Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 1054–1070

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Time-dependent dilatancy for brittle rocks

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ARTICLE INFO

Article history:
Received 5 April 2017
Received in revised form
1 August 2017
Accepted 8 August 2017
Available online 23 November 2017

Keywords:
Time-dependent dilatancy
Microcracking
Subcritical crack growth
Rock deformation and failure

ABSTRACT

This paper presents a theoretical study on time-dependent dilatancy behaviors for brittle rocks. The theory employs a well-accepted postulation that macroscopically observed dilatancy originates from the expansion of microcracks. The mechanism and dynamic process that microcracks initiate from local stress concentration and grow due to localized tensile stress are analyzed. Then, by generalizing the results from the analysis of single cracks, a parameter and associated equations for its evolution are developed to describe the behaviors of the microcracks. In this circumstance, the relationship between microcracking and dilatancy can be established, and the theoretical equations for characterizing the process of rock dilatancy behaviors are derived. Triaxial compression and creep tests are conducted to validate the developed theory. With properly chosen model parameters, the theory yields a satisfactory accuracy in comparison with the experimental results.

1. Introduction

The occurrence of volumetric dilatancy before macro-failure is a unique feature of crystalized rocks (Cook, 1970; Cristescu, 2002). In rock engineering, the dilatancy phenomenon is commonly observed and it plays a critically important role in the stability of underground structures (Tan, 1982; Bosman et al., 2000). Studies showed that deformation due to dilatancy and discretization accounts for 60% of the total deformation in some tunnels (Duan and Song, 2007). Rock dilatancy phenomenon also has a close relation with dynamic disasters such as rockburst and seismicity. Tan (1986) and Tan et al. (1989) emphasized the importance of time-dependent dilatancy occurring prior to rock failure and proposed a creep, viscoelastic constitutive model to predict rockbursts. Direct evidence of crustal dilatancy has also been observed prior to earthquakes. Scholz et al. (1973) and Tan and Kang (1983) thus employed the dilatancy-expansion mode as the physical basis for seismicity prediction. Time-dependent dilatancy is therefore an important issue in a wide range of sciences and engineering disciplines.

The dilatancy scenario of rocks was for the first time observed by Bridgman (1949) using uniaxial compression tests. Subsequently, studies of this scenario have been performed by Brace et al. (1966), Cook (1970), Cogan (1976), Tan et al. (1989) and others. Based on experimental studies, Scholz (1968) suggested that dilatancy could be the result of time-dependent microcracking. Acoustic emission (AE) and scanning electron microscope (SEM) observations later supported this hypothesis (Tapponnier and Brace, 1976; Haimson and Chang, 2000; Zhang et al., 2015).

As shown in Fig. 1, the stress–strain behaviors of brittle rocks in compression can be divided into four stages:

(1) Stage I: Upward concavity due to the closure of pre-existing cracks. This stage can be neglected for hard rocks at high confining pressures.
(2) Stage II: Elasticity stage. During this stage, there is a fairly good linearity between stress and strain and no time-dependent behavior is observed.
(3) Stage III: Development of dilatancy associated with stable, slow microcrack propagation, which is also called the subcritical microcrack growth. This stage starts when the stress difference $|\sigma_1 - \sigma_3|$ exceeds a certain limit f_3^* (or $\sqrt{J_2}$ exceeds f_3, where $J_2 = S_{ij}S_{ij}/2$ is the second invariant of the deviatoric stress tensor, and S_{ij} is the deviatoric stress tensor. Because $|\sigma_1 - \sigma_3| = \sqrt{3J_2}$, one can obtain $f_3^* = \sqrt{3}f_3$). The parameter f_3^* (or f_3) is important in predicting rock failure and

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.08.002

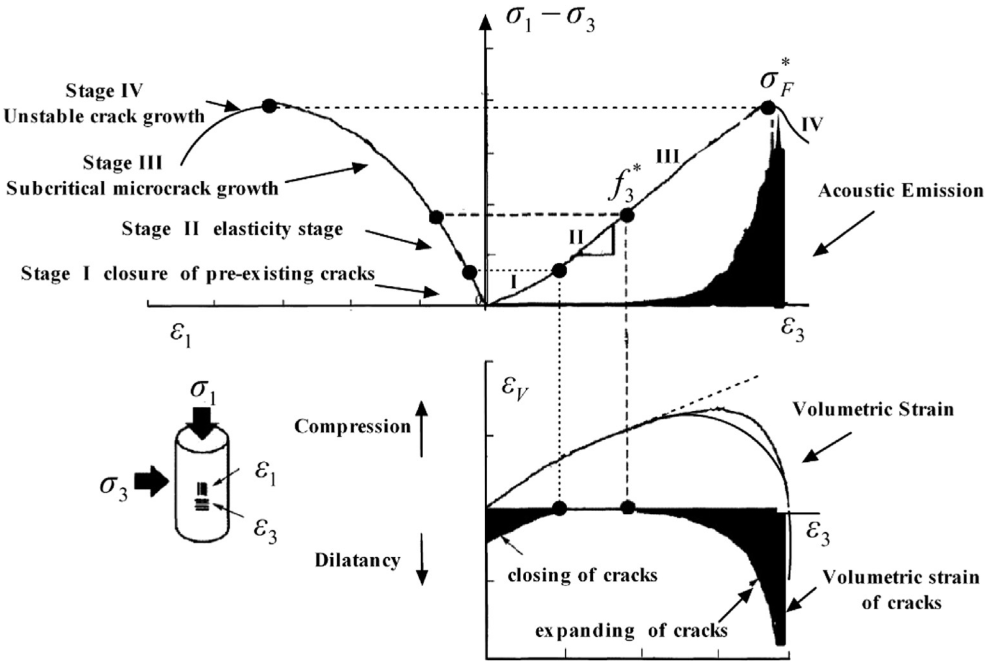

Fig. 1. Sketch of damage stages for brittle rocks (Hoek and Martin, 2014). Crack initiation stress, i.e. the long-term strength, f_3^*, is indicated.

it is called the long-term strength (Tan, 1986; Martin and Read, 1992; Szczepanik et al., 2003). AEs are observed in this stage. Dilatancy, AEs and microcracking are occurring simultaneously and thus the time-dependent dilatancy can be attributed to the time-dependent microcracking behaviors.

(4) Stage IV: Unstable microcracking behaviors leading to the growth of macro-fractures. This stage begins when the stress difference $|\sigma_1-\sigma_3|$ reaches the maximum strength σ_F^* (i.e. $\sqrt{J_2}$ reaches σ_F, and $\sigma_F^* = \sqrt{3}\sigma_F$). In this stage, the material is broken into fragments and can no longer be regarded as a continuum medium.

Although studies have proved that the time-dependent dilatancy originates from the cracking of numerous microcracks in rocks, it is challenging to establish an equation to describe dilatancy based on this mechanism. This is because dilatancy is a macroscopic phenomenon, whereas microcracking behaviors occur at the microscopic scale. In this instance, developing the relationship between the microscopic mechanism and macroscopic phenomenon remains unaddressed. Therefore, the objective of this paper is to address this problem and tries to interpret the time-dependent behavior of brittle rocks employing the mechanism of microcracking. The paper is presented as follows. After the Introduction, Section 2 describes the laws governing the growth of microcracks. Section 3 introduces the dilatancy or damage parameter. The theoretical models are derived in Section 4. Section 5 describes the application of the model to triaxial and creeping testing results of sandstone and existing triaxial testing data of Kuru granite in the literature. Section 6 discusses the performance and applicability of the theory and conclusions are drawn in Section 7.

2. Growth of microcracks

The time-dependent behaviors of brittle rocks are directly related to the evolution of cracks at the microscopic scale, so the stress-induced initiation and propagation of microcracks should be first discussed.

Fracturing of brittle rocks in compression can occur in various forms depending on the type of loading, the structure of rock, and the extent of rock internal damage. Substantial literature shows that rocks often exhibit visible characteristics of tensile failure when subjected to a low confinement compressive loading (Diederichs et al., 2004; Read, 2004), such as splitting or spalling failure of rock samples under uniaxial compression. Spalling can also be observed under more complex types of loadings, provided that there is a free surface (for example in deep underground excavation, skin rockburst is an example of fracture of this type). As the confinement increases, the role of shear cracks will be more important. When confining pressure reaches up to a sufficiently high value, the tensile crack may even be repressed, and the behavior of many rocks changes from brittle to plastic/ductile. In this paper, we mainly discuss the fracture of brittle rocks (crystalized rocks without visible internal damage) at lower confining pressures. In this circumstance, researchers (Vásárhelyi and Bobet, 2000; Bahat et al., 2005) pointed out that the influence of mode I fractures dominates, especially at the microscopic level. Hence, other modes will not be discussed in the work.

Different models have been proposed to explain the phenomenon of extensive crack growth in compression. The majority of works relate the crack growth to the action of a stress concentrator. The examples of such a stress concentrator are pre-existing cracks, pores, or stiff inhomogeneities. The pre-exiting cracks with contact faces can be considered as the strongest source of the secondary crack growth, at least in comparison with pores. Of all the most likely micromechanical models, theoretical analyses usually suggest the so-called wing crack model. This model considers the sources of tensile stress concentration located at the tips of inclined pre-existing cracks (see Fig. 2a) with length of $2a$ and oriented at an angle β to σ_1, which is the maximum principal compressive stress. The cracks are assumed to be closed under the axisymmetric triaxial loading conditions. The applied stresses