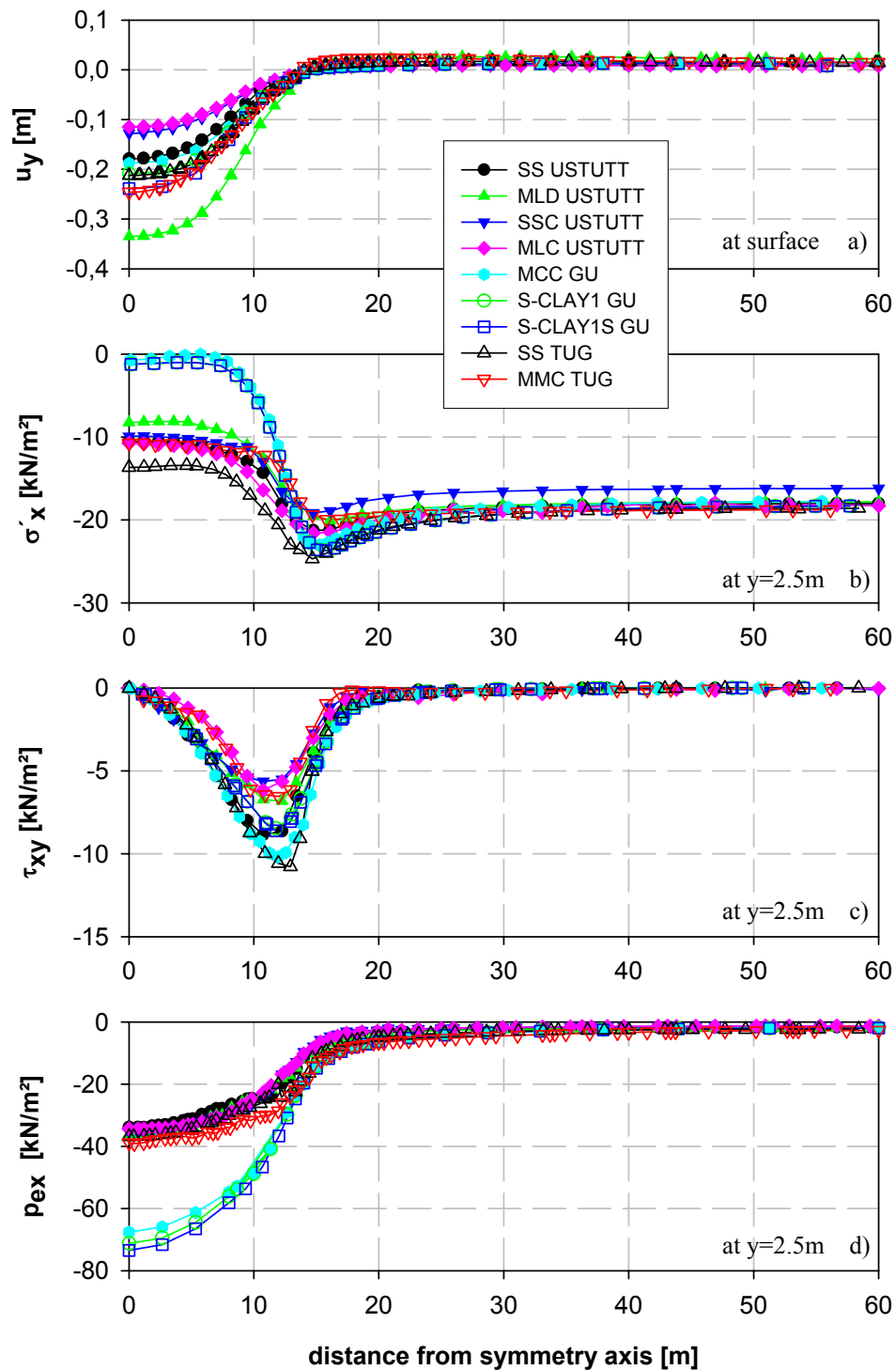
Figure 2. Results after construction: a) surface settlement trough,
b) horizontal effective stresses, c) shear stresses d) excess pore pressures at horizontal profile y=2.5m
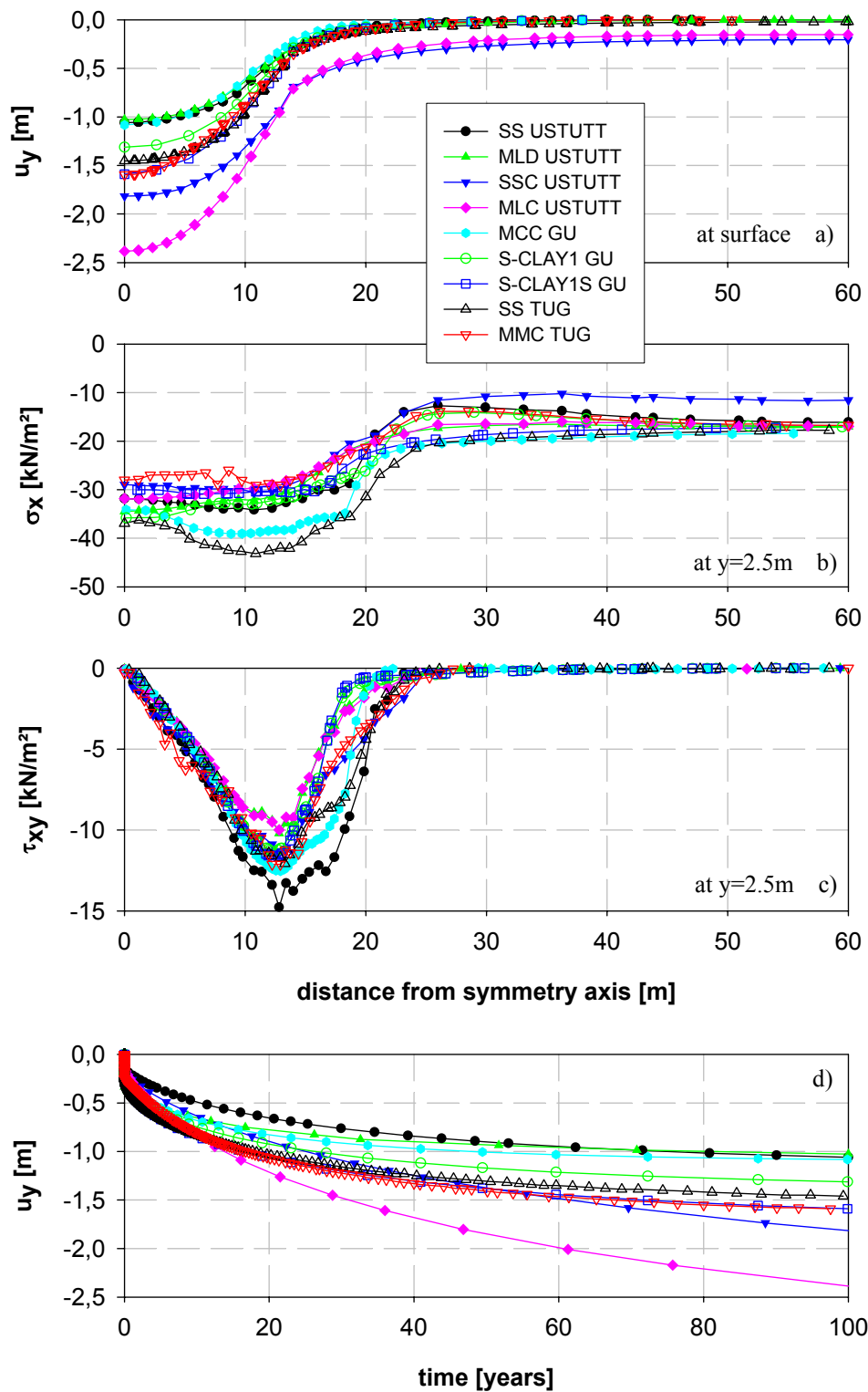
Figure 3. Results after 100 years of consolidation: a) surface settlement trough,
b) horizontal effective stresses, c) shear stresses at horizontal profile y=2.5m
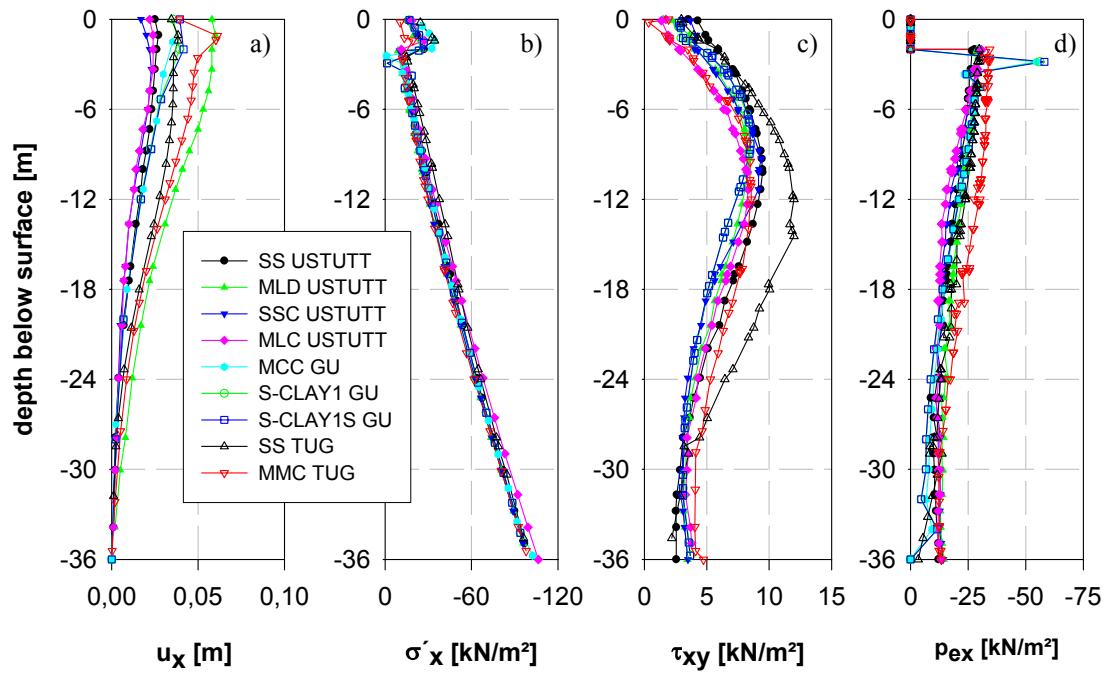d) time settlement curve for point x=y=0m

Figure 4. Results after construction at vertical profile x=8m: a) horizontal displacements,
b) horizontal effective stresses, c) shear stresses, d) excess pore pressures

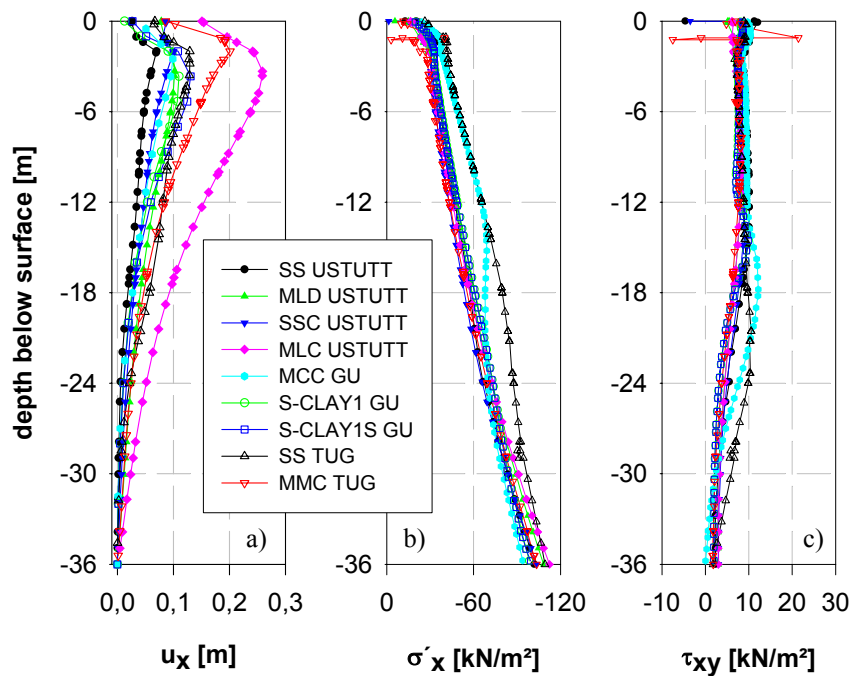Figure 5. Results after 100 years of consolidation at vertical profile x=8m:
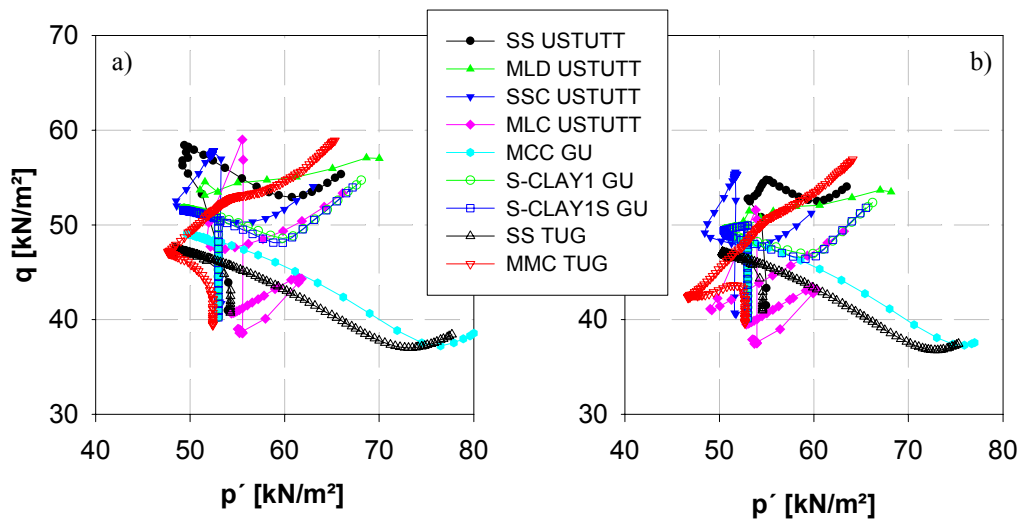a) horizontal displacements, b) horizontal effective stresses, c) shear stresses

Figure 6. Stress paths: a) p´-q at x=0 and y=12m, b) p´-q at x=8 and y=12m

Fig. 3a shows the surface settlement trough after 100 years of consolidation. The models considering creep predict the highest settlements at the symmetry axis, as expected. MLC predicts significantly higher values than SSC. All the other models predict settlements of about 1.10 to 1.60m. Again the effect of anisotropy increases the predicted settlements. Interestingly, MLD (destructuration on multilaminate framework) predicts lower settlements than the other anisotropic models in the long term, whereas the opposite was true in the short term. Figs. 3b and 3c show, respectively, the effective horizontal stresses and the shear stresses at 2.5 m depth after consolidation, with a scatter in values of about 30 to 40%. Fig. 3d shows the time settlement curves predicted. The curves of the models accounting for creep (MLC and SSC) clearly show still ongoing deformations after the 100 years of consolidation. For the 'non-creeping' models at least 95% of the settlements have occurred after 100 years of consolidation. There are some differences in the time-settlement response, but within the range of what can be expected.

In Fig. 4 simulation results at the vertical profile x = 8m are plotted immediately after construction. Fig. 4a shows horizontal displacements, with maximum values predicted by multilaminate models (MMC and MLD) and lowest values by the creep models. Fig. 4b shows effective horizontal stresses and only minor differences are seen. Shear stresses (Fig. 4c) are at a maximum at y = -10 to -12m, and the highest values are obtained from the SS model from TUG (influence of the cap parameter). The excess pore pressures (Fig. 4d) do not vary significantly; the irregularities at the top are purely due to difficulties in excess pore pressure predictions close to the draining boundary when using SAGE CRISP.

In Fig. 5 the results at the vertical profile x = 8m are presented after 100 years of consolidation. Now, in the long term, the creep models predict higher horizontal displacements than the other models, but the qualitative response is again very similar for all models. Effective horizontal stresses and shear stresses (Fig. 5b & c) are very similar for the anisotropic models, but the isotropic MCC and SS (TUG) models give slightly different results at greater depths. This is related to the unrealistic K_0 prediction by the Modified Cam Clay type of models.

Finally, the predicted stress paths in terms of the mean effective stress p' against deviatoric stress q are plotted in Fig. 6 at two chosen points. Some variations are apparent, but at the end of the consolidation all result in roughly the same location for all other models but the MCC and its approximation with the SS model (SS TUG). That would suggest that in terms of stress paths, the way the K_0 is predicted influences the results more than e.g. anisotropy. Stress paths closer to the surface suggested that the embankment is close to failure, and therefore, the differences between the models are perhaps excessively highlighted. Consequently, Krenn, Karstunen, Wheeler & Zentar (2003) have proposed a slightly modified benchmark specification.

5 CONCLUSIONS

Results from a numerical exercise comparing various constitutive models have been presented considering a simplified analysis of the construction of an embankment on soft soil. The results suggest that by including anisotropy the predicted settlements are higher than by isotropic models, both in the long and short term. As expected, creep models increase settlements further in the long term. Given that natural clays are anisotropic, viscous materials, with some bonding, any predictions that ignore these features for these type of problems are likely to be unconservative in terms of settlement prediction.

Interestingly, the two different approaches for modelling anisotropy result in very different predictions of horizontal displacement: the multilaminate models MLC and MMC predict noticeably higher horizontal displacement than the rotational hardening anisotropic models (S-CLAY1 and S-CLAY1S). This demonstrates how useful benchmarks simulations, such as the ones presented, are in comparing constitutive models and understanding their features.

Further studies are currently under progress in order to evaluate the performance of the different constitutive models for other types of problems such as a deep excavation and a tunnel. The true validation of the advanced constitutive models developed as part of SCMEP project will require comparisons of model simulations with instrumented field structures.

ACKNOWLEDGEMENT

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