Computers and Geotechnics 104 (2018) 69–80

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Numerical investigation of the shear behavior of granite materials containing discontinuous joints by utilizing the flat-joint model

Xu-Xu Yang*, Wei-Guo Qiao

Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China
College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China

ARTICLE INFO

Keywords:
Shear behavior
Discontinuous joints
Flat-joint model
Granite material
Rock bridge

ABSTRACT

In this paper, the shear behavior and failure mechanism of granite material bridges between discontinuous joints subjected to direct shearing were investigated using a flat-joint modeling approach. Through a comprehensive calibration and validation study, good agreement was successfully achieved considering the different normal stress levels, and three failure mechanisms were observed in both the numerical modeling and physical experiments. The joint persistency and UCS/Ts ratio were then meticulously investigated and found to have a pronounced effect on the failure mode, the peak shear strength and the shear deformation modulus of the granite samples containing discontinuous joints.

1. Introduction

For rock masses encountered in geotechnical engineering, failures always occur along discontinuities. The discontinuities, such as fractures, joints, beddings, and faults, derived within the rock mass, in general, are regarded as the dominant factors governing rock mass strength and hydraulic conductivity. In engineering practice, for stability analysis and support design of underground excavations, it is of great importance to understand the shear behavior of rock discontinuities.

Since the 1960s, much attention has been paid to the shear strength and dilation deformation of rock discontinuities [1,2], mostly focusing on the effect of applied normal stress. With the development of test apparatuses and monitoring equipment, researchers began to look into the joint properties, including the rock type, surface roughness, water content, and filling material, for more precise estimation of the shear behavior of discontinuities [3–6]. Among these joint properties, the joint roughness has obtained more attention compared with other subjects because of its significant impact on the shear behavior of rock discontinuities. Ge et al. [7] compared different rock joint roughness measurements and quantification procedures in their paper and tried to evaluate the capability of applying them to any size sample from the laboratory to field scales. In particular, for quantifying the joint surface roughness, several methods were proposed and subdivided into three categories: the joint roughness coefficient (JRC) method [8], the statistical parameter method [9,10], and the fractal dimension method [11–13]. The joint roughness is a result of the asperities between the joint surfaces, of which the shape, size, number, and strength control the mechanical properties [14–16]. The effective aperture is also affected by these asperities and in turn induces an uncertainty in the hydraulic conductivity. Recently, some researchers were concerned about the asperity degradation mechanism [17–19] and indicated that one of the main difficulties in the estimation of the shear behavior of rough joints is related to the unknown mechanism of asperity degradation during the shearing process. Bahaaddini et al. [19] reported that the shearing mechanism of rough joints was observed to be sliding, asperity surface wear and asperity shearing off, according to their experimental and numerical test results.

The aforementioned studies have shed light on a better understanding of the shear behavior of rock discontinuities with respect to the significant impact of asperity. However, as one particular type of asperity clamped between joint surfaces, rock bridges have been given less consideration [20,21]. In contrast to regular asperities, rock bridges are intact rock segments cutting off the discontinuities in the extension direction and provide much stronger bonds to the opposite joint surfaces. In this work, the discontinuities containing rock bridges are termed "discontinuous joints" for unification. According to Lajtai et al. [22], two types of discontinuous joint patterns were explored in the yield pillars of the potash mines of Saskatchewan, which are the en echelon tensile crack array and the en echelon shear crack-array. Between the individual member joints of these two joint arrays, the rock bridges exist to separate them. With increasing stress, these crack arrays

* Corresponding author.
E-mail address: yangxu_skdrm@hotmail.com (X.-X. Yang).

https://doi.org/10.1016/j.compgeo.2018.08.014
Received 27 May 2018; Received in revised form 3 July 2018; Accepted 16 August 2018
0266-352X/

further collapse to form the envelope or hourglass structures of the potash mines. Li et al. [23] conducted *in situ* borehole camera monitoring of the failure evolution of surrounding rock masses in the deeply buried tunnels of the Jinping II hydropower station and observed that before the final failure happens, discontinuous joints occur intermittently, with rock bridges isolating them. With the converging deformation of the surrounding rock masses, these discontinuous joints connected with each other, going through the rock bridges and eventually forming a macro-fracture. In some sense, the rock bridges between discontinuous joints are the natural enforcement of jointed rock masses because the progressive failure of rock bridges is essential for rock masses to lose their total resistance capacity. Moreover, the rock bridges are dramatically important for the hydraulic permeability of rock mass because even one tiny rock bridge area would block the whole flow channel in a rock fracture. Therefore, the strength and failure behavior of discontinuous joints containing rock bridges deserves much more research attention.

Some pioneering researchers performed laboratory experiments on artificial rock-like materials to understand the complex shear behavior of discontinuous joints [24–27]. Gehle and Kutter [25] demonstrated that, according to physical experiments, based on the direction of the initial cracks that occurred in the rock bridges, wing cracks grow either toward the distant dip of the adjacent initial cracks, which can form some asperities at the end of the test, or directly toward the tip of the neighboring cracks. That is, the rock bridges convert to regular asperities after shearing. Asadizadeh et al. [26] recently performed shearing tests on discontinuous joints containing both rock bridges and asperities and claimed that the cracking process of specimens includes three categories, which are the tensile cracking, shear cracking and a combination of tension and shear or mixed mode tensile-shear cracking. Gerolymatou and Triantafyllidis [27] indicated that the shear strength of material with discontinuous joints is strongly dependent not only on the spacing but also on the orientation of the joints. Although some insightful results have been obtained for rock models containing discontinuous joints under shear loading conditions, the experimental results are very sensitive to sample-preparation processes and boundary loading conditions, and any change in the contact conditions between the sample and loading platens may result in different failure processes. In addition, with respect to the artificial rock-like materials used in the aforementioned experiments, the ratio of the UCS (uniaxial compression strength) to tensile strength is unrealistically lower than that of natural rock masses. For example, the ratios of the UCS to tensile strength of rock-like materials are only 6.70 in [26] and 5.45 in [27], whereas for intact rock materials, this ratio is usually 10–20. Thus, the use of artificial rock-like material models with a lower UCS to tensile strength ratio may be problematic.

The emergence of the flat-joint model (FJM) analysis proposed by Potyondy [28] in 2012 was a step forward in discrete element modeling (DEM) of rock masses. The flat-joint model was implemented in both PFC2D and PFC3D by Itasca [29] in 2015. Compared to its previous version, i.e., the parallel-bond model, to simulate intact rock materials in particle flow modeling, the flat-joint model is capable of reproducing the expected high UCS to tensile strength ratio and internal friction angle, even deriving a nonlinear strength envelope [30]. With these improvements, this model has been validated by several researchers through a strict comparison between simulation results and experimental properties of intact rock or rock-like materials and has obtained satisfactory calibration results [31,32]. However, the capability of the flat-joint model to simulate rock masses by incorporating pre-existing joints has still not been validated in the literature, and a complete simulation procedure needs to be further studied.

In this manuscript, by utilizing the newly proposed flat-joint model, the shear behavior of discontinuous joints is numerically investigated. The analysis is conducted in two stages. In the first stage, a validation study comparing numerical models to physical experiments on granite materials containing discontinuous joints in the laboratory is undertaken. Comparisons are made on the basis of the failure modes, shear strength and shear deformation modulus. Second, the numerical models are further used to conduct a parametric study to evaluate the effect of the joint geometrical parameter and rock bridge mechanical property on the global shear behavior of a discontinuously jointed rock mass. The joint geometrical parameter taken into consideration is the joint persistency, while the rock bridge property of concern is the UCS to tensile strength (UCS/Ts) ratio.

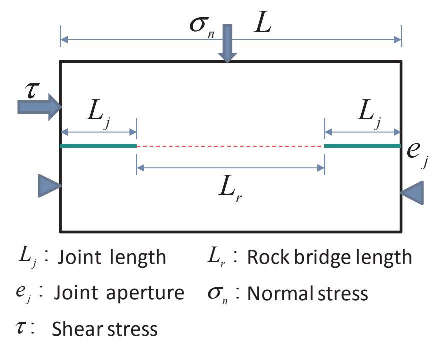

Fig. 1. A conceptual rock model containing discontinuous joints.

2. Laboratory tests

2.1. Sample preparation and test apparatus

A conceptual model for a rock mass containing discontinuous joints is shown in Fig. 1. To identify the characteristics of this rock structural type, the joint persistency, k, which states that the degree of joint continuity is defined by the joint length, L_j, and the rock bridge length, L_r, is as follows:

$$k = \frac{2L_j}{L_r + 2L_j} = \frac{2L_j}{L} \quad (1)$$

In the case of $0 < k < 1$, the fracture plane contains both a solid rock bridge and joints. On the basis of the conceptual model, granite material from Qingdao City in the Shandong Province of China was chosen to prepare the test samples. Table 1 list the mechanical properties of the granite material used for tests.

In accordance with Fig. 1, the granite samples for direct shear tests were rectangular with a size of length 200 mm × width 100 mm × height 100 mm. A high pressure water jet cutting machine was used to cut side notches at half height, as shown in Fig. 2. The joints were open with an aperture of 3.5 mm. The joint length was 75 mm, corresponding to the joint persistency, k, being 0.75. The granite samples were then subjected to direct shear tests under different normal stress levels (0.2 MPa, 2.0 MPa, 4.0 MPa, 6.0 MPa, and 8.0 MPa). For checking the repeatability, at least three samples were tested for each test scenario, i.e., under the same normal stress level.

The direct shear tests were performed using a self-developed JAW-600 shear machine (Fig. 3(a)) in Shandong University of Sciences and Technology. The shear and normal loads were applied using hydraulic actuators equipped with servo valves. All direct shear tests were conducted under displacement-controlled conditions with a loading rate of 0.1 mm/min. The shear and normal loads and deformations were recorded simultaneously during the tests, and the failure process of the sample was captured using a high-frequency video camera at the same time (Fig. 3(b)).

2.2. Test results

By observing the failure surface after the tests, it was possible to investigate the effect of normal stress on the failure mechanism of granite samples containing discontinuous joints. Fig. 4 shows the failure