Water Science and Engineering 2018, 11(2): 131–138

HOSTED BY

ELSEVIER

Available online at www.sciencedirect.com

Water Science and Engineering

journal homepage: http://www.waterjournal.cn

A new shear rheological model for a soft interlayer with varying water content

Chong Ma [a,b], Hong-bin Zhan [b,c,*], Wen-min Yao [b], Hua-zhou Li [b]

[a] *School of Mathematics and Physics, China University of Geosciences, Wuhan 430074, China*
[b] *Faculty of Engineering, China University of Geosciences, Wuhan 430074, China*
[c] *Department of Geology and Geophysics, Texas A&M University, College Station, TX 77843-3115, USA*

Received 2 May 2017; accepted 13 January 2018
Available online 5 July 2018

Abstract

The rheological behavior of a soft interlayer is critical to understanding slope stability, which is closely related to the water content of the soft interlayer. This study used the soft interlayer of the Permian Maokou Formation in Southwest China as an example to perform ring shear creep tests with different water content amounts. The effect of water content on the creep properties of the soft interlayer was analyzed, and a new shear rheological model was established. This research produced several findings. First, the ring shear creep deformation of the soft interlayer samples varied with the water content and the maximum instantaneous shear strain increment occurred near the saturated water content. As the water content increased, the cumulative creep increment of the samples increased. Second, the water content significantly affected the long-term strength of the soft interlayer, which decreased with the increase of water content, exhibiting a negative linear correlation. Third, a constitutive equation for the new rheological model was derived, and through fitting of the ring shear creep test data, the validity and applicability of the constitutive equation were proven. This study has developed an important foundation for studying the long-term deformation characteristics of a soft interlayer with varying water content.

Keywords: Soft interlayer; Ring shear creep test; Rheological constitutive model; Water content

1. Introduction

The deformation of a soft interlayer is critical to the stability of rock mass engineering. A soft interlayer tends to become either the main pathway of or a barrier to groundwater pollutant migration, depending on its permeability tensor, which is often considerably different from those of the upper and lower strata. For instance, the permeability of the interlayer may exhibit high anisotropy, i.e., a relatively large permeability along the bedding direction and a relatively small permeability perpendicular to the bedding. Consequently, a soft interlayer may become the main pathway for contaminant migration along the bedding direction, but it can also become an effective barrier to cross-strata contaminant migration along the direction perpendicular to the bedding. This unique feature of a soft interlayer has not been carefully investigated before. To better understand the contaminant transport through a soft interlayer, which may or may not be fully saturated, one has to understand the unsaturated permeability tensor of the layer, which is closely related to its rheological behavior with varying water content.

The rheological behavior of a rock or soil mass is a general concern in many geotechnical engineering problems (Sun, 1999). Rheological tests serve as the main means of knowing the rheological and mechanical properties of a rock

This work was supported by the National Natural Science Foundation of China (Grant No. 41521001) and the Natural Science Foundation of Hubei Province (Grant No. 2018CFB385).
* Corresponding author.
E-mail address: zhan@geos.tamu.edu (Hong-bin Zhan).
Peer review under responsibility of Hohai University.

https://doi.org/10.1016/j.wse.2018.07.003

or soil mass (Bhat et al., 2013; Lai et al., 2014). With the rapid advancement of rheological studies in recent decades, the limitations of rheological tests on a rock or soil mass under highly simplified and sometimes unrealistically ideal conditions have become clear.

To better tackle geotechnical problems in the actual geological environment, rheological tests on a rock or soil mass under complex and realistic conditions are necessary. Fujii et al. (1999) conducted a comparative study on the circumferential creep properties of water-saturated and dry sandstones, and found that the moisture state had a strong effect on circumferential strain. Ngwenya et al. (2001) studied the rheological behavior of water-saturated sandstone under low temperature conditions and developed a modified form of the power-law constitutive equation. Zhu and Ye (2002) discussed the law of influence of the moisture state on the creep properties of rocks through comparative analysis of the results of rock creep tests under dry and water-saturated states and showed that the transient creep modulus and creep deformations were all affected by water content. Yang et al. (2007) performed creep tests on natural, dry, moderately moisturized, and water-saturated shales; analyzed the effects of different water content amounts on creep properties; and showed that water content had a strong influence on the mechanical properties of rock creep. Okubo et al. (2008) did a comparative analysis of the viscoelastic characteristics and creep models of water-saturated and air-dried weathered tuffs, and proposed a new creep model capable of reflecting the changes in Young's modulus of water-saturated and air-dried rocks. Pellet et al. (2013) conducted a series of direct shear tests to examine the effect of water saturation on the mechanical properties of clay-infilled discontinuities and showed that both angles of friction and cohesion decreased while the discontinuity was saturated. Liu et al. (2013) conducted creep loading and unloading tests on dry and water-saturated deep amphibolites, and found that water affected the creep properties of rocks more significantly under higher stress. Wang (2014) studied the degradation effect of the creep properties of sandstone and argillite under different water-saturation and water-loss cycles and showed that, as the number of water saturation-dehydration cycles increased, the rock's rheological properties became increasingly clear. Brantut et al. (2014) performed triaxial deformation experiments on a porous limestone saturated with water, and showed that only low levels of strain were reached during the occurrence of brittle creep failure. Ma et al. (2016) studied the triaxial rheological properties of silty mudstone and demonstrated that the rock showed different rheological properties with different water content amounts and confining pressures. In addition, Lockner (1993) and de Meer and Spiers (1995) conducted a study on the creep properties of rocks under the effect of temperature.

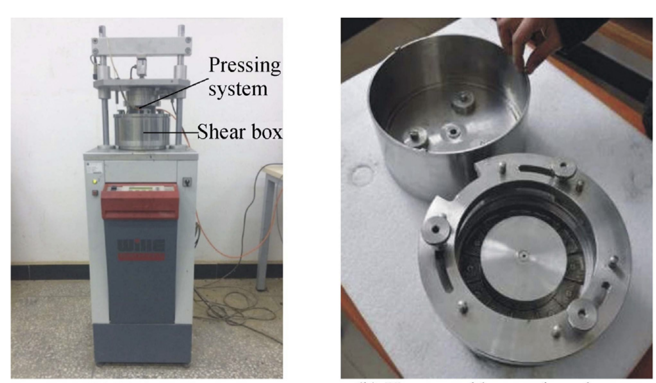
In studies of stability problems of mine slopes and reservoir bank slopes, soft interlayers often exhibit distinctive rheological behavior due to their unique geological features, and have significant impacts on slope stability. For example, the soft interlayer of the Maokou Formation is the main sliding zone of limestone mine slopes in Sichuan Province, in China, and has become one of the major safety concerns with regard to mining activity. The water content of a soft interlayer varies over time due to changes in rainfall, reservoir water level, etc., which will inevitably affect its creep mechanical properties. Therefore, it is particularly important to study the creep properties of the soft interlayer of the Maokou Formation with varying water content. The objective of this study was to develop a new shear rheological model and its associated constitutive equation for a soft interlayer with varying water content by performing ring shear creep tests on samples from the Maokou Formation. This study has developed an important foundation for studying the long-term variation of permeability of a soft interlayer and is significant to studies of the migration and prevention of groundwater pollution.

2. Materials and methods

2.1. Ring shear creep test

The ARS fully automatic closed-loop controlled ring shear apparatus (Wille Geotechnik, Germany), as shown in Fig. 1, was used in ring shear creep tests. The ring shear apparatus consists of a main unit, a main controller, and a recording and control storage unit. Driven by a high-precision motor, it can achieve linear or instantaneous changes of shear rate, shear pressure, and normal pressure. This apparatus is capable of providing a maximum axial pressure of 10 kN, a maximum shear stress of 1000 kPa, a maximum shear rate of 32 mm/min, and a maximum axial displacement of 25 mm.

Samples used in the ring shear creep test were taken from the soft interlayer of the Permian Maokou Formation of a large limestone mine slope on Mount Emei, in Sichuan Province, in China. According to the in situ moisture state of the soft interlayer and parameters such as the Atterberg limit, the samples were remolded and subjected to ring shear creep tests with five different water content amounts (15%, 19%, 23%, 27%, and 31%) to investigate the difference in creep



(a) Main unit (b) Upper and lower shear boxes

Fig. 1. ARS ring shear apparatus.