Engineering Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Engineering Geology

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

Short communication

Experimental study and modeling of shear rheology in sandstone with non-persistent joints

L.Z. Wu[a], B. Li[a], R.Q. Huang[a,*], P. Sun[b]

[a] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, Sichuan 610059, PR China
[b] Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, PR China

ARTICLE INFO

Keywords:
Sandstone
Rheology test
Non-persistent joint
Elasto-viscoplastic model
Long-term strength

ABSTRACT

Understanding the long-term mechanical behavior of cracks in rock masses is important for engineering projects and for controlling rock mass stability, particularly on rock slopes. In this study, laboratory-prepared cubic sandstone samples with non-persistent joints were subjected to shear creep testing using a rock shear rheometer. The results indicate that long-term shear strength is influenced by the long-term internal friction angle and cohesion, and decreasing cohesion is a key factor for changes in long-term shear strength under constant load. Additionally, damage to the shear modulus is related to the initial damage conditions and joint persistence of the samples. A new creep model is developed that considers the effect of crack or joint length on time-dependent rock behavior. The elasto-viscoplastic behavior of non-linear creep is also described. The modified shear creep model shows promising results for estimation of failure time, shear creep deformation and long-term stability of a rock slope for cases where planar-type failure occurs along a crack or joint surfaces in which no cohesion exists in the crack or joint surface contacts.

1. Introduction

The long-term stability of rock slopes or masses in an engineering project is related to creep deformation of joints, cracks or faults under sustained loads. A better understanding of the time-dependent behavior of rocks or rock masses is required to determine long-term mechanical behavior in mines, nuclear waste repositories and tunnels constructed in various rock types (Malan, 2002; Ma and Daemen, 2006; Sterpi and Gioda, 2009). Creep experiments are often used to determine the time-dependent strength and/or deformation modulus of rocks, but creep does not occur unless the load/stress level exceeds a certain threshold, which can be defined as the long-term strength of the rock (Bieniawski, 1970; Aydan et al., 2014).

Previous experiments on time-dependent behavior of rock have been carried out, mostly under compressive loads, on soft rocks such as shale, moderately hard rocks such as marble and hard rocks such as granite (i.e., Okubo et al., 1991, 1993; Aydan et al., 1993; Boukharov et al., 1995; Chan, 1997; Hunsche and Hampel, 1999; Yang et al., 1999; Malan, 1999; Silberschmidt and Silberschmidt, 2000; Berest et al., 2005; Fabre and Pellet, 2006; Yang and Jiang, 2010; Yang and Cheng, 2011; Lo and Feng, 2014; Gunther et al., 2015; Wu et al., 2016). For example, three-point bending creep fracture tests were carried out on sandstone (Chen and Azzam, 2007), and multi-level loading and unloading cyclic uniaxial compression creep tests have been used to measure the influence of strain history on rock deformation (Li and Xia, 2000). Elastoplastic models describing short-term behavior and time-dependent deformation have been described in terms of progressive degradation of the elastic modulus and failure strength of the material caused by microstructural evolution (Shao et al., 2003; Yang et al., 2014). An elasto-viscoplastic constitutive model was implemented by Maranini and Brignoli (1998) and Xu et al. (2006) using experimental results, where non-linear creep characteristics were expressed by the exponential distribution over time. A series of shear tests and shear creep tests were carried out by Xu et al. (2013) and Zhang et al. (2016) based on various joint roughness coefficient values, and shear creep models were used to investigate the elasto-viscoplastic characteristics of the rock samples. Changes in creep rates and different creep stages can be used to identify long-term shear strength, as the long-term shear strength is generally 60–70% of the conventional shear strength (Xu et al., 2013; Zhang et al., 2016).

However, there has been little work on creep models of rock with non-persistent joints, particularly when incorporating shear creep and the effects of crack or joint lengths on excavation-induced deformation and long-term stability of rock slopes (Xu et al., 2013; Wang et al., 2015; Zhang et al., 2016). In existing creep models, it is difficult to identify damage attenuation of the shear modulus, making it difficult to

* Corresponding author.
E-mail address: hrq@cdut.edu.cn (R.Q. Huang).

http://dx.doi.org/10.1016/j.enggeo.2017.04.003
Received 22 October 2016; Received in revised form 23 March 2017; Accepted 2 April 2017

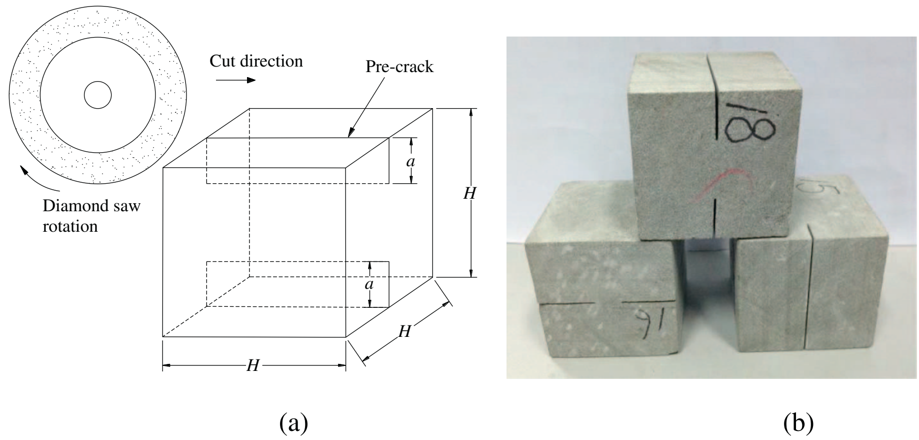

Fig. 1. Illustrations of sandstone specimens with non-persistent joints showing (a) details of the cubic specimen where a is the crack depth and H is the length, width and height, and (b) photographs of the prepared specimens with non-persistent joints.

effectively simulate transformation from steady creep to accelerated creep.

In this study, results are presented from shear creep tests performed on sandstone samples with pre-existing cracks and to examine the resulting shear creep behavior. An elasto-viscoplastic shear creep model is also discussed, and the model output results compared with the results of shear creep tests of sandstone samples with non-persistent joints. Planar failure time along a crack or joint surface, shear creep deformation and the long-term stability of rock slopes is examined using the modified shear creep model.

2. Materials and methods

2.1. Preparation of sandstone samples with non-persistent joints

Cubic sandstone samples with a side length of 10 cm were prepared in the laboratory. The specimen preparation details are shown in Fig. 1a and photographs of the specimens are shown in Fig. 1b. To ensure uniform loading, the surfaces of the samples were smoothed to within ± 0.03 mm. A vertical milling machine and a diamond saw blade were used to cut 1.0 mm wide cracks into the samples. The cracks were not filled with any material. The mechanical parameters of the sandstone are listed in Table 1.

2.2. Test design

For a specimen of length H and crack depth a, the joint persistence values k ($k = 2a/H$) were 0, 0.3, 0.5, and 0.7. Normal loads (Q, kN) were applied with normal stresses (σ) of 1 MPa, 2 MPa and 3 MPa (Fig. 2), where $\sigma = Q/[A(1 - k)]$ and $A = H^2$ (A is the area of rock bridge; see List of symbols). The tests were divided into 12 groups with each group comprising three rock samples with the same crack length and normal stress and identical stress paths were applied in each group. Normal stress (σ) was first applied to each rock specimen, followed by horizontal loads (N, kN) applied as shear stress (τ), which was increased gradually, where $\tau = N / [A(1 - k)]$. During each group test, the same loading path was maintained for each rock sample, with the initial shear stress set at 2 MPa, and a constant shear load maintained until the displacement was no > 0.001 mm per day. Then, the shear stress was increased by 2 MPa, and the process repeated. Stress was applied at a loading rate of 5 kN/min and there was no contact between the pre-cracked surfaces during the shear creep test. Details of the testing scheme are provided in Table 2.

Table 1
Mechanical parameters of the sandstone used in this study.

σ_0 (MPa)	E_0 (GPa)	G_0 (GPa)	v_0	c_i (MPa)	c_j (MPa)	φ_i (°)	φ_j (°)	Void ratio (%)
97.85	15.29	6.27	0.22	17.2	0	53.2	32.4	0.15

Note: σ_0 is uniaxial compressive strength; E_0 is elastic modulus; G_0 is shear modulus; v_0 is Poisson ratio; c_i and φ_i are cohesion and internal frictional angle of an intact rock; c_j and φ_j are the initial cohesion and the frictional angle of the joint, respectively. These parameters are determined by the conditions of the non-persistent joint samples before creep testing.

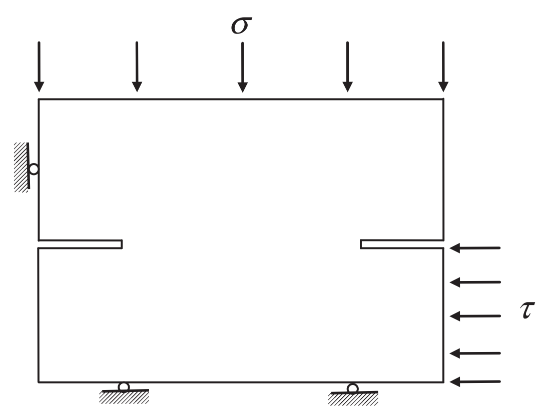

Fig. 2. Schematic diagram illustrating loading directions of normal (σ) and shear stress (τ) applied to the sample.

The creep tests considered the effect of crack length on the shear modulus of the specimens subjected to various loads. For a specimen of length H and crack depth a, the joint persistence values k were 0, 0.3, 0.5 and 0.7. Normal loads (Q) or normal stress (σ) were applied first to each rock specimen, followed by horizontal loads (N) or shear stress (τ_i, i = 1–8) (Fig. 2). The shear stress was initially set at 2 MPa and then increased by 0.5 MPa, with normal stress at 1 MPa. During each test, the same load was maintained for each rock sample, and a constant shear load maintained with the creep test time (Δt_i). Normal and shear stress were applied at a loading rate of 5 kN/min. Details of the testing scheme are listed in Table 3.