MODELING THE MECHANICAL BEHAVIOR OF SAND-CEMENT MIXTURES

MODÉLISATION DU COMPORTEMENT MÉCANIQUE DES MÉLANGES DE SABLE-CIMENT

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ABSTRACT: Soil-cement mixtures are largely used in civil engineering applications. Nevertheless, their mechanical behavior is not properly defined in current constitutive modeling. In this study, an elastoplastic subloading surface model for cemented materials is used to simulate the behavior observed in consolidated undrained triaxial tests performed on samples of sand-cement mixtures. The mixtures were made of a silty sand and Portland cement type I (150, 200 and 250 kg/m^3 of cement), for a water to cement ratio (in terms of weight) of 0.6, and tested after 28 days curing. A destructuring law proposed by Maranha et al. (2016) was included to simulate the presence of the hydrated cement minerals connecting the sand grains (bonds) and their eventual breakage due to loading. The calibration values for the constants and initial values of internal variables of the model, as well as trend lines found defining them as a function of the cement dosage are presented. This model showed promising results for the materials investigated.

1 INTRODUCTION

Hardened soil-cement mixtures are artificially structured materials widely used in civil engineering. Several studies can be found in the Literature (e.g. Reddy and Gupta 2008, Consoli et al. 2012), where their mechanical behavior is analyzed, but the existing constitutive relationships (e.g. Lee et al. 2004, Arroyo et al. 2012) are insufficient to represent it.

In this study, an elastoplastic model featuring the Subloading Surface Concept (Hashiguchi, 1989; Maranha et al., 2016) is defined to reproduce the results obtained from undrained triaxial tests performed on mixtures of a silty sand and Portland cement type I adopting three different dosages of cement.

2 CEMENTED ELASTOPLASTIC SUBLOADING SURFACE MODEL

The subloading surface concept was introduced by Hashiguchi (1989), and later modified by Maranha et al. (2016). This concept enables elastoplastic behavior inside the yield surface by introducing a subloading surface. The yield surface of the model is derived from the Modified Cam-Clay model (MCCM) and it is defined in effective stress space, **σ**, as:

$$f(\boldsymbol{\sigma}) = \left(\frac{q}{M}\right)^2 + \bar{p}\left(\bar{p} - p_C\right), \text{ with } \bar{p} = p + \xi p_c, \qquad (1)$$

where q is the deviatoric stress invariant, p is the effective mean stress, M is the slope of the critical states line in the q-p space, and ξ is a constant that quantifies tensile strength as a function of the internal variable p_c. The subloading surface is homothetic to the yield surface and contains the current stress.

The effect of the structure given by the cement is considered by means of internal variable p_c, which defines the dimension of the yield surface, while destructuring is computed through the law proposed by Maranha et al. (2016). The evolution of the structure is defined by the variation of the internal variable, R_b (Equation 2), as presented in Equation 3, where p_{cu} is the dimension of the yield surface without structure, u_b is a model constant which rules the rate of destructuration, R_{bf} is a constant defining the lower limit for destructuring, and $\dot{\varepsilon}^p$ is the plastic strain rate tensor. R_{bf} can assume values ranging from 1, when the material is fully destructured, to the maximum (initial) value of R_b, when the material bonds remain intact for any mechanical action.

$$R_b = p_c / p_{cu} \qquad (2)$$

$$\dot{R}_b = u_b\left(R_{bf} - R_b\right)\left\|\dot{\boldsymbol{\varepsilon}}^p\right\| \qquad (3)$$

Further details on the definition of the model can be found in Ribeiro et al. (2016).

3 LABORATORY TESTS

Three different mixtures were prepared in laboratory with a non-plastic silty sand (12% of particles smaller than 0.075 mm; solid particle density, Gs=2.64) and Portland Cement Type I (CEM 42.5R). The dosages adopted were 10%, 13% and 17% of cement by weight of dry soil (respectively, 150 kg/m^3, 200 kg/m^3 and 250 kg/m^3) while the soil dosage (1500 kg/m^3) was kept constant. The mixtures were performed mechanically following ASTM D1632-07 and adopting a water to cement ratio (w/c) of 0.6. Tap water was used. Consolidated undrained triaxial tests were made following ASTM D4767-11 after 28 days of submerged cure.

The pore pressures generated are very small. This means that the principle of effective stress due to Terzaghi (1923 in Terzaghi, 1943) cannot be adopted for materials with such a large soil skeleton stiffness due to particle bonds. Therefore, the generalization of the effective stress principle proposed by Biot (1941) was adopted (further details in Ribeiro et al. 2016).

4 MODEL CALIBRATION

The model presented was implemented in Itasca™ FLAC®, which is an explicit geotechnical finite difference software. The embedded scripting language of the software (FISH) was used. The calibration intends to reproduce the response of the material observed in the experiments, without reproducing explicitly all the phenomena, including localization.

In the deviatoric stress vs axial strain plane, the numerical simulations (Figure 1) showed a satisfactory adjustment of the experimental data before rupture (peak). An excessive softening is computed by the model for the dosages of 200 kg/m^3 and 250 kg/m^3. This still needs to be studied in order to properly reproduce the post rupture behavior.

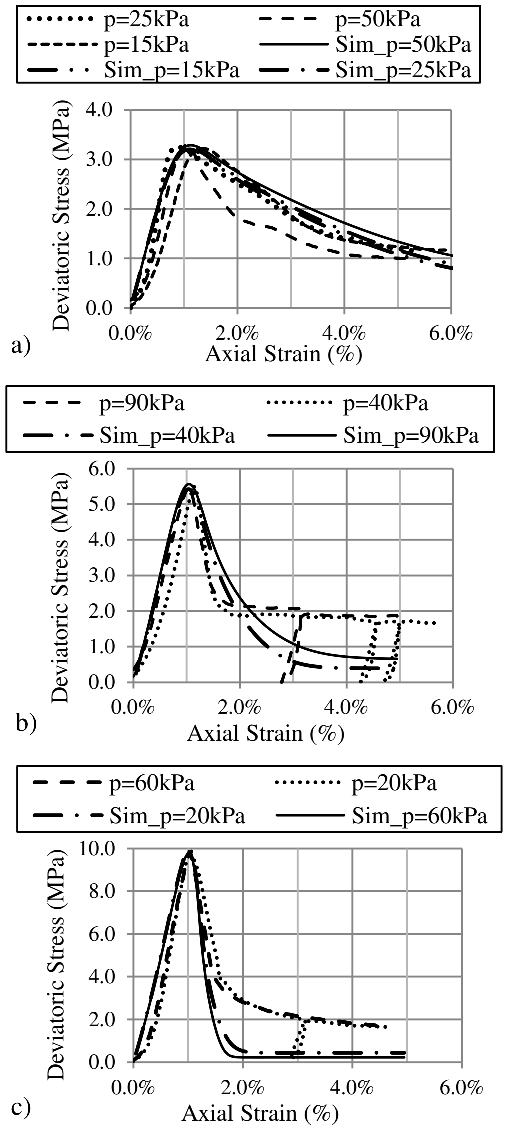

Figure 1. Simulations vs experimental data – deviatoric stress vs axial strain: a) 150 kg/m^3; b) 200 kg/m^3; c) 250 kg/m^3.

As this model was defined for soil-cement mixtures, in which structure is mainly provided by connections (or bonds) due to the presence of hydrated cement minerals, it was found relevant to define some variables and constants (p_c, R_b, R_{bf} and u) of the model as a function of the cement dosage (see Ribeiro et al., 2016). In Figure 2 it is presented the fitting function found for initial value the internal variable p_c. A linear relationship was found for the initial value of R_b, as well as for the constants R_{bf} and u.

5 CONCLUSION

A subloading surface model with a cemented yield surface and a destructuring law (or debonding law) was presented and used to reproduce the behavior of soil-cement mixtures measured in consolidated undrained triaxial tests. The model was able to reproduce the tests in satisfactory manner, especially before the rupture of the material (peak) which is not possible with conventional elastoplastic formulations. After the rupture an excessive softening was observed in the deviatoric stress vs axial strain plane. The low generation of pore pressures was handled by the consolidation theory proposed by Biot (1941), which was already implemented in the core code of Itasca™ FLAC®.

The calibration variables of the model related with the presence of bonds showed a clear dependence on the dosage of cement. This indicates that the model is adequate to reproduce the mechanical response of this kind of materials.

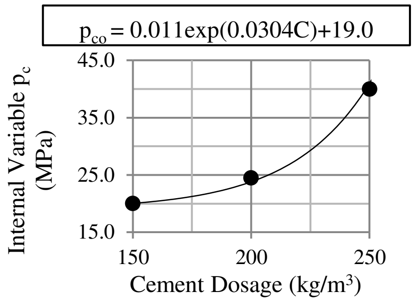

Figure 2. Initial value for the internal variable p_c, as a function of the cement dosage, C (R^2 = 0.9952).

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