Computers and Geotechnics 48 (2013) 29–40

Contents lists available at SciVerse ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Modeling of inherent anisotropic behavior of partially saturated clayey rocks

Dawei Hu [a,b], Hui Zhou [a,*], Fan Zhang [c], Jianfu Shao [b], Junfeng Zhang [d]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
[b] LML, UMR8107, CNRS, University of Lille I, Villeneuve d'Ascq, France
[c] Hubei University of Technology, Wuhan 430068, China
[d] Key Laboratory for Hydrodynamics and Ocean Engineering, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 18 May 2012
Received in revised form 6 September 2012
Accepted 7 September 2012

Keywords:
Inherent anisotropy
Unsaturated
Discrete approach
Clayey rocks

ABSTRACT

Clayey rocks are frequently chosen as a geological barrier material for underground repositories. The inherent anisotropic mechanical behavior and the evolution of mechanical behavior with water content are two crucial material properties for the safety analysis of these structures. The present paper focuses on numerical modeling of the inherent anisotropy and the effect of water content, as well as the interactions of these properties in partially saturated clayey rocks with preferably oriented bedding planes. A discrete thermodynamic approach is adopted for describing the inherent anisotropic mechanical behavior, and the anisotropy of the elastic parameters, plastic evolution and damage evolution are considered. Capillary pressure is introduced to describe the effect of the water content with the help of the effective stress concept, and a procedure for the identification of the model parameters is presented. Finally, the proposed model is applied to a study of triaxial compression tests of argillite with different orientations of the bedding planes and variable water content. In summary, the main features of the studied material are well reproduced by the model.

1. Introduction

Due to favorable geological properties characterized by the absence of major fractures, very low permeability and high mechanical strength, clayey rock is frequently chosen as a possible geological barrier material, such as that used for the capping rock in deep geological storage of CO_2 and underground repositories for nuclear waste. In the context of underground storage of nuclear waste, the initially saturated argillites will be submitted to various coupled perturbations, such as mechanical loading due to excavation, water and gas flow, de-saturation and re-saturation. Due to the presence of clay elements such as smectite, the mechanical behavior of argillites is very sensitive to the saturation degree. A number of experimental investigations [1–10] have been performed on various clayey rocks in partially saturated conditions. Certain constitutive models have been proposed using the concept of effective stresses on the partially saturated field. Recently, certain alternative approaches [11–16] have been presented for the modeling of partially saturated geomaterials.

Inherent anisotropy is another important property of clayey rocks. This class of rocks usually exhibits a selected preferable orientation of distinct bedding planes, which result in inherent anisotropic behavior on the macro-scale. A large body of research [10,17–27] has been conducted on inherently anisotropic rocks, including experimental characterization, theoretical studies and numerical modeling. Various topics have been covered, including micro- and macro-structural factors in anisotropy and the interactions between inherent and induced anisotropies. According to experimental investigations [10], this anisotropic behavior becomes less and less pronounced as the water content degree increases.

However, to our knowledge, there is still no published constitutive model that can describe the two effects of capillary pressure and inherent anisotropy as well as their interaction in clayey rocks. The present work aims to model the behavior of inherently anisotropic clayey rocks under the effect of variable water content degree. The presented model applies the effective stress concept within the existing discrete approach. Section 2 summaries the previous experimental results on mechanical behavior of clayey rocks, including the saturation degree and the inherent anisotropy. Based on these experimental results, Section 3 proposes a discrete damage-plasticity model for inherently anisotropic clayey rocks with consideration of the effect of capillary pressure. Finally, the numerical algorithm, identification of model parameters and the numerical results are given in the last section.

2. Summary of experimental investigations

A comprehensive experimental program has been carried out on argillite (including Tournemire argillite and Meuse/Haute-Marne argillite) at the Lille Laboratory of Mechanics, and the

* Corresponding author.
E-mail address: hzhou@whrsm.ac.cn (H. Zhou).

0266-352X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compgeo.2012.09.002

results have been reported by Niandou et al. [23], Chiarelli et al. [4] and Zhang et al. [10]. A short summary of test data on argillite is given in this section, and these data will be used in Section 4 to validate the numerical predictions. The average volumetric fractions of various mineral phases of Tournemire argillite and Meuse/Haute-Marne argillite are 15% and 27% for calcite, 19% and 23% for quartz, 44% and 45% for clay matrix, respectively. The representative porosity of Tournemire argillite and Meuse/Haute-Marne argillite are in the range of 8% and 11.8%, respectively.

2.1. Mechanical behavior of Tournemire argillite with natural water content

According to porosity and natural water content tests, the natural water content of Tournemire argillite is approximately 8%, and the initial saturation degree is nearly 95%. Hydrostatic compression tests have shown that there is a difference in strain between the parallel and perpendicular directions relative to the natural bedding plane; this difference indicates an initial anisotropy in the argillite. The effects of inherent anisotropy on elastic behavior and strength properties were analyzed based on a series of triaxial compression tests performed on samples with different orientations of the bedding planes. Fig. 1 presents the evolution of the axial Young's moduli and strength with respect to the orientation of the bedding planes. The axial Young's modulus is the lowest at $\theta = 0°$ (i.e., when the bedding planes are normal to the loading direction, this value continuously increases with the orientation of the bedding planes). Fig. 1 shows that that the failure stress of the argillite depends on the orientation of the bedding planes, and there are two maximum values that occur at $\theta = 0°$ and $\theta = 90°$. The minimum strength is found between $\theta = 30°$ and $\theta = 60°$. This anisotropy of the strength is related to the failure mechanism. In general, the fracture angle strongly depends on the bedding plane orientation, and the failure occurs in two principal modes, extension and shearing. However, fractures can develop both in the argillite matrix and in the bedding planes.

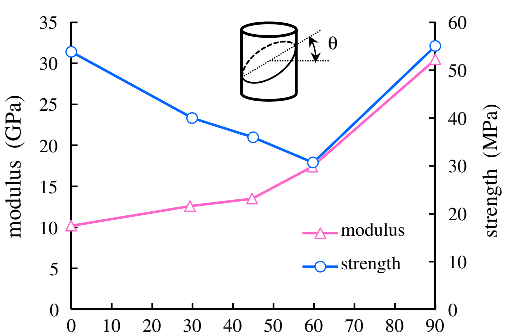

Fig. 1. Variation of axial Young's modulus and strength vs. orientation of bedding planes with a confining pressure of 5 MPa (after [23]).

2.2. Effect of water content on mechanical behavior of Meuse/Haute-Marne argillite

To study the influence of water content on the mechanical behavior of Meuse/Haute-Marne argillite, micro-indentation and mini-compression tests were performed in the parallel and perpendicular directions on samples with respect to the bedding planes and under different levels of relative humidity. As the relative humidity decreases, both the elastic modulus and failure strength increased in both the parallel and perpendicular directions, and the plastic deformation became less and less pronounced (see Fig. 2). The capillary pressure due to de-saturation, which plays a role similar to the confining stress and therefore affects the mechanical behavior, can explain this observation. When comparing the mechanical behavior of argillite in the parallel and perpendicular directions, anisotropic behavior is observed in the elastic modulus and mechanical strength. This anisotropic behavior becomes less and less pronounced as the relative humidity increases, which means that the elastic modulus and mechanical strength of a sample with perpendicular bedding planes ($\theta = 0°$) is more sensitive to the saturation degree than that with parallel bedding planes ($\theta = 90°$).

3. Formulation of discrete plastic damage model for partially saturated material

Following the above experimental investigations, a general framework is set up for the modeling of plastic damage in partially saturated material. The discrete thermodynamic approach is adopted to describe the inherent anisotropy and induced anisotropic mechanical behavior. Capillary pressure is introduced to describe the influence of water content on the mechanical behavior, and hydric responses (variations of fluid pressures with mass change and skeleton deformation) are not considered in this work (see [28]).

3.1. General framework

The general framework of the coupled plastic damage model in partially unsaturated conditions is first presented under the

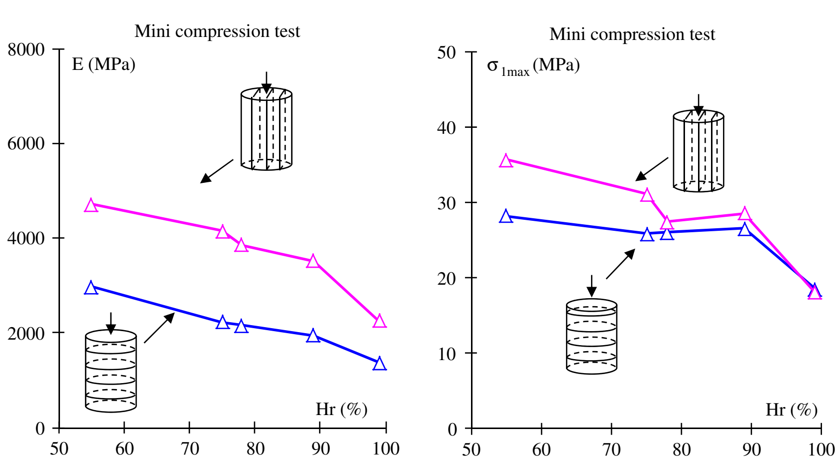

Fig. 2. Evolution of elastic modulus and peak stress as functions of relative humidity; comparisons between two bedding plane orientations (after [10]).