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Mechanical modeling of MX-80 – Quick tools for BBM parameter analysis

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ABSTRACT

The purpose of this work is to develop fast and user-friendly numerical tools, able to model simple experimental setups, which are suitable when evaluating the parameters of the Barcelona Basic Model. The work focuses on mechanical modeling of MX-80 bentonite clay in different laboratory experiments. The developed tools are found to meet the requirements. This is proven by the shown examples where the BBM parameters are evaluated using the developed tools.

1. Introduction

Thermo-hydro-mechanical modeling of buffer and backfill material is an important subject in the Swedish nuclear waste disposal program and Code_Bright is one of the codes employed in that program. Thermoelastoplastic constitutive laws, based on the Barcelona Basic Model (BBM) are used in the code for description of the mechanical behaviour of compacted bentonite.

In general, the characteristics of BBM are not self-evident, especially under multiaxial conditions. A number of quick tools, written in the MathCad® environment, have therefore been developed for facilitating parameter studies and evaluation of oedometer tests and triaxial tests. The developed routines also enable tests of alternative expressions for the employed moduli and enable an independent verification of the solutions provided by the code.

This paper gives a description of the problems considered and of the solution scheme employed. A brief outline of the implementation is then followed by examples where the quick tools have been used. Results obtained with Code_Bright are given for comparison. Finally, some concluding remarks are given.

2. Problem formulation

The problems to be modelled here consider a soil sample that is either thought to be introduced in an oedometer or in a triaxial test cell and thereafter subjected to different loading conditions as specified below. To describe the state in the present formulation the net pressure p', the deviatoric variable q and the suction s are introduced (for the definitions see appendix). The problems have been formulated so that the setup is approximated as a homogeneous problem, i.e. the sample is represented by one point only. In Fig. 1, the schematic test geometry is shown together with the chosen coordinate system, where the x-coordinate is directed in the axial direction and the y and z-coordinates are directed in the radial direction, respectively. The coordinate system coincides with the principal directions.

The y and z-coordinates are here equivalent, thus the corresponding principal stress and strain components are equal, $\sigma_z = \sigma_y$ and $\varepsilon_z = \varepsilon_y$, respectively. The three additional conditions specified in (1) define the individual experimental setup of: (1) Compression test with uniaxial strain and constant suction, (2) swelling test with uniaxial strain and constant axia load, and (3) triaxial compression tests at constant suction

$$
\begin{array}{l}
1.\ \text{Uniaxial compression} \\
\begin{cases} d\epsilon_y = 0 \\ ds = 0 \\ d\sigma'_x \quad \text{specified} \end{cases} \\
2.\ \text{Uniaxial swelling} \\
\begin{cases} d\epsilon_y = 0 \\ d\sigma'_x = 0 \\ ds \quad \text{specified} \end{cases} \\
3.\ \text{Triaxial compression} \\
\begin{cases} d\sigma'_y = 0 \\ ds = 0 \\ d\epsilon_x \quad \text{specified} \end{cases}
\end{array}
\tag{1}
$$

Left to be specified is the constitutive law that is used, which in this case is the version of BBM that is implemented into Code_Bright. A brief recapitulation of the model is given in appendix. For more information about BBM see Alonso et al. (1990) and CIMNE (2002).

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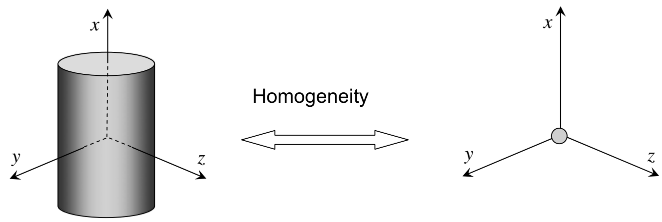

Fig. 1. Schematic test geometry with the used coordinate system indicated.

When solving the problems an incremental solution scheme is used. This can be viewed as solving the equation system

$$\boldsymbol{\sigma}^2 = \boldsymbol{\sigma}^1 + \int_1^2 d\boldsymbol{\sigma}$$
$$p_0^{*2} = p_0^{*1} + \int_1^2 dp_0^* \tag{2}$$

under the condition

$$f(\boldsymbol{\sigma}, s, p_0^*) = 0 \tag{3}$$

when the material behaves inelastically. In (2) and (3) p_0^* is a hardening parameter with a given law of evolution. In this implementation (3) has not been used directly, but $df = 0$ has been used instead. An Euler forward integration of the constitutive relations is used from the known state 1 to the unknown state 2 in (2), i.e. the integral is approximated with an increment evaluated at state 1.

When specifying the incremental equations solved more in detail, a somewhat different notation as compared to what is normally used in BBM has been utilized in this work. The normal continuum mechanics sign convention has also been used where stresses and strains are positive in tension. The elastic stiffness is expressed as a Young's modulus, E, and by convenience a swelling modulus K_s is defined as shown in (4). In (4) κ_i and κ_s are elastic moduli present in BBM, e is the void ratio and ν Poisson's ratio

$$E = \frac{p'(1+e)\cdot 3(1-2\nu)}{\kappa_i}$$
$$K_s = \frac{(1+e)(s+0.1)}{\kappa_s} \tag{4}$$

Formula (5) shows the incremental equations solved for one solution increment in a general problem formulation embracing all test conditions. The equivalence between the y and z-coordinate as well as $df = 0$ has been used when deriving the system of five equations. The equations consist of two elastic and two plastic stress–strain relations and one evolution law for the hardening parameter p_0^*

$$\Delta\varepsilon_x^e = \frac{1}{E}[\Delta\sigma'_x - 2\nu\Delta\sigma'_y] - \frac{\Delta s}{3K_s}$$
$$\Delta\varepsilon_y^e = \frac{1}{E}[(1-\nu)\Delta\sigma'_y - \nu\Delta\sigma'_x] - \frac{\Delta s}{3K_s}$$
$$\Delta\varepsilon_x^p = -\frac{\frac{\partial g}{\partial\sigma'_x}}{\frac{\partial g}{\partial p'}\frac{\partial f}{\partial p_0^*}\frac{dp_0^*}{d\varepsilon_v^p}}\left[\frac{\partial f}{\partial\sigma'_x}\Delta\sigma'_x + 2\frac{\partial f}{\partial\sigma'_y}\Delta\sigma'_y + \frac{\partial f}{\partial s}\Delta s\right] \tag{5}$$
$$\Delta\varepsilon_y^p = -\frac{\frac{\partial g}{\partial\sigma'_y}}{\frac{\partial g}{\partial p'}\frac{\partial f}{\partial p_0^*}\frac{dp_0^*}{d\varepsilon_v^p}}\left[\frac{\partial f}{\partial\sigma'_x}\Delta\sigma'_x + 2\frac{\partial f}{\partial\sigma'_y}\Delta\sigma'_y + \frac{\partial f}{\partial s}\Delta s\right]$$
$$\Delta p_0^* = -\frac{1+e}{\lambda(0)-\kappa_{i0}}p_0^*[\Delta\varepsilon_x^p + 2\Delta\varepsilon_y^p]$$

where the plastic relations are active when the stress state is situated on the yield surface. The functions and parameters appearing in (5) are defined in the appendix where BBM is recapitulated.

To simulate one of the experimental setups, (5) are solved with the conditions corresponding to the considered experiment as specified in (1).

The tools can be arranged to give a direct link between applied conditions (initial and experiment specific according to (1)), different parameter settings and output in the form of variable evolutions. This facilitates simple and quick investigations of the impact of changing parameter values on the simulated response.

3. Implementation in MathCad®

The implementation in MathCad® is straight forward, where the solution of (5) and (1) is performed for each prescribed load-increment. In Fig. 2 below the user interface of one of the developed tools is shown. As Fig. 2 shows the interface provides a clear overview of the parameter setting, here organized to correspond well with the user interface of Code_Bright. Clearly, alterations of the parameters are also easily performed in the implementation. As Fig. 2 also shows, the responses of the simulation are easily visualized in graphs using the MathCad® graphical capabilities.

4. General parameter analysis and evaluation

An overview of how the parameter values were identified for the different experimental conditions is given here. There is an intrinsic difference in how "available" the parameters are for the three test conditions. Table 1 summarizes which parameters that have unique values for a given stress–strain–suction evolution and parameters that require assumed values for the different experimental conditions.

Below follows a discussion of how the parameter values were identified for the different test conditions.

4.1. Compression tests with constant suction

Results from uniaxial as well triaxial compression tests display unambiguous values for κ_i, and ν. For uniaxial plastic cases, $\lambda(s = s^*)$, where s^* is the current suction, can also be quite close to a directly evaluated modulus.

The expressions used for evaluating the elastic parameters under uniaxial and triaxial compression are shown below. The porous-elastic modulus κ_i is evaluated by the relation:

$$\kappa_i = -\frac{\Delta e}{\Delta \ln p'} \tag{6}$$

which is valid for uniaxial as well as triaxial elastic conditions. Under uniaxial plastic conditions κ_i may be replaced with $\lambda(s = s^*)$. Data on axial and radial stresses from uniaxial tests gives directly the Poisson's ratio, ν

$$\nu = \frac{\Delta\sigma_y}{\Delta\sigma_x + \Delta\sigma_y} \tag{7}$$

Under triaxial elastic conditions when the radial stress is constant, the Poisson's ratio is given by the axial and radial strains:

$$\nu = -\frac{\Delta\varepsilon_y^e}{\Delta\varepsilon_x^e} \tag{8}$$

In order to determine whether the state is elastic or plastic a loading/unloading sequence might be relevant. Here, however, the appearance of the void ratio – stress graph is used to get an indication of the elastic or plastic state.

A description of the yield surface and the plastic potential requires assumed values of two of the three parameters (p_s, p_0, M) in the case of uniaxial tests and one of the three parameters in the case of triaxial tests (M is given as the inclination of a line drawn between p_s and (p, q) at failure). It should be noted that the apparent preconsolidation axial stress can generally not be identified with p_0 (Fig. 3).