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An elasto-plastic constitutive model for soft rock considering mobilization of strength

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Abstract: A new elasto-plastic constitutive model is presented in the framework of plasticity theory. The strength characteristics of a diatomaceous soft rock is investigated. The friction angle and cohesion of soft rock are mobilized as a function of plastic strain. A hyperbolic hardening function for the mobilized friction and a mixed parabolic and exponential equation for the mobilized cohesion are proposed. In view of the unified strength theory and the mobilizations of strength components, a yield function is given. A plastic potential function is determined by using the non-associated plastic flow rule. An elasto-plastic constitutive model is developed and verified. The results indicate that the proposed model can predict the behavior of soft rock accurately. The advantages of the proposed constitutive model are analyzed. The evidences support that the proposed constitutive model is a mixed hardening/softening model. A hump hardening/softening function for mobilized friction is extended to a more generalized condition.

Key words: constitutive model; mobilized strength component; unified strength theory; soft rock

1 Introduction

Soft rock is widely distributed in the world. The mechanical behavior of soft rock is complex and exhibits strain hardening or strain softening characteristics in a certain range of confining pressure. Although commonly used, it is difficult to describe the behavior of soft rock and even more complicated to develop constitutive models for its behavior. To guarantee stability in geotechnical engineering, it is essential to investigate the behavior of soft rock and develop a constitutive model that can capture main mechanical features. Some constitutive models for soft rock have been developed [1−5]. These models mentioned above well predict the behavior of some soft rocks in different ways and provide some highlights for the development of constitutive models.

As a cohesive-frictional material, the cohesion and friction in soft rock play an important role in resisting deformation and failure under loading. In classical strength theory, such as the Mohr−Coulomb criterion, the strength components of material are assumed to be mobilized simultaneously and keep constant. However, many evidences support some contradictory theoretical viewpoints about the traditional understanding. VERMEER and BORST [6], MARTIN [7], HAJIABDOLMAJID [8] and SCHMERTMANN and OSTERBERG [9] demonstrated that the strength components of soils and hard rocks are non-simultaneous mobilization, and the mobilizations of rocks and soils are clearly different. Furthermore, there are few evidences to support the mobilization of soft rocks.

VERMEER and BORST [6] found that it is a novel idea to introduce strength mobilization to develop a constitutive model. Some researchers [8,10−15] analyzed the strength characteristics of rocks and soils and developed various constitutive models by considering mobilization of strength components based on the idea of VERMEER and BORST [6]. But these models are based on the Mohr−Coulomb criterion and ignore the effect of the intermediate principal stress.

However, many studies demonstrated that the intermediate principal stress significantly affects the mechanical behavior of some rocks and soils [16−25]. ZHANG et al [2] studied the influence of intermediate

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principal stress on the mechanical behavior of soft rock based on plane strain tests.

Thus, it is necessary to develop a new constitutive model that can reflect the effect of the intermediate principal stress. A three-dimensional strength criterion must be introduced. Many strength criteria have been proposed, but no criterion can describe all geomaterials due to the complexity of the property of geomaterials. Thus, it is necessary to select a versatile criterion that can predict the behavior of geomaterials as possible. YU [26] surveyed the advances in strength theory (such as yield criteria and failure criteria) of several materials, including metallic materials, rock, soil, concrete, ice, iron, polymers, and energetic materials, under complex stresses, discussed the relationships between various criteria, and presented a method for choosing a reasonable failure criterion for research and engineering applications. LI et al [27] compared several strength criteria under a general stress state and found that the unified strength theory is most versatile. The unified strength theory has been widely recognized and used in geotechnical engineering and other areas of engineering and is summarized [28,29].

YU et al [30] developed a constitutive model based on the unified strength theory and applied it to analyze the stability of underground excavations. However, the constitutive model neglects the hardening law and is an ideal elasto-plastic model, which leads to several errors when predicting the behavior of geomaterials. LI et al [15] developed a constitutive model based on the unified strength theory by considering the mobilized friction and ignoring the effect of cohesion, but the model can only reflect strain softening behavior. The objective of this work is to investigate the mobilized strength components of soft rock based on experiments. In the framework of plasticity, a hardening/softening constitutive model is to be developed by considering the unified strength theory and the mobilization of strength.

2 Strength characteristics of soft rock

2.1 Experiment

To investigate the strength behavior of soft rock, a representative diatomaceous soft rock is considered in the present work. The diatomaceous soft rock was taken from the diatomaceous mud rock stratum at Noto Peninsula in Ishikawa Prefecture, Japan, and belongs to the late Miocene age (see Ref. [31]). The rock is composed of the debris of diatoms, clay and volcanic ash. The consolidation test of the rock indicates that the preconsolidation pressure of the rock is 1.5 MPa. A series of consolidated undrained triaxial compressive tests on saturated diatomaceous soft rock samples of 50 mm in diameter and 100 mm in length were performed. Herein, only the normally consolidated rock was investigated. Considering the need of practical engineering and the limitation of the maximum confining cell of triaxial apparatus, the confining pressures of 2, 2.5, 3 and 3.5 MPa, were adopted for the consolidated undrained test.

Figures 1 and 2 show the results of the stress−strain relationship and the pore water pressure−strain relationship under different confining pressures, respectively. The results in Fig. 1 indicate that the stress−strain behavior exhibits pronounced strain softening characteristics. The stress increases to a peak value with the increase of strain and then begins to decrease to residual value gradually. The peak strengths of the soft rock under different confining pressures occur in a range of the strain of 2.5%−4%. Figure 2 shows the relationship between pore pressure and strain. The pore pressure under different confining pressures increases with the increase of strain.

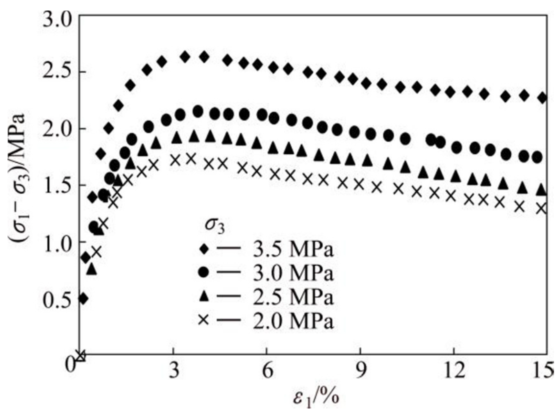

Fig. 1 Stress−strain curves of diatomaceous soft rock under different confining pressures

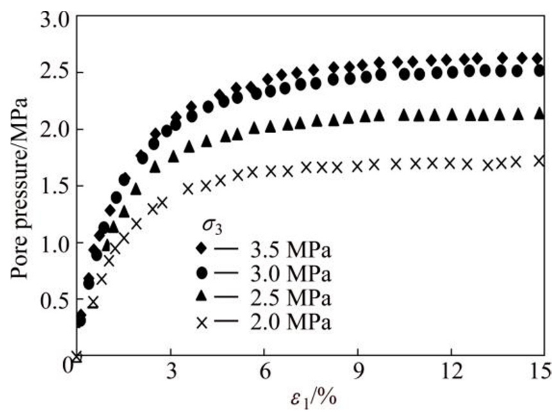

Fig. 2 Pore pressure−strain curves of diatomaceous soft rock under different confining pressures

2.2 Mobilization of strength

The strength of geomaterials is generally assumed to be composed of two parts, i.e., frictional strength component and cohesive strength component. Generally,