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AUTOMATIC ONLINE CALIBRATION SOFTWARE EXCALIBRE

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Abstract: *This paper introduces a website application called ExCalibre, which calibrates three advanced soil models, namely elastoplastic Modified Cam-Clay model, hypoplastic clay and hypoplastic sand model. Even though these models have been long known and verified in numerous scientific works, their employment in the engineering practice is still limited. This state is caused by the lack of knowledge of advanced soil models as well as complicated calibration methods to be used in practice. Consequently, simple constitutive models such as Morh-Coulomb are often used, which cannot accurately simulate the soil response under various loading conditions and thus negatively affect the final structure design. The current work is focused on providing a powerful tool to calibrate the aforementioned advanced soil models and thus improve the current engineering design. This application is developed in the close cooperation of the Czech Technical University, the Charles University and SG Geotechnika plc.*

Keywords: calibration, hypoplasticity, elastoplasticity, soil, model

1. Introduction

Soil as a building material consists of solid particles and pores filled with air and water, supporting and transferring the structure loading. Together with steel and concrete form a group of basic engineering materials. Unlike steel or concrete, soil in nature is state and path dependant which exhibits clear nonlinear and plastic behaviour even at the low stress levels and can be further influenced by a soil particle's mineralogy and water characteristics.

Whilst an elastoplastic Mohr-Coulomb (MC) model is used in the vast majority of numerical simulations, its reliability in the attempt to simulate the soil behaviour under various loading conditions and stress levels is very limited. This is due to the fact that MC model treats the same soil at different states as different soils, i.e. the same soil at different states have different MC set of parameters. Furthermore, MC model as an elastoplastic model divides the total strain into elastic and plastic components. The basic form of MC model defines four parameters, namely E, ν, c and φ. Young's modulus E and Poisson's ratio ν control the elastic relation between the stress and strain inside the yield surface, while cohesion c and friction angle φ define the size and shape of the yield surface. The MC model is appreciated for its simplicity and reliability in describing shear failure. However, linear stress strain relation upon loading and inability to adequately simulate the soil behaviour across various stress ranges suggests that MC model might not be suitable as a constitutive model for a wide range of applications in numerical simulations.

Even though there are some modifications of MC model with additional yield surfaces (cut-off and cap models) or nonlinear elastic properties, they still have substantial limitations in terms of predicting soil behaviour compared to critical state models. Furthermore, the critical state models define so called state

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boundary surface (SBS) in the space of stresses and void ratio $e \times p \times q$, which surrounds all the admissible states. A typical example of the critical state model is an elastoplastic Modified Cam-Clay model (MCC) (Roscoe and Burland, 1968). As a promising alternative to the elastoplasticity was founded the theory of hypoplasticity (Gudehus, 1996, Wolffersdorff, 1996, Masin, 2014), that unlike elastoplasticity does not define the yield surface, thus inherent distinguish between the elastic and plastic strain is abandoned and the strain increment is led by the evolution of density and stress state. Since those models are highly reliable and their calibration are far from abilities of common engineer, our effort aims at providing a sound calibration tool for three advanced soil models, elastoplastic MCC model (Roscoe and Burland, 1968), hypoplastic sand (Wolffersdorff, 1996) and hypoplastic clay model (Masin, 2014) and to give a clear calibration results based on experiment data. Hereinafter, the constitutive models are described and the ExCalibre application is unveiled.

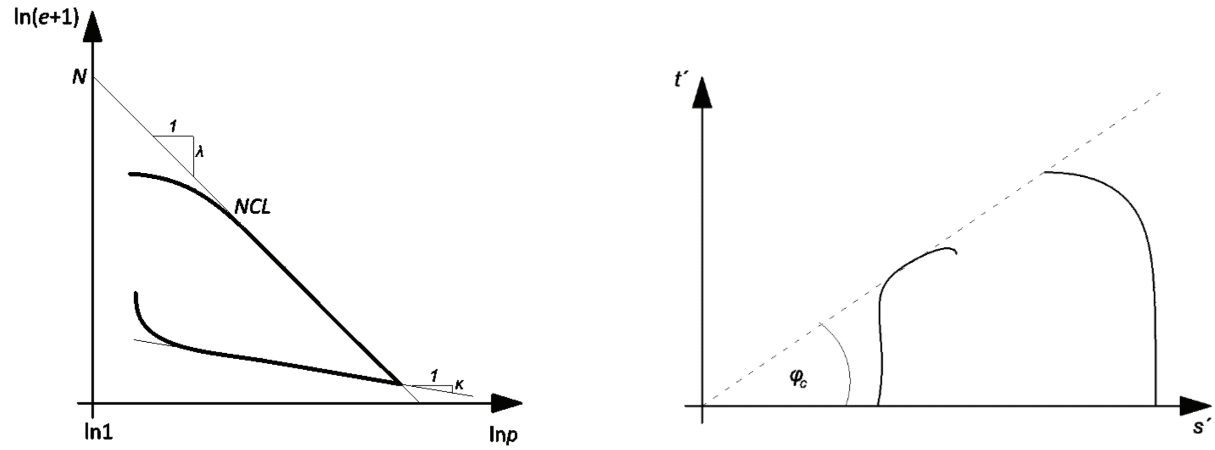
2. Hypoplastic clay and Modified Cam-Clay model

Although these two models are based on different theories, the physical meaning of their parameters is similar. Hypoplastic model defines five parameters λ^*, κ^*, N, φ_c and ν. (Masin, 2014) The parameters for an isotropic consolidation λ^*, κ^* and N are defined in the $\ln p \times \ln(e+1)$ space, see Figure 1a. The parameters λ^* and κ^* control the slope of the normal consolidation line (NCL) and swelling line, respectively. A position of NCL in $\ln p \times \ln(e+1)$ space is determined by the parameter N. Similarly to Hypoplastic model, MCC model defines parameters for the isotropic compression λ, κ and e_0, however, in the $\ln p \times e$ space.

The critical state friction angle φ_c is defined in the effective stress space $t' \times s'$, see Figure 1b and equations (1), where σ_1' and σ_3' represent the principal stresses. MCC substitutes parameter φ_c for M_{cs}, which defines slope of the critical state line in $p \times q$ space, where p and q represents the mean and deviatoric stress respectively. The remaining parameter ν of Hypoplastic clay model controls the ratio of bulk modulus K_i and shear modulus G_i at an isotropic state, whereas Cam-Clay uses ν to relate the state-dependent bulk modulus K and the elastic shear modulus G.

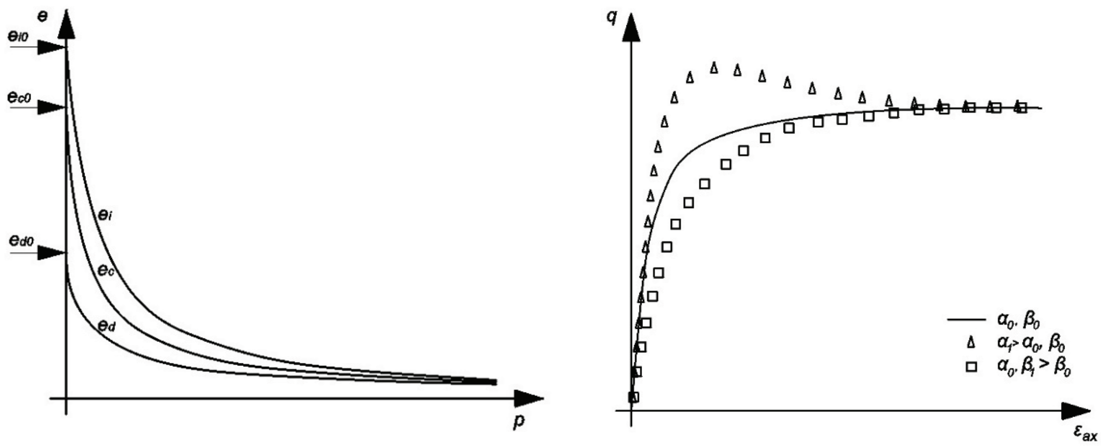
Although the parameters of both models are similar in meaning, models do not exhibit the same behaviour. MCC behaves nonlinearly, but still elastically inside the yield surface and plastic strain occurs only when a soil state reaches the yield surface and is exposed to further loading. On the contrary, hypoplastic clay model does not exhibit any elastic strain and behaves completely nonlinearly and plastically during both loading and unloading. Given the fact that both models are based on a different theory, SBS of hypoplastic clay model changes with parameters, whereas MCC has firmly fixed elliptical shape of the yield surface.

$$s' = \frac{\sigma_1' + \sigma_3'}{2}, \quad t' = \frac{\sigma_1' - \sigma_3'}{3}, \quad p' = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3}, \quad q = \sigma_1' - \sigma_3' \tag{1}$$



a) Parameters of an isotropic consolidation *b) Critical state friction angle*

Fig. 1: Hypoplastic clay parameters



a) Parameters of the isotropic consolidation *b) Parameters α and β*

Fig. 2: Hypoplastic sand parameters

3. Hypoplastic sand model

The hypoplastic sand model (Wolffersdorff, 1996) defines eight parameters. Five of those parameters h_s, n, e_{d0}, e_{c0} and e_{i0} are defined for an isotropic compression in $\ln p \times e$ space. Parameters e_{d0}, e_{c0} and e_{i0} represent void ratios at p = 1 kPa and denote position of limiting compression lines for the densest, critical and isotropic states, see Figure 2a. Parameters h_s and n controls slope and curvature of the isotropic compression lines respectively.

Three remaining parameters α, β and φ_c control the peak friction angle, the shear stiffness and the critical state friction angle, see Figure 2b.

For the sake of brevity, calibrations of aforementioned constitutive models are omitted and can be found in (Mašín, 2014, Herle and G. Gudehus, 1999, Kadlicek et al., 2016)

4. Data

In order to thoroughly examine a calibration application and to create a reliable database of parameters for both fine and coarse grained soil constitutive models a substantial number of specimens were gathered not only from Czech Republic itself but also from USA, China, England and other regions. Soil specimens were classified according to USCS classification and further subjected to oedometric or isotropic compression and triaxial drained or triaxial undrained experiments. Data of the experiments were further processed and prepared in the predefined form of MS excel files for a calibration. All available data were calibrated for each constitutive model and the overview of calibration is available on the website of ExCalibre application.

5. Website

The main tool of the ExCalibre application is to accurately calibrate the parameters of the soil model on the input data, which has to be ordered in the appropriate predefined form. The example data template is accessible on the webpage and available for a download. The calibration is as accurate as the data provided. Therefore, one should carefully consider the reliability of the data for a calibration as it might significantly influence the calibration results.

Three aforementioned advanced constitutive models are available for the calibration and once the calibration is successfully completed, the results of the calibration are plotted against all input experimental data, see Figure 3. The calibration strictly distinguishes between undisturbed and reconstituted specimens and some parameters are primarily calibrated on the reconstituted samples. However, the main effort is to precisely calibrate undisturbed samples.

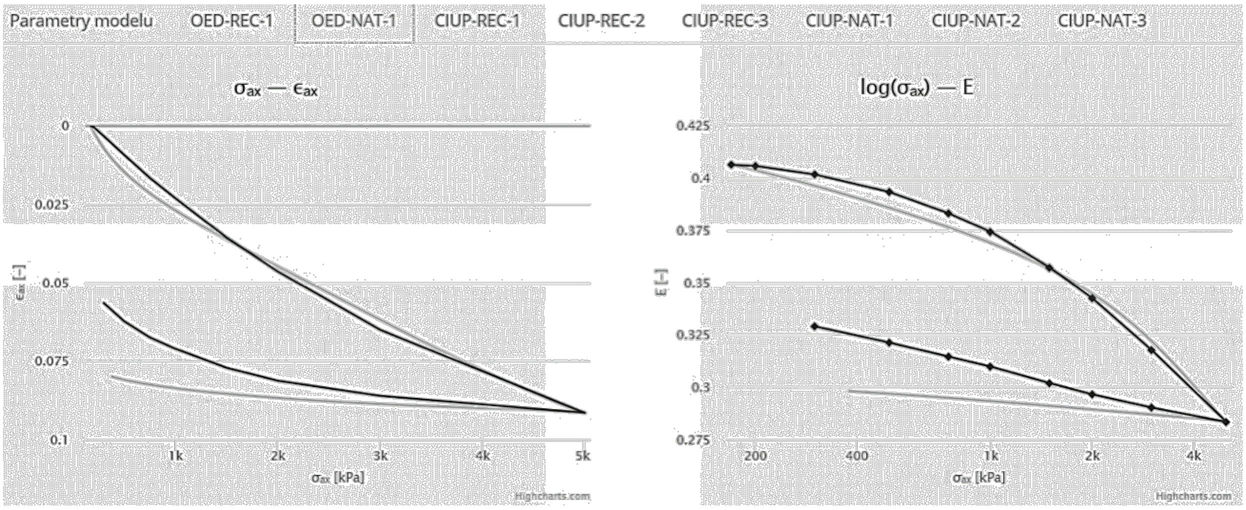


Fig. 3: Calibration results for oedometric experiment

Once the calibration is finished and one is not fully satisfied with the results of the calibration, the manual calibration is available, where the results of the calibration can be further adjusted according to the specific requirements and conditions related the engineering problem.

ExCalibre calibration is currently available on: https://soilmodels.com/excalibre-en/

6. Summary & Conclusions

Since the constitutive models are under a constant development and more advanced soil models such as the hypoplastic clay model are long available and tested in various works, engineering society should not only be encouraged to employ more up-to-date constitutive models but also be provided with tools that ease the operation with those models. Such a tool is introduced in this paper which provides instant evaluation of the parameters for three advanced soil models with clear overview of the calibration results.

Acknowledgements

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