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SUR L'EMPLOI DES LOIS CONSTITUTIVES AVANCÉES POUR LA MODELISATION D'UNE FONDATION

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ABSTRACT – A constitutive model is a system of hypothetical principles that represent the character of a phenomenon and from which predictions can be made. But what principles to include for what phenomenon of soil behavior? This paper gives some thoughts on this question by simulating a large scale load test of a spread footing with three different constitutive models; the issue of parameter selection and significance is discussed also.

RÉSUMÉ –

1. Introduction

"(For)… problems of soil-structure interaction, analyses should use stress-strain relationships for ground and structural materials and stress states in the ground that are sufficiently representative, for the limit state considered, to give a safe result" (Eurocode 7).

Recently, many new constitutive laws have been developed and implemented in commercial finite element programs. No doubt, other new models are being developed and will also become available soon, for example models that incorporate the soil's small strain behavior. Yet, the question is, when is it necessary to use such models to be *"sufficiently representative"* and which parameters are important to know when using these models?

In the following, a large scale load test of a spread footing on sand conducted at the Texas A&M University is used to investigate these issues by means of three different soil models: the standard Mohr-Coulomb Model, the Hardening-Soil Model implemented in the FE code PLAXIS, and a new Bounding Surface Model incorporating the soil's small strain stiffness behavior. However, model performance is not only related to the model chosen, but also to the input parameter selection made by the user. Therefore, some investigations are presented on the significance of different input parameters and on the potential of default parameters. It is shown that parameter significance is highly related to the problem on hand and hence, default parameters can often be used for standard problems.

2. Test Conditions and Constitutive Models

2.1. Large Scale Load Tests of Spread Footings at Texas A&M University

Five load tests on spread footings ranging from 1x1 to 3x3 m in size were conducted at Texas A&M University National Geotechnical Experimentation Site (Briaud and Gibbens, 1997).

Vertical loads were applied at the center of the footings which rested on flat ground. Load-settlement curves as well as inclinometer and extensometer measurements were recorded for each load test (Figure 1).

Numerous soil tests have been performed at the sandy site. These data together with the load settlement curves are used in the following to conduct a finite element simulation of the load test using three constitutive soil models, which differ in their level of sophistication. In particular, the 'North' 3x3 m footing (Briaud and Gibbens, 1997) has been chosen for the Finite Element simulation; this footing has a thickness of 1.22 m and a embedded depth of 0.76 m.

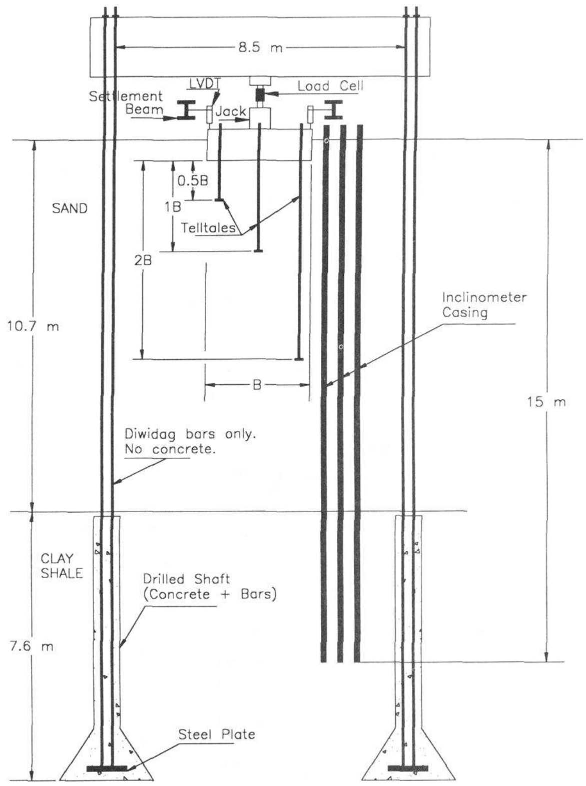

Figure 1. Load test setup (from Briaud and Gibbens, 1997).

2.2. Constitutive Models

Constitutive soil models used in the finite element simulation of the load test are briefly described in the following, with a focus on the input parameters the user needs to specify.

2.2.1. Mohr-Coulomb Model (MC)

A standard Mohr-Coulomb Model is used as the basic soil model for the following analysis. The Mohr-Coulomb Model gives elastic perfectly-plastic soil behavior with a total of five material parameters: the soil's elastic parameters E (Young's modulus) and ν (Poisson's ratio), and the plastic parameters φ (friction angle), c (cohesion), and ψ (dilatancy angle).

2.2.2. Hardening-Soil Model (HSM)

A hardening plasticity model that allows for shear- and compression hardening is the Hardening-Soil Model as implemented in PLAXIS (Schanz et.al., 1999; Brinkgreve, 2002). Its cap closed Mohr-Coulomb type yield surface (Figure 2a) is allowed to expand during plastic straining. Total strains are calculated by a stress dependent stiffness, different for both, loading and unloading.

Input parameters needed for the HSM are again the strength parameters φ, c, and ψ. Soil stiffness is defined by the parameters E_{50}^{ref} characterizing the soil's shear behavior, E_{oed}^{m} mainly controlling the volumetric behavior and E_{ur}, the unloading-reloading modulus.

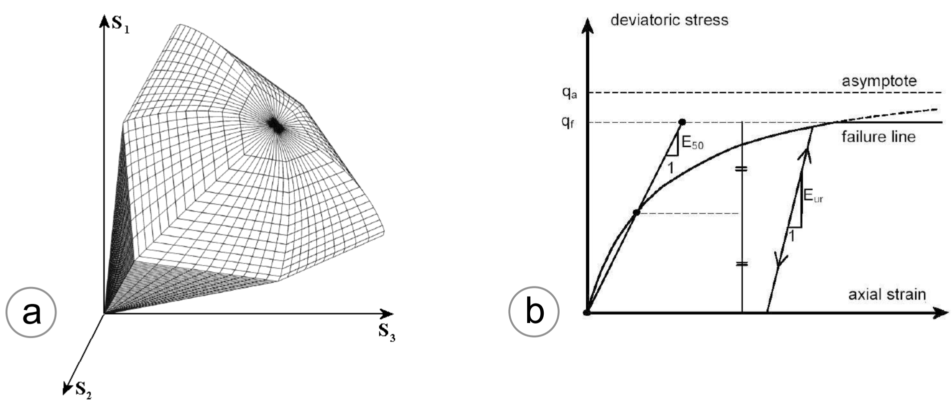

Figure 2. a.) HSM yield surface; b.) Derivation of E_{50}^{ref} from triaxial testing: E_{50}^{ref} is the secant modulus taken at $q_f/2$.

An Ohde/Janbu type parameter m controls the stress dependency of the stiffness. The derivation of the above stiffness parameters by a triaxial test is shown in Figure2b.

2.2.3. Bounding Surface Model (BSM)
The Bounding Surface Model used in the following is based on this by Dafalias (Dafalias, 1986; Benz, 2003). It has been extended by a vector based small strain stiffness formulation and a super-elliptic stress-strain relationship. Material stiffness is related to the distance of the actual stress point to its image point on the bounding surface (Figure 3). In analogy to the shear hardening of the HSM the hardening process is driven by the rate of plastic shear straining and includes both, kinematical and volumetric hardening of the yield surface.

Input parameters needed for the BSM somehow relate to these of the HSM. Since the BSM is based on critical state principles, input parameters for the critical state strength and the critical state line location are needed, too. For the small strain stiffness formulation two additional parameters are required: the shear modulus at very low straining and the amount of shear strain where the small strain stiffness has completely vanished.

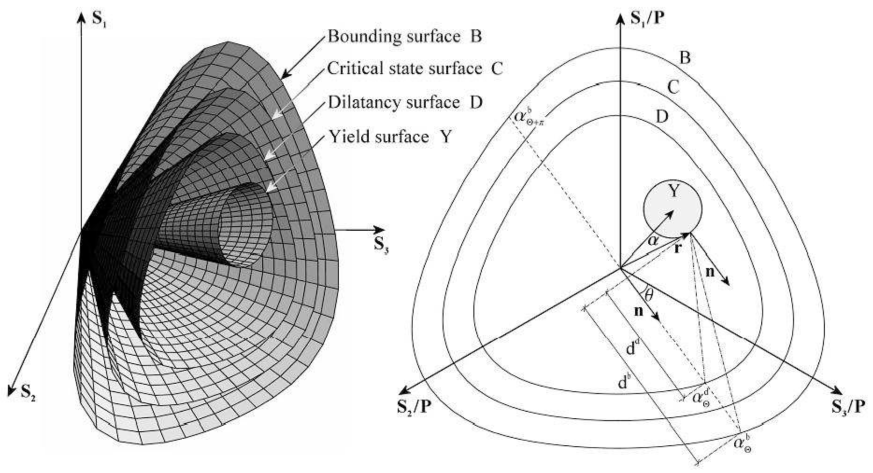

Figure 3. BSM soil stiffness is a function of the distance d^b from the actual stress point to its image on the bounding surface. The inner yield surface is allowed to translate and expand during plastic straining; bounding and dilatancy surfaces expand and contract as a function of hydrostatic pressure and void ratio.

2.3. Finite Element Model

An axis symmetric model is created in the FE code PLAXIS in order to calculate settlements and lateral displacements beneath the 3x3 m footing. The quadratic footing is idealized by a circular one of the same total area. The groundwater table is considered at a level of -5.0 m. The chosen geometry and finite element mesh are shown in Figure 4.

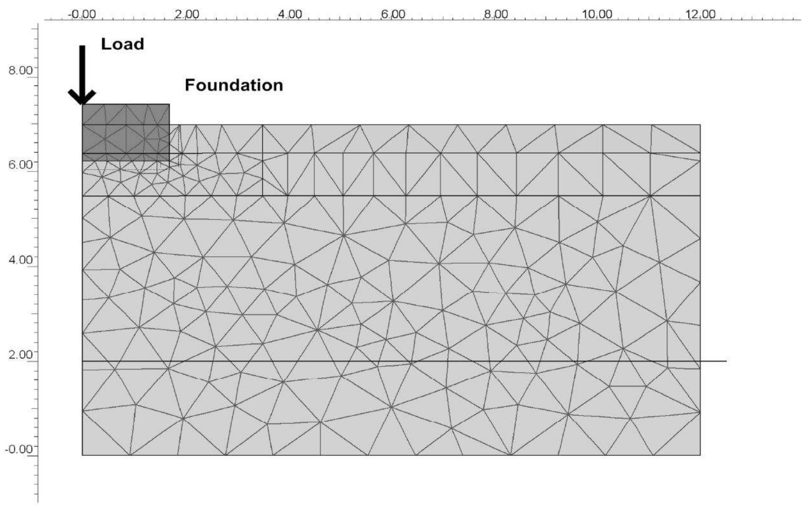

Figure 4. FE model of the large scale load test.

3. Model Calibration

Various soil tests have been performed on the test site as well as in the laboratory (Briaud and Gibbens, 1997). The most important one for calibration of the constitutive models is a drained triaxial test on reconstructed samples under three different confining pressures: 34.5 kN/m², 138 kN/m², and 345 kN/m². A comparison between experimental data and results of the calibrated models are shown in Figure 5.

Besides the triaxial tests other important information on the material's stiffness, especially the stiffness under small strains, is gained by the resonant column test as well as by the in situ cross-hole seismic experiment. In situ dilatometer tests and standard penetration tests show a relatively high overconsolidation of the test site, due probably in an earlier stage to the water waves action and later to the sand desiccation.

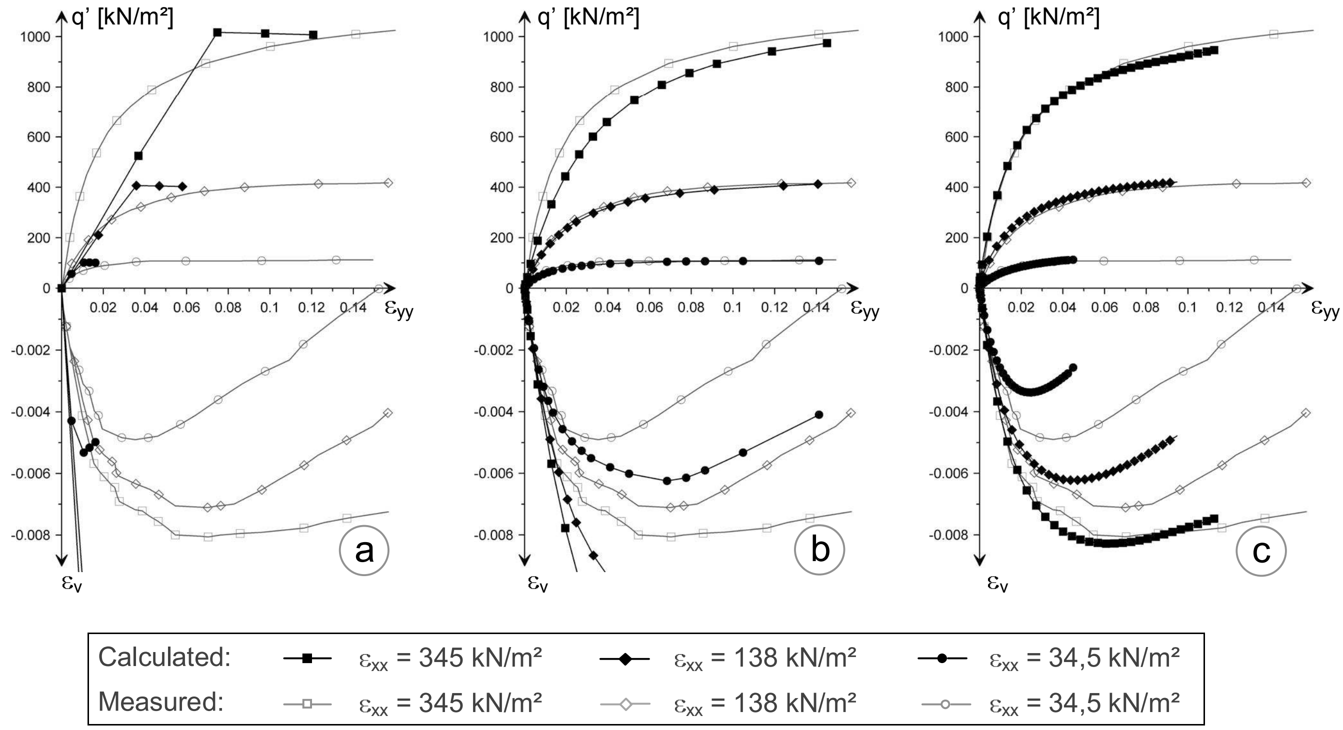

Figure 5. Model-calibration. Triaxial tests on a reconstituted sample (3.0 m depth) at different confining pressures have been simulated with a.) MC, b.) HSM, and c.) BSM.

4. Model Performance

4.1. Load Settlement Curves

Load settlement curves of the 3x3 m footing (Figure 6) have been calculated with the constitutive models briefly described in Section 2 and the parameters found when calibrating the models in Section 3. The only change that has been made is increasing the Young's modulus of the Mohr-Coulomb Model by factor 2 as proposed by Tatsuoka (Tatsuoka et.al.,1997). Doubling the stiffness shall account for the de-structuring of reconstituted sand in triaxial testing.

However, even with the increased stiffness, the Mohr-Coulomb Model does over-predict the settlements by far. Main reason for this is that it is not possible to model the overconsolidation at the test side properly when using the Mohr-Coulomb Model. Hardening plasticity is vital in such an environment. Hence, the HSM performs quite well. Modeling the overconsolidated sand is not a problem. However, unloading-reloading cycles can not be properly modeled by the HSM. The model formulation with a single unloading-reloading modulus E_{ur} can not be used to predict hysteretic effects.

Hysteretic effects can be seen in the load-settlement curve of the BSM. The first loading-unloading-reloading cycle is modeled nicely besides the effect of overconsolidation. The implementation of the BSM used in the calculation is a preliminary version which has no cap yet. Hence, the enlargement of the elastic region can not be modeled adequately; the model's response upon further loading is too stiff. Considering this shortcoming of the preliminary version of the BSM, the model performs also quiet well, especially when considering the distribution of lateral soil deformation in Section 4.2.

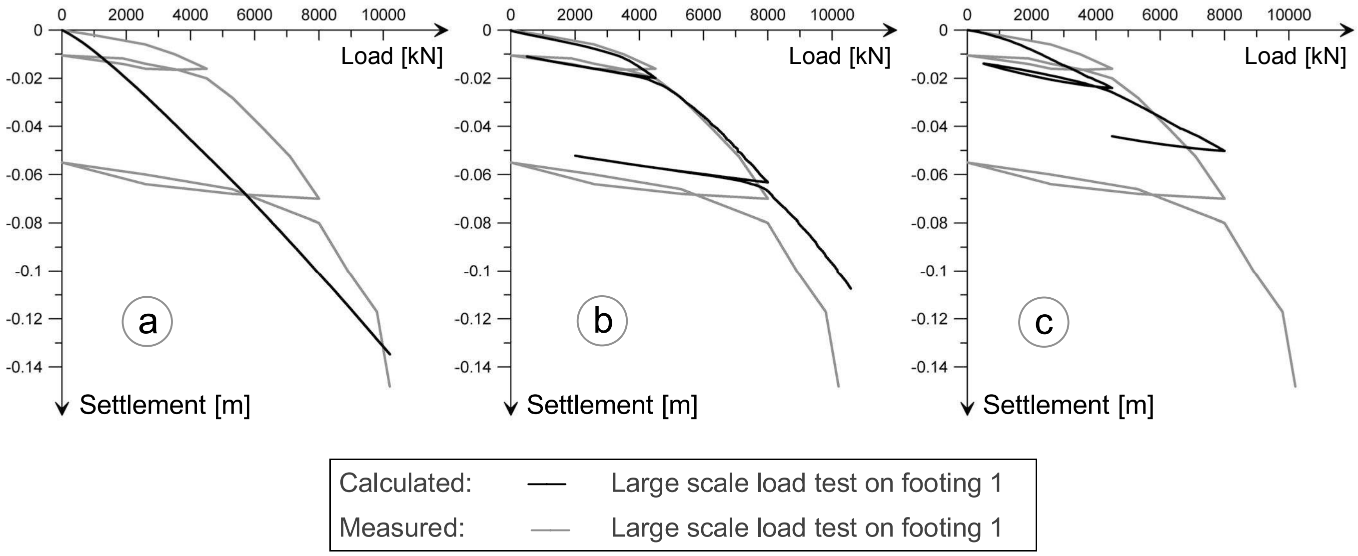

Figure 6. Load-settlement curves. Test results compared to predictions from a.) MC, b.) HSM, and c.) BSM.

4.2. Lateral Displacements

Inclinometer measurements at the Texas A&M University test site were taken at distances of 1.75 m and 4.00 m from the center of footing 1. Inclinometer readings at a vertical load of 4.5 MN were taken for the comparison of lateral displacements shown in Figure 7.

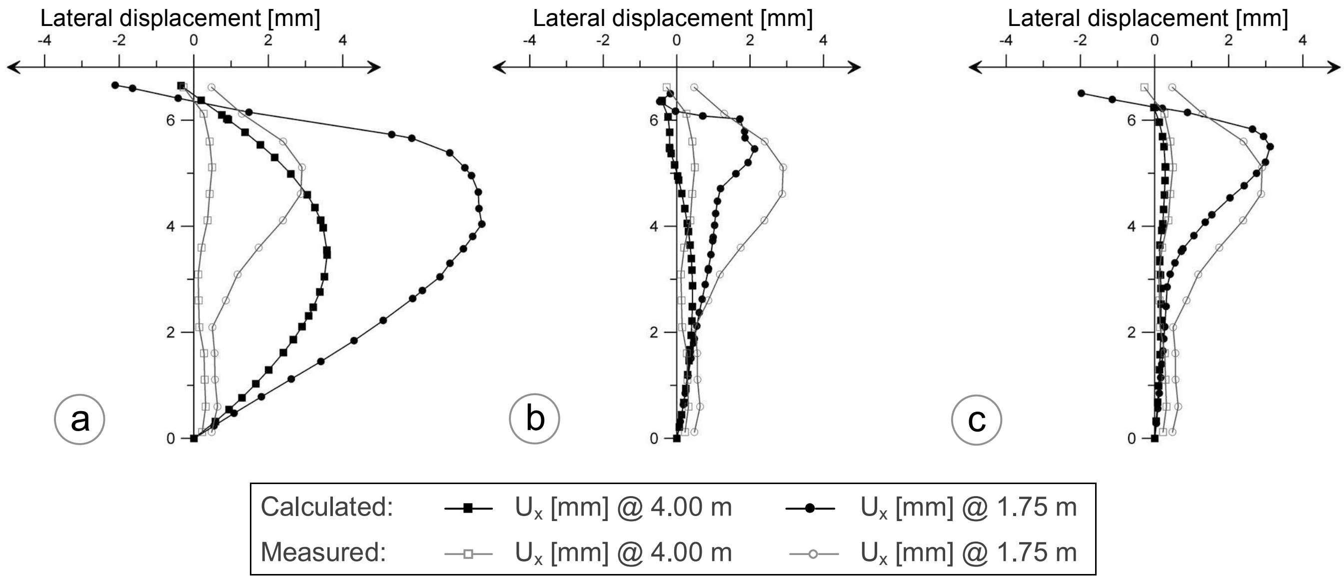

Figure 7. Inclinometer readings at a distance of 1.75 m and 4.00 m of the footing's center compared to FE results. a.) MC; b.) HSM, c.) BSM.

It appears that the FE mesh should have been enlarged in depth since the measured displacements at the bottom end of the FE model are not zero. However, for the purpose of this qualitative oriented comparison the FE model can be still considered as adequate.

Obviously, the MC model should not be used to predict lateral displacements; whereas the HSM and BSM give rather good predictions near the footing. In a grater distance, only the BSM with its small strain stiffness formulation gives realistic results. Therefore, if attention shall be paid not only to the total settlements of a footing, but also to the displacement trough around it, the chosen constitutive model should be necessarily capable of modeling the soil's small strain stiffness behavior.

5. Parameter Variation

The main problem in using advanced models consists in the comparatively large number of parameters needed to simulate the supplementary introduced behavior mechanisms. Fortunately, not all these parameters are equally important for the simulation results and for some of them the use of default values can furnish an acceptable approximation. In order to investigate the relative importance of the parameters an analysis was performed using first of all the calibrated parameter set of the HSM constitutive law. Compared hereto are series of analyses where the values were individually varied by $\pm$ 25% (using an idea of Mestat and Riou 2003).

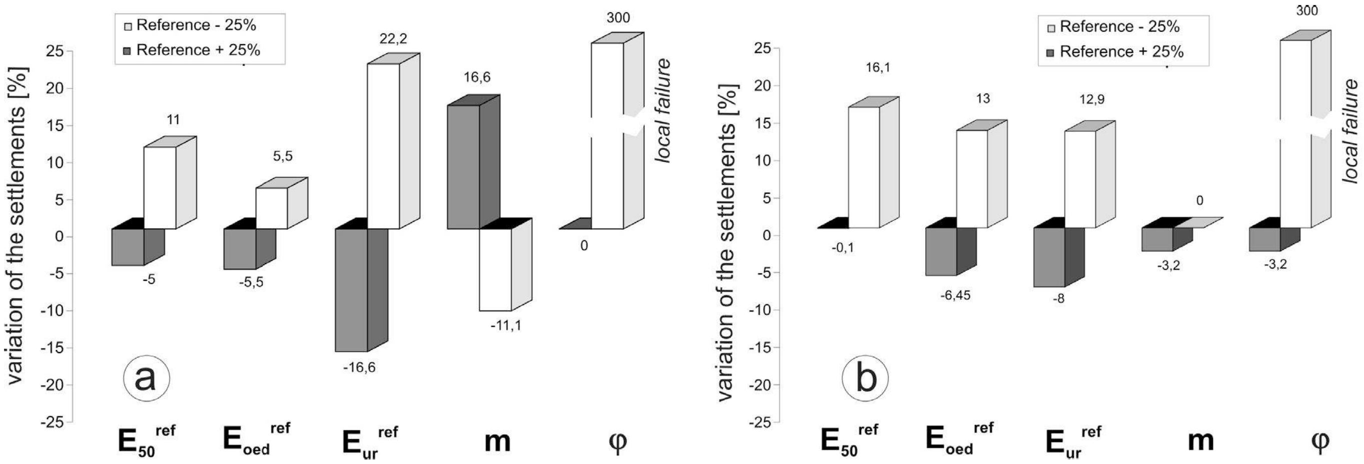

Figure 8. Sensitivity analysis for the 3x3 m A&M footing. Overconsolidated soil – a) 4,5 MN; b) 8 MN load.

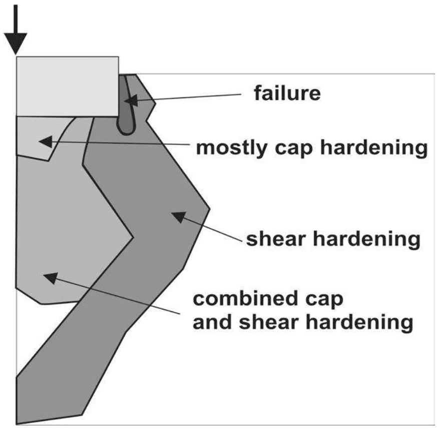

Figure 9. Domains of different hardening behavior.

The relative influence of parameter variation for the 3x3 m footing of the A&M experiment is presented in Figure 8 as percentage of settlement variations for a load of 4500 kN respectively 8000 kN.

Due to the soil overconsolidation the influence of the un-/reloading modulus is important for small loads. By large loading both normally consolidated shear and volumetric stiffness control the soil behavior. The domains where different type of hardening occurred are presented in Fig. 9 (8000 kN loading stage). The internal friction has practically no influence up to a near-failure stage.

The presented example proofed the influence of the loading stage on the relative importance of the parameters. However, the parameters can have different significance if different mechanisms are envisaged.

In Figure 10 the example of a navigable lock resting on a boulder clay layer is presented (Schwab 2003). All the construction history was simulated: excavation, construction of the lock, backfilling and loading with water at different levels. The same type of sensitivity analysis as for the foundation experiment has been carried out.

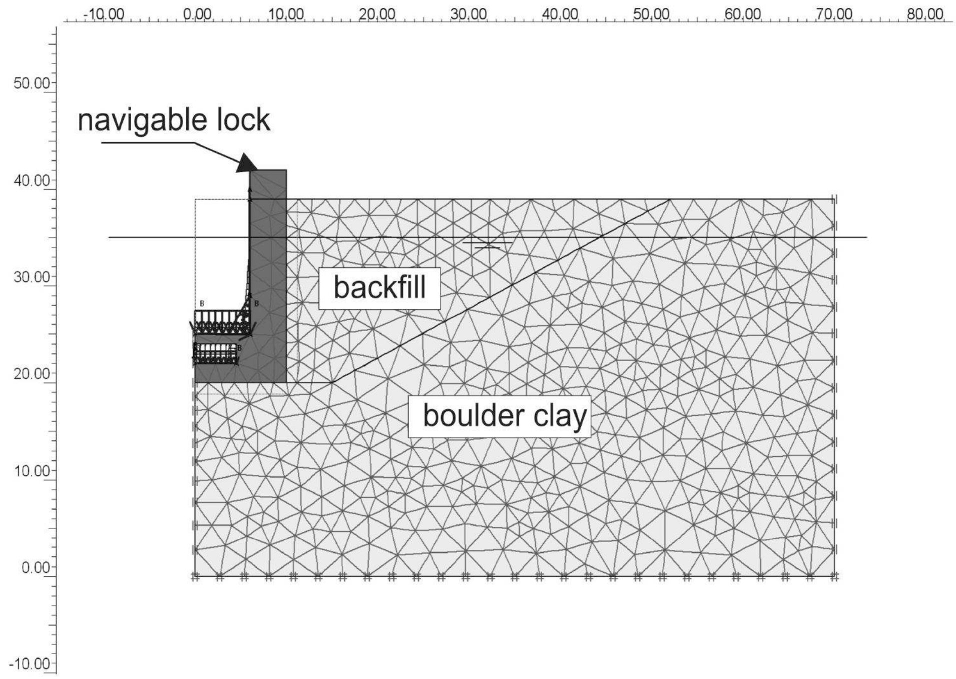

Figure 10. Finite element mesh used in the simulation of the navigable lock.

The results of the sensitivity analysis are shown in Figure 11. On the left hand side the parameter influence on the settlements which result from water level raising in the lock is shown. Since the soil is overconsolidated due to the prior excavation, the un-/reloading properties play a decisive role. For the earth pressure distribution the soil strength is obviously very important, where the (virgin) stiffness of the backfill controls mainly the mobilized pressure.

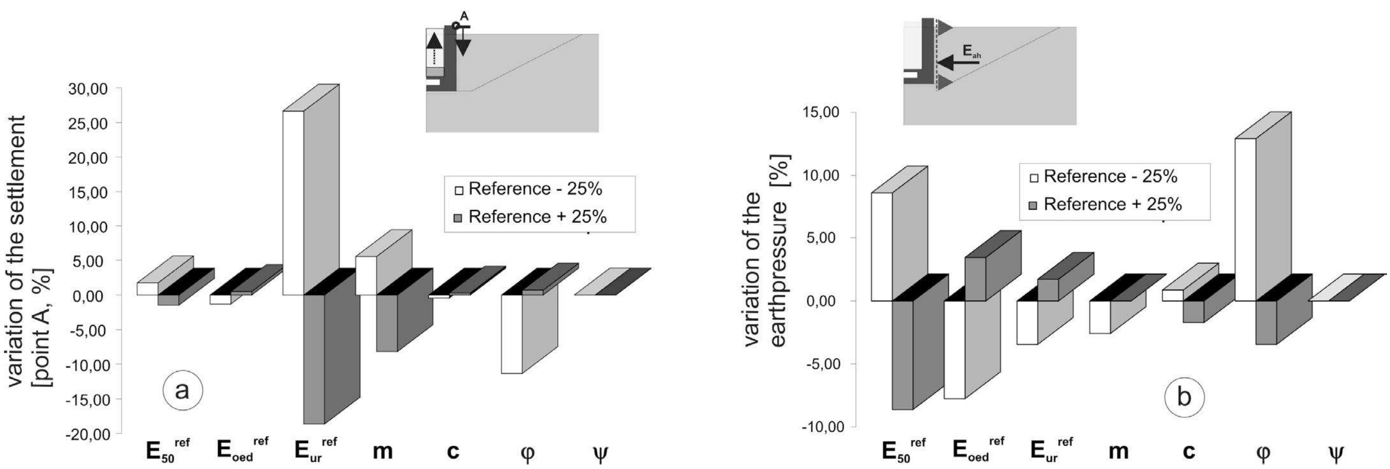

Figure 11. Sensitivity analysis for the navigable lock example – a) settlements due to the water level change; b) earth pressure.

6. Conclusions

By simulating a large scale load test with finite element calculations, the benefits of advanced constitutive models have been pointed out. Mechanisms that a constitutive law needs to incorporate depend solely on the soil-structure interaction problem on hand. In soil reloading problems (e.g. overconsolidation), hardening plasticity is essential, whereas for simulating lateral displacements, increased small strain stiffness is supplementary required.

As a matter of fact, advanced constitutive laws do need more input parameters. Fortunately, not all of these parameters are equally important regarding the simulation results. The parameter significance is related to:

- The actual problem; different parameters can be crucial in a deformation problem compared to these in an earth pressure calculation problem.
- The actual stage in the loading history; in an early overconsolidated stage, different parameters are important compared to these, that are important in a near failure stage.

Knowing these facts can facilitate the use of advanced constitutive models. Clustering the parameters driving the same mechanism might supplementary simplify the use of these models. However, further research is needed to clarify this aspect.

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