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MODELLING COMPRESSIBILITY OF SOFT SOILS WITH ANISOTROPIC MATERIAL MODELS

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ABSTRACT. This paper aims to highlight some of the important aspects of soft soil behaviour, such as the effect of creep and anisotropy, which can be captured with the advanced, constitutive models that are available today. This paper describes to some of the aims and objectives of the on-going PhD project at Chalmers University of Technology, which relates to the implementation and validation of a new constitutive model, involving extensive series of laboratory experiments to increase the knowledge of the creep process in the clays found in the Gothenburg area in Sweden.

1. Introduction

Time-dependent behaviour in clays forms a major engineering challenge in road design and construction in areas with deep deposits of soft clay. Soil improvement and construction of building foundations or embankments can be quite complicated and expensive in such areas, with geotechnical costs easily exceeding 20% of the total construction costs. With increasing emphasis on life-time costs, the initial design and construction costs need to be balanced against the possibly high maintenance costs. In order to do this optimally, there is a need to predict long-term settlement with a higher degree of accuracy than currently done in geotechnical engineering practice. To be able to predict the long-term settlements of building foundations or embankments constructed on soft soils, it is necessary to include the effect of rate-dependence and creep.

However, to incorporate only creep in a isotropic material model like the modified Cam Clay would not be satisfactory, as has been shown by numerous of researchers. It is also necessary to take in to account the fabric of the soil i.e. the anisotropy developed during deposition, sedimentation and consolidation history and any following straining.

This paper aims to highlight some of the important aspects of soft soil behaviour, followed by the description of, some of the advanced constitutive models available today that could capture the effect of creep. Although these model are capable of capture many of the important aspects of soft soils they are limited to normally consolidated and lightly over consolidated clays. Yet, the predictions on creep deformation following unloading are of great importance in practical applications, such as preloading with surcharge, as well as excavations and tunnelling in soft soil areas.

In this paper some of the aims of an on-going PhD project are discussed. The objectives of the project is to develop, implement and validate a new constitutive model that could account for creep deformations in the over-consolidated state. Extensive series of laboratory experiments will be conducted to validate the new constitutive model, and increase the knowledge of the creep process in the very soft sensitive clays found in the Gothenburg area in Sweden.

2. Behaviour of soft soils

The compressibility behaviour of soft soils has been studied for the past hundred years. The literature contains a substantial number of research papers on both compressibility and the consolidation process and how to model it with or without creep effects.

The pioneering work on stress-strain behaviour during one-dimensional consolidation was done by Terzaghi (1923). He published a theory for one-dimensional consolidation and today it is regarded as the classic consolidation theory.

Since then numerous researchers from various parts of the world have examined the problem of the behaviour of soft clays or soft soils, including Bjerrum (1967), Sällfors (1975), Mesri et al. (1977), Leroueil et al. (1985), Larsson (1986), Boudali et al. (1994) and Claesson (2003) to name but a few.

When a clay sample is suddenly loaded in the oedometer test, there is decrease in void ratio, resulting from 1D compression with time, is as schematically shown in Figure 1. The consolidation process is traditionally divided into a primary and a secondary consolidation/compression phase. During the primary consolidation phase, settlement is controlled by the dissipation of excess pore pressures, controlled by the deformation and Darcy’s law. During secondary consolidation, the rate of settlement is controlled by soil viscosity, Leroueil (2006). Secondary consolidation or creep is often characterised by the slope of the consolidation/compression curve.

It is a quite common opinion among geotechnical engineers that the behaviour soft soils, such as clays, is very strain-rate dependent. This effect has been recognised by several authors, including Suklje (1957), Crawford (1964), Sällfors (1975), Leroueil et al. (1985), Claesson (2003). A general observation is that the higher the strain-rate, the higher the effective stress for a certain strain.

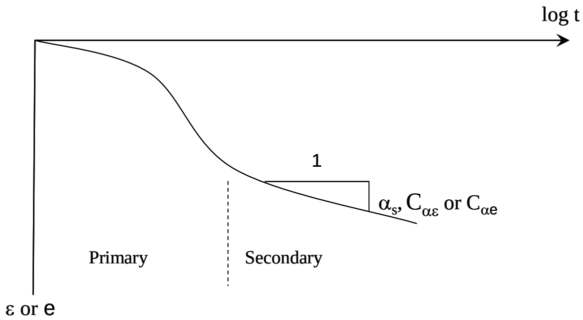

Figure 1. Typical consolidation curve for one load step in an incremental oedometer test..

This is shown in Figure 2, where two constant rate of strain (CRS) –oedometer tests have been conducted on a sample of soft clay taken at a depth of 16 m from Nödinge, just north of Gothenburg. The CRS oedometer tests are performed with two different strain rates, 0.7 %/hr and 0.07 %/hr, respectively.

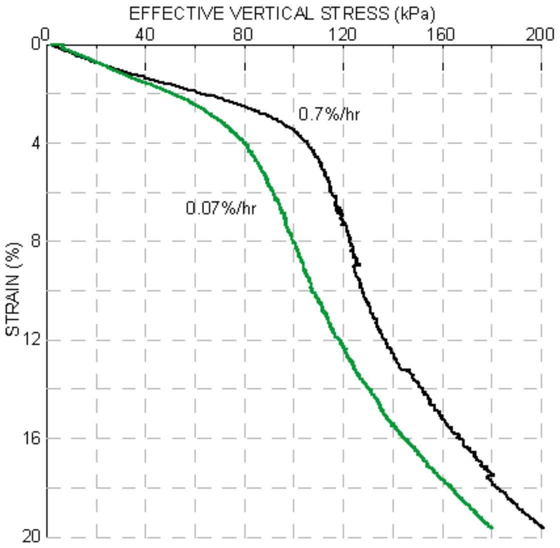

Figure 2. CRS oedometer tests, sample height 20 mm, with different strain rates, Nödinge depth 16 m.

Effect of Anisotropy

To be able to accurately model or predict deformations it is essential that the constitutive model incorporates anisotropy. The effect of anisotropy has been studied by several researchers e.g. Larsson (1981), Wheeler et al. (2003),. Experimental results on reconstituted Finnish clays Karstunen et al. (2008), demonstrate that any loading that produces irrecoverable strains and deviates from the loading that has created the initial anisotropy of the clay, will change the anisotropy.

Most deposits of natural soft clays have experienced K_0 loading. In order to test natural soil samples in a representative way, the best practice would be to try to preserve this initial anisotropy by K_0 consolidation before shearing the sample to failure. An isotropic consolidation would namely already destroy some of the initial anisotropy. If e.g. a K_0-CU (consolidated undrained) triaxial tests is conducted on samples of soft clays, the results in compression and extension is quite different, as could be seen in Figure 3.

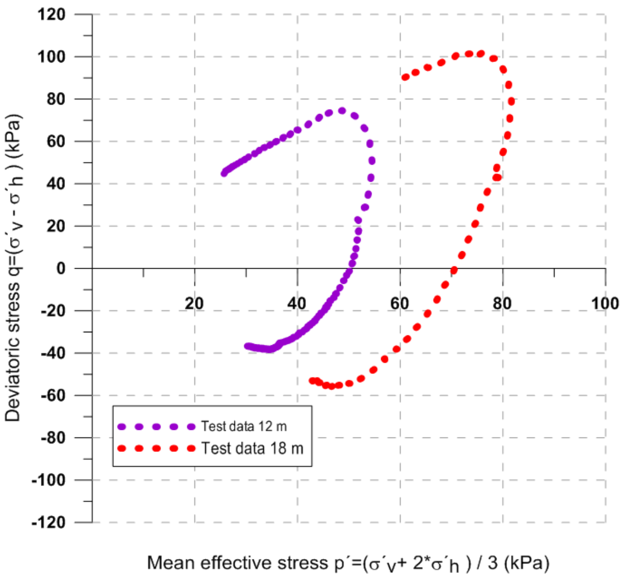

Figure 3. Triaxial test in compression and extension for very soft clays from Gothenburg at depths 12 m and 18 m.

It is very clear from Figure 3 that anisotropy, and in particular evolution of anisotropy, has a major effect of undrained shear strength. In natural clays, the undrained strength is also affected by the presence of some apparent bonding, which is gradually destroyed during shearing. This process is referred to as destructuration.

Numerous studies has been conducted to investigate the inclination of the yield surface for different types of clays see e.g. Larsson (1977), Wheeler et al. (2003), Leroueil (2006). The results from their investigation all indicates that the soil has anisotropic state at in-situ, and during subsequent loading this anisotropy may change.

3. Constitutive models

During the last decades a number of elastic-plastic constitutive models incorporating anisotropy has been developed by different researchers see e.g., Pestana et al. (1999), Wheeler et al. (2003), Dafalias et al. (2006).

During the last decade some of these models have been extended to incorporate also creep and strain-rate effects see e.g. Leoni et al. (2008), Grimstad et al. (2010), Yin et al. (2010). All of these constitutive models adopt an elliptical yield surface, which for the case of isotropic loading history reverts to the Modified Cam-Clay model in order to capture the changes in the anisotropy of the soil. The use of these models is limited to normally consolidated or lightly overconsolidated clays.

Starting point in this paper will be on the constitutive model developed by Karstunen and her co-workers, called the S-CLAY1S model (Karstunen et al. (2005)), and it´s further developments that incorporate the strain-rate effects. This forms the basis for the discussion about a new constitutive model, which is formulated so that it should be able to better capture the soil response in over-consolidated state.

Model principles for the S-CLAY1S model

The S-CLAY1S model is an extension of the S-CLAY1 model. The extension incorporates a hardening law that accounts for bonding and destructuration. In three-dimensional stress space the yield surface of S-CLAY1S model is a sheared ellipsoid, given by

$$\begin{aligned} f &= p' + \frac{3}{2}\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\}^T\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\} - \\ &-\left(M^2 - \frac{3}{2}\boldsymbol{\alpha}_d{}^T\boldsymbol{\alpha}_d\right)\cdot\left(p'_m - p'\right)p' = 0 \end{aligned} \qquad (1)$$

For the special case of triaxial space, for soil samples that have been cut vertically from the ground, the yield surface could be presented as Figure 4. The effect of bonding is described by an intrinsic yield surface with the same shape and inclination as the yield surface.

For more detailed explanation of the model the reader is referred to Karstunen et al. (2005) and Wheeler et al. (2003).

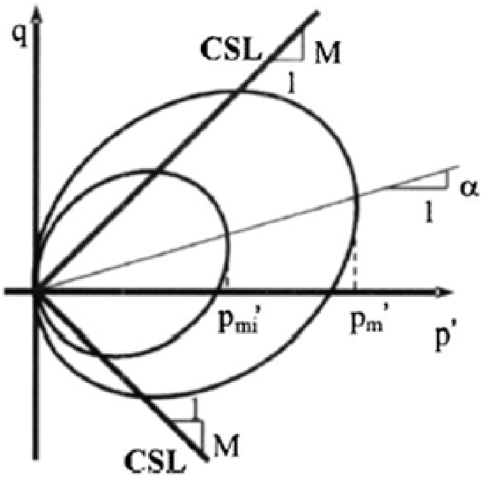

Figure 4. S-CLAY1S yield surface in triaxial space, Karstunen et al. (2005).

Anisotropic creep model

Most of the rate-dependent constitutive models mentioned above uses the equation proposed by Vermeer et al. (1998), given by eq. (2), to calculate the volumetric creep strains Leoni et al. (2008) or vertical creep strains Grimstad et al. (2010) as

$$\dot{\varepsilon}_v^c = \frac{\mu^*}{\tau}\left(\frac{p'_{eq}}{p'_p}\right)^{\frac{\lambda^*-\kappa^*}{\mu^*}} \qquad (2)$$

Where κ^*,λ^*,μ^* is the modified indexes according to Vermeer et al. (1999) and the p_{eq} is the equivalent mean effective stress with the corresponding preconsolidation pressure, p_p, see Figure 5 for details.

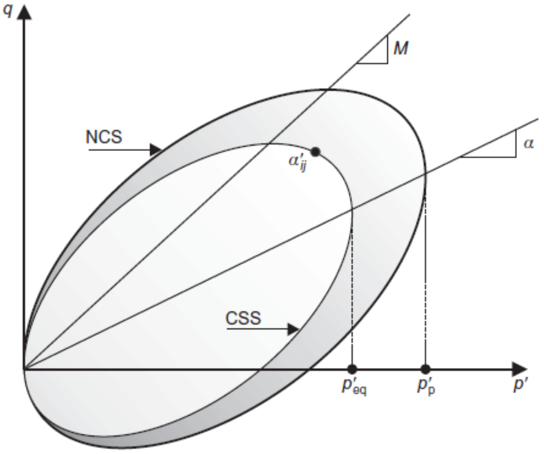

Figure 5. Anisotropic reference surface in triaxial space Leoni et al. (2008).

The size of the reference surface, which acts as the boundary between small creep strains and large creep strains, is defined with p_{eq} as:

$$p^{eq} = p' + \frac{\frac{3}{2}\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\}^T\{\boldsymbol{\sigma}_d - p'\boldsymbol{\alpha}_d\}}{\left(M^2 - \frac{3}{2}\boldsymbol{\alpha}_d{}^T\boldsymbol{\alpha}_d\right)\cdot p'} \qquad (3)$$

Therefore, based on eq. 2, creep strains occur everywhere is the stress space. For more information about anisotropic creep model the reader is referred to e.g. Grimstad et al. (2010) and Leoni et al. (2008). The problem with the existing formulations is that the magnitude of creep strains in overconsolidated region is too large and the undrained strength is over-predicted.

New Anisotropic creep model

In order to improve the predictions of creep deformation for overconsolidated clays, a new constitutive model is proposed in this on-going project, which should be able to capture the overconsolidated state better then above discussed creep models.

In order to reduce the size of the reference surface on the dry side, the shape of reference surface is taken as a simplified form of the MIT-S1 yield surface, see Pestana et al. (1999),.

The preliminary results shows that the proposed model is able to capture the soil response upon shearing in the normally consolidated region similarly to the current creep models, but also for the overconsolidated state it gives qualitatively very reasonable results, as shown in Figure 6.

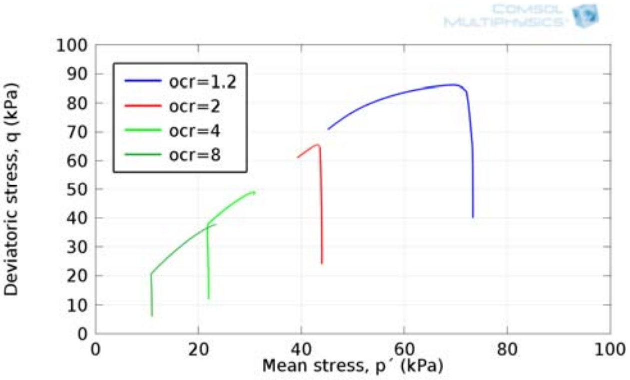

Figure 6. Preliminary results from the new constitutive model for K_0-CU triaxial tests for different over consolidation ratios.

4. Laboratory experiments

During this project a number of different laboratory experiments have been and will be conducted e.g. K_0-CU triaxial test at different over consolidation ratios, incremental loading (IL) oedometer test, CRS test with different strain rates and IL (K_0) triaxial test with control of radial deformation.

These laboratory experiments are conducted on soft clays to a depth of approximately 50 m in the Gothenburg area. The main purpose of these test are to investigate the creep properties for the soft clays in this area and to establish input parameters for more advanced constitutive material models.

5. Conclusions

This paper discusses the importance of incorporation of creep and anisotropy in a material model to describe the behaviour of soft soils in order to give good deformation predictions, especially for long term conditions.

The existing creep models discussed in the paper are all based on the rotated ellipsoids and due to their mathematical formulation end up giving unrealistically high undrained shear strength at the “dry side” of the critical state line. The formulation is the new constitutive model proposed with a new reference surface seems to overcome this problem, and based on preliminary results is able to capture both the normally and overconsolidated effects in a satisfactory way.

6. Acknowledgements

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