Mechanical Constitutive Models of Unsaturated Expansive Clays: A Review of BExM

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1. Introduction

Expansive clays (ex., bentonite) is favored as a buffer material for an HLW repository. When the expansive clay is installed for the buffer, it remains unsaturated for a certain period of time after installation. Mechanical constitutive models of unsaturated expansive clays are essential for the performance assessment and design of engineered barrier system (EBS) in the repository. Mechanical constitutive models of unsaturated expansive clays have been studied by many researchers. Among them, the BBM (Barcelona Basic Model) presented by Alonso et al. [1] has been widely used. It is a model for nonexpansive or slightly swelling clays, considering only the macrostructural level responsible for major structural rearrangement and also allowing for the small reversible swelling in the elastic zone. However, it has been pointed out that the BBM has limitations in applying to expansive clay with large swelling strain. The BExM (Barcelona Expansive Model), which overcomes the limitations of the BBM, has been used to describe the mechanical behavior of unsaturated expansive clays. The present paper reviews the model concept and mathematical formulation of the BExM and intends to provide the technical knowledge and information needed to test and model the mechanical behavior of the bentonite buffer for the KRS repository.

2. Model Concept

The BExM [2] is an extension of BBM in order to apply to the expansive clays with large swelling. It is based on the consideration of two levels of structure (Fig. 1 and 2): macrostructural level for major structural rearrangement and microstructural level at which the swelling of active minerals take place. The BExM takes account into the large irreversible volumetric change in the expansive clays as well as small reversible swelling in the elastic zone.

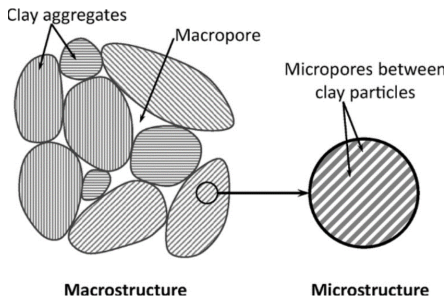

Fig. 1. Macrostructure and microstructure in expansive clays.

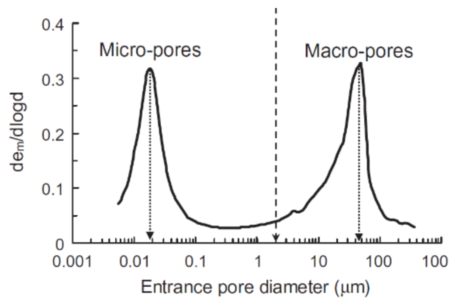

Fig. 2. Pore size distribution of the compacted expansive clays.

The following assumptions are made in this model: 1) excessive volume change tendency of expansive clays is mainly attributed to the presence of highly expansive clay minerals; 2) the microstructural level is mainly saturated and the effective stress concept holds and the microstructural behavior is elastic and volumetric; 3) mechanical, hydraulic and chemical equilibrium exists between microstructure and macrostructure; 4) coupling between microstructure and macrostructure results in possible build-up of macrostructural elastoplastic strains when elastic microstructural strains take place. Many experiments have shown that the volume change behavior is controlled by many factors including the type of clay minerals, the current degree of saturation, past wetting-drying cycles, fabric and structure created during the compaction, presence of non-expansive minerals, their sizes, percentages and distribution in the matrix. The BExM encompasses these factors, thereby allowing predicting the mechanical behavior of expansive clays under various disposal conditions.

3. Mathematical Formulation

The BExM accounts for two levels of clay structure. The microstructural level corresponds to the aggregates of active clay mineral particles with intra-aggregate pores, whereas the macrostructural level corresponds to the larger scale clay structure.

The microstructural elastic volumetric strain is calculated as follows:

$$\mathrm{d}\varepsilon_{vm}^{e} = \frac{de_m}{1+\ e_m} = \frac{d(p+s)}{K_m}$$

$$K_m = \frac{\exp[\alpha_m(p+s)]}{\beta_m}$$

The macrostructural elastic volumetric strain is expressed as a function of mean net stress and suction:

$$\mathrm{d}\varepsilon_{vM}^{e} = \frac{de_M}{1+\ e_M} = \left(\frac{k}{1+e_M}\right)\frac{dp}{p} + \left(\frac{k_s}{1+e_M}\right)\frac{ds}{s+\ p_{atm}}$$

The variation of preconsolidation mean net stress (p_0) with suction is given by an LC (loading and collapse) yield curve function:

$$\frac{p_0}{p_c} = \left(\frac{{p_0}^*}{p_c}\right)^{\frac{\lambda(0)-k}{\lambda(s)-k}}$$

$$\lambda(s) = \ \lambda(0)[r+(1-r)\exp(-\beta s)]$$

Macrostructural plastic strain resulted by mechanical loading:

$$\mathrm{d}\varepsilon_{vML}^{p} = \frac{\lambda(s)-k}{1+e_M}\frac{dp_0}{p_0}$$

Macrostrutural plastic strain induced by microstructural strain:

$$\mathrm{d}\varepsilon_{vMSI}^{p} = f_I\ \mathrm{d}\varepsilon_{vM}^{e}$$

$$\mathrm{d}\varepsilon_{vMSD}^{p} = f_D\ \mathrm{d}\varepsilon_{vm}^{e}$$

where f_I and f_D are the interaction functions between microstructural and macrostructural levels in case of suction increase and suction decrease, respectively (refer to Fig. 3).

Incremental total macrostructural strain:

$$d\varepsilon_{vM}^{p} = \ \mathrm{d}\varepsilon_{vML}^{p} + \ \mathrm{d}\varepsilon_{vMSI}^{p} + \ \mathrm{d}\varepsilon_{vMSD}^{p}$$

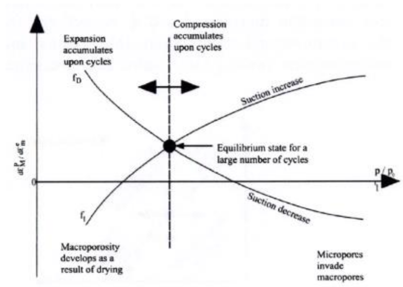

Fig. 3. Interaction and coupling functions in BExM.

4. Summary and Conclusions

More researches have been carried out for the development and enhancement of the unsaturated non-expansive clays models, while much lesser contributions have been made for the expansive clay modelling. The BExM is a representative constitutive model which may be used to predict the mechanical behavior of expansive clays. The microstructure in the constitutive model had a central role in the overall behavior of the expansive clays. The HLW repository uses as a buffer material the expansive clays (i.e., bentonite) with large swelling. The BBM may have a limitation in its application, and thus the BExM is strongly suggested to use for understanding and predicting the mechanical behavior of bentonite buffer with high reliability.

REFRENCES

[1] Alonso, E.E., Gens, A., and Josa, A., “A constitutive model for partially saturated soils,” Geotechniqure 40(3), 405-430 (1990).

[2] Alonso, E.E., Vaunat, J., Gens, A. “Modeling the mechanical behavior of expansive clays,” Engineering Geology 54, 173-183 (1999).