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Research Paper

Constitutive model for soft rocks considering structural healing and decay

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ABSTRACT

The behavior of soft rock depends on the contact area between mineral particles and the tensile strength of the interparticle cementation, which are usually referred to as structures. We investigated the effects of structural decay and healing on the behavior of soft rock through monotonic and slide-hold-slide triaxial tests under the drained condition with constant effective confining pressure. We developed a constitutive model for soft rocks incorporating structural healing and decay in the context of the extended critical state theory. The model was validated via laboratory tests and captured the behavior of soft rock, including the healing and decay phenomena.

1. Introduction

In soft rock, mineral particles consist of aggregates of microcrystals formed by ionic, atomic, or molecular bonding, and these mineral particles are usually cemented or adhered mutually at the interparticle contact interfaces [1]. Thus, the stiffness and strength of the soft rock will depend primarily on the contact area between mineral particles and the tensile strength of interparticle cementation, which are usually referred to as rock structures.

The effects of the decay of the structures of soft rocks have been studied extensively. For example, the effects of the rock structures on the stress–strain characteristics have been investigated via laboratory experiments such as oedometer tests on Culebra shale [2], one-dimensional compression tests on chalk [3] and tuff [4,5], and monotonic triaxial compression tests on calcarenite and tuff [6]. Leroueil and Vaughan [7] and Kavvdas [8] discussed the effects of structures on the strength and stiffness of natural soils and weak rocks, and pointed out the similarities in behavior between natural soils and soft rocks.

Shao and Henry [9] have developed an elastoplastic model for porous rocks by extending a model for sands [10], and they have predicted the behavior of porous chalk. Gens and Nova [11], Kavvdas et al. [12], Adachi and Oka [13], and Lagioia and Nova [14], among others, have also proposed constitutive models for various types of weak rocks such as mudstones, claystones, marls, shales, tuffs, weak limestones, and weak sandstones, and validated their simulation through comparison with a series of laboratory tests. The common features of the constitutive models for soft rocks are: (a) the models are formulated by extending the original models for unstructured geomaterials; (b) the structure of the weak rock is assumed to be destroyed due to the breakage of the interparticle cementation during loading.

Meanwhile, Dieterich and Kilgore [15] indicated that the contact area of the solid interface increases over a period of time, and that frictional resistance arises from the development of the contact area. It is reasonable to expect that a similar mechanism exists in the contacts between the mineral particles of soft rock at a microscopic level. Thus, we presume that the structure of soft rocks will recover to some extent after the loading process. This leads to an increase in the stiffness and strength of soft rocks during the hold phase. Though a number of models [9,11–14]have considered the effects of structural decay, the healing effect of the structure over time has not been considered.

Thus, it is crucial to consider both the effects of structural healing as well as structural decay in constitutive models, especially when estimating the long–term behavior of soft rocks. Therefore,

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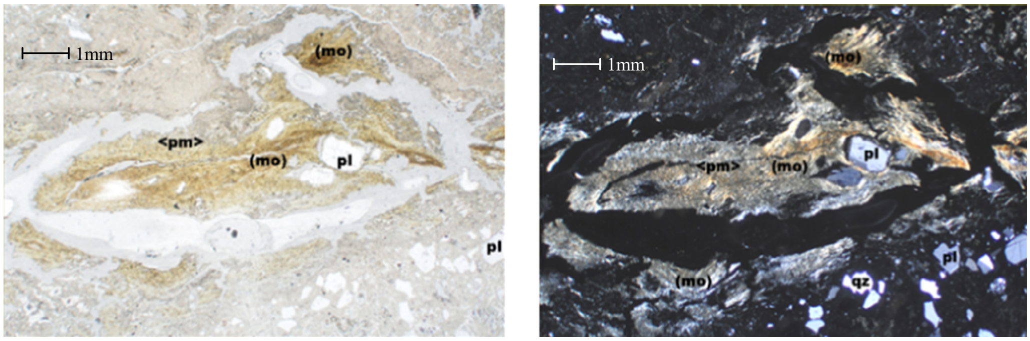

Fig. 1. Photomicrographs of pumice lapilli tuff (magnification ×15; qz: quartz, pl: plagioclase, pm: pumice, mo: Montmorillonite with Fe) (a) original image; (b) image focusing on the Fe montmorillonite.

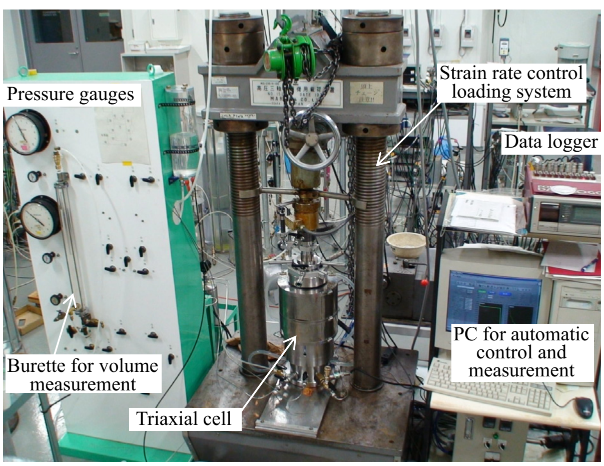

Fig. 2. Triaxial testing apparatus.

the objective of the current study was to consider the effects of both structural healing and decay on the behavior of soft rocks. We first conducted triaxial tests on soft sedimentary rock with repeated slide-hold-slide (SHS) processes to observe the effects of structural healing and decay on the strength and stiffness of soft rock. After the slide-hold-slide processes, we investigated the effect of time on the structural recovery of soft sedimentary rock. We then developed a constitutive model that considered the effects of both structural healing and decay of soft rocks. In our model, the critical state theory was extended to consider the effect of the rock structure. Moreover, the subloading surface concept [16] was incorporated into the model to appropriately consider the combined effects of density and structure. The healing and decay of the structure was modeled using a newly introduced state variable and evolution law. The model was finally validated via monotonic and slide-hold-slide triaxial tests under drained condition.

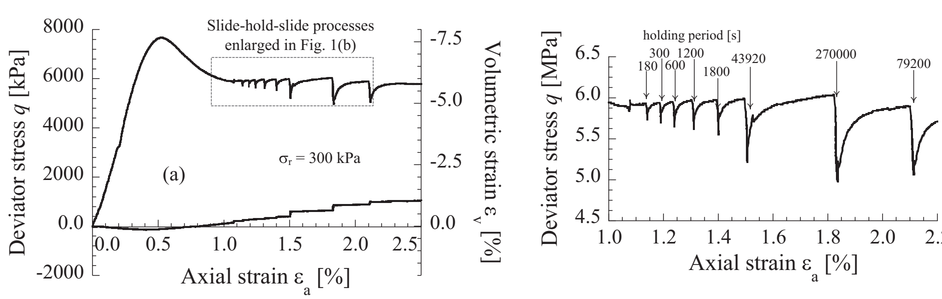

Fig. 3. Stress–strain relationship in the SHS triaxial test (σ_r = 300 kPa): (a) Overview; (b) Enlarged view.

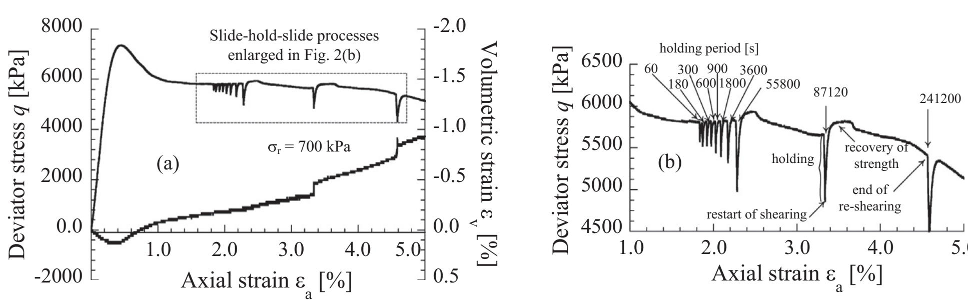

Fig. 4. Stress–strain relationship in the SHS triaxial test (σ_r = 700 kPa): (a) Overall view; (b) Enlarged view.