Constitutive modeling for compacted bentonite buffer materials as unsaturated and saturated porous media

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Abstract

Bentonite has remarkable swelling characteristics and low permeability that enhance the stability of the buffer materials in repositories for the geological disposal of radioactive waste. It is necessary to apply reliable numerical simulation techniques to assess the safety and mechanical stability of repositories over a long period of time. Having a constitutive model that can describe the mechanical behavior of bentonite is key to such numerical simulations. This paper proposes an elasto-plastic constitutive model to describe the changes in the mechanical properties of bentonite due to saturation in the progress of a repository becoming submerged under groundwater. In the proposed model, the swelling index is formulated as a function of the degree-of-saturation to express not only the swelling behavior, but also the dependency of the degree-of-saturation on the dilatancy characteristics. The montmorillonite content is used as a material parameter to determine the normal consolidation line. The experimental results of swelling volume and swelling pressure tests in previous literature are shown to have been satisfactorily predicted by the proposed model.

Keywords: Constitutive relations; Expansive soils; Numerical modeling; Stress analysis; Elastoplasticity (IGC: D05/D06/E14)

1. Introduction

Bentonite materials exhibit characteristics of high swelling and low permeability that make buffer materials suitable for use in repositories for the geological disposal of radioactive waste. Buffer materials are expected to act as self-sealing barriers to water channels, to prevent the leakage of radionuclide-contaminated groundwater, and to mitigate the stress caused by rock creep acting on the body of waste.

Bentonite buffer materials will be in an unsaturated condition as a result of compaction. After the closing of a repository, the bentonite materials will become saturated due to the seepage of groundwater. Reliable numerical simulations must therefore be developed in order to verify the long-term safety and mechanical stability of the compacted and unsaturated bentonite materials during their subsequent saturation. Having a constitutive model that can describe the mechanical behavior of bentonite in both unsaturated and saturated states is key to such numerical simulations.

To address the swelling characteristics of bentonite materials, various constitutive models have been proposed. Komine and Ogata (1996) proposed relational equations...
for the swelling strain and swelling pressure of compacted bentonite based on the diffuse double-layer theory and showed the predictions of swelling test results with high accuracy. Namikawa et al. (2004) examined the applicability of some existing elasto-plastic constitutive models for non-expansive soil to saturated bentonite materials. Hirai and his colleagues (2005, 2006) presented an improved Cam-Clay model in an attempt to describe the mechanical behavior of saturated bentonite. Furthermore, various studies on the constitutive modeling of unsaturated bentonite have been done. The constitutive model proposed by Shuai and Fredlund (1998) expressed various swelling test results using an oedometer. Alonso and Gens (1999) proposed the Barcelona expansive model (BExM) to be used for the unsaturated state of expansive soil materials. By distinguishing micro-level void structures from macro-level ones, BExM expresses the mechanical behavior of unsaturated expansive soil. Sun and Sun (2012) highlighted the difficulty of applying BExM, especially with regard to parameter setting, and proposed an unsaturated constitutive model from a macroscopic perspective. Cui et al. (2002) proposed an unsaturated elastic constitutive model, in accordance with the concept of critical swelling curves, and simulated water absorption and swelling behavior under constant confining pressure, as well as compression behavior under constant suction conditions. Unsaturated constitutive models proposed by Oka et al. (2008) and Tachibana et al. (2012) expressed swelling behavior by adding new components of strain to the constitutive models that have been used for general clay materials.

On the other hand, in a study by Takayama et al. (2012), fundamental considerations of an elasto-plastic constitutive modeling for fully saturated bentonite were investigated. They examined the mechanical characteristics of bentonite based on recent experimental data taken from the literature. According to the results of triaxial CU tests on bentonite, conducted by Sasakura et al. (2002, 2003), Takaji and Suzuki (1999), and Ann et al. (2010), it was seen that the effective mean stress changed very little during shearing. This implies that bentonite possesses few dilatancy characteristics from the viewpoint of the critical state theory. In addition, converting the effective vertical stress obtained from oedometer tests into effective mean stress, using the relationship between the coefficient of earth pressure at rest (K0) and the over-consolidation ratio (OCR) obtained by Sasakura et al. (2003), it was found that the hysteresis response between loading and unloading processes scarcely appeared in the relationship between the void ratio and the effective mean stress. The behavior given by oedometer tests generally includes dilatancy behavior. However, because saturated bentonite has hardly any dilatancy characteristics, this relation can be considered as the isotropic loading and unloading response. Therefore, saturated bentonite can be regarded as a material in which the swelling line corresponds to the normal consolidation line (NCL).

Since there is no constitutive model for unsaturated bentonite which can express the mechanical behavior of saturated bentonite, a new constitutive model for unsaturated bentonite is proposed in this study. This study extends the elasto-plastic constitutive model for unsaturated non-expansive soil to that for bentonite materials. To verify the model’s capability to represent the swelling and collapse behavior of bentonite materials, as seen in previous studies by Cui et al. (2004, 2006), simulations of swelling volume tests are performed. Furthermore, the swelling pressure is calculated using the proposed model to predict the experimental results obtained from the swelling pressure tests by Suzuki and Fujita (1999).

It should be noted that the present study focuses on the mechanical behavior of KuniGel V1, because repository designs in Japan currently suggest it as a candidate for bentonite buffer material. Moreover, since bentonite buffer materials in a repository will be in a compacted state and confined by the surrounding rock, the present study examines bentonite with a relatively high density. While KuniGel V1 is a bentonite clay composed mainly of montmorillonite, it also contains quartz, plagioclase, and other minor constituents. Table 1 shows the basic geotechnical properties of KuniGel V1 measured by Komine (2005). The montmorillonite content of KuniGelV1 produced before the year 2000 is 48%, but that after the year 2000 increases to 57%.

### 2. Constitutive modeling

According to Takayama et al. (2012), saturated bentonite possesses few dilatancy characteristics and the swelling line under the saturated condition corresponds to NCL. Moreover, it can be modeled as an elasto-plastic material in which plastic volumetric strain occurs to a very limited extent up to the critical state. In this section, a mechanical model for unsaturated bentonite, which takes into account these mechanical properties of saturated bentonite, is formulated by extending the effective degree of the saturation (Se)-hardening model proposed by Ohno et al. (2007), which is the elasto-plastic constitutive model for unsaturated non-expansive soil.

#### 2.1. Se-hardening model for unsaturated soil

The Se-hardening model represents the mechanical characteristics and behavior of unsaturated soil such as