



Multi-peak deformation behavior of jointed rock mass under uniaxial compression: Insight from particle flow modeling

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ABSTRACT

Evaluation of mechanical properties of jointed rock mass is very important for geological engineering problems related to underground opening, slope stability, dam foundation and hydraulic fracturing, etc. It is generally known that both strength and deformability of rock mass may change with joint geometry and arrangement. By PFC (Particle Flow Code) modeling, this paper aims at understanding the damage mechanism of the multi-peak deformation behavior of jointed rock mass with different joint orientations and continuity factors under uniaxial compression observed in the physical model tests. With the smooth joint contact model, not only has the inherent roughness in conventional joint model been avoided, but also we can monitor the joint aperture, number of closed joints, and forces acting on the joints during the damage process. It is shown that mobilization of joint strength plays an important role in the multi-peak deformation behavior of rock mass. If the joint strength is slightly mobilized or immobilized (i.e., most joints keep open) during the test, strain softening occurs. However, if the joint strength is significantly or fully mobilized, yielding platform or strain hardening may happen.

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1. Introduction

It is generally known that understanding the mechanical behavior of jointed rock mass is very important for the geological engineering such as rock excavation in underground or open pit mining, tunneling and dam foundation construction of hydropower station, wellbore maintaining and hydraulic fracturing in oil and gas exploration, etc. In the past decades, lots of studies have been focused on the strength estimation, deformation characteristics, and failure mechanism of rock mass with persistent joints. Nevertheless, according to the ISRM suggested method (ISRM, 1978), joint persistence implying the areal extent or size of a joint within a plane, is a very important parameter when considering the safety of rock tunnels, dam foundations, and slopes, especially if the joints are unfavorably oriented for stability. Much more work is required to be done on the behaviors of rock mass containing non-persistent joints, depicted as the co-planar joints separating volumes of intact rock (Prudencio and Van Sint Jan, 2007).

In practical engineering, some empirical methods have been developed to estimate the strength and deformability of the jointed rock mass. For example, deformation modulus of rock mass (E_M) can be assessed by its empirical relations with the values of Rock Mass Rating (RMR) (Bieniawski, 1978; Serafim and Pereira, 1983), Q (Barton, 2002), or Geological Strength Index (GSI) system (Hoek et al., 2002; Cai et al., 2004). These indirect methods are widely used for practical

engineering design. Nevertheless, they cannot be expected to always provide accurate values of deformation modulus owing to the complicated geometrical and mechanical properties of the joints. In order to study the strength and deformation behavior of the jointed rock mass, direct test method is required.

Compared with the in-situ test, physical model test is an economical and practical method to investigate mechanical behavior of rock masses. There are two ways to simulate the rock mass with non-persistent joints: (1) existing fissures are placed when the rock-like material is molded; (2) a large amount of modeling blocks are assembled to simulate rock mass with different sets of persistent or non-persistent joints. Different loading conditions were applied on these two types of samples including uniaxial, poly-axial compression (Bobet and Einstein, 1998; Brown, 1970; Chen et al., 2013, 2012; Horii and Nemat-Nasser, 1985; Ladanyi and Archambault, 1972; Prudencio and Van Sint Jan, 2007; Singh and Seshagiri Rao, 2005; Singh and Singh, 2008; Tiwari and Rao, 2006; Wong and Einstein, 2009) and direct shear (Gehle and Kutter, 2003; Ghazvinian et al., 2012; Lajtai, 1969; Li et al., 2014). In addition, large size of samples containing non-persistent joints were also applied in physical model tests to study the responses of tunnels (Gong et al., 2015, 2013; He, 2011; He et al., 2010; Singh et al., 2009) and slopes (Alejano et al., 2011). Most physical model tests focused on the influence of the joints arrangement on the failure modes and strength characteristics of rock mass, by observation on the macro failure processes and mechanical behaviors. Furthermore, some studies attempted to establish the strength criterion for rock mass containing non-persistent joints based on the observed failure mechanisms (Cording and Jamil,

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1997; Jennings, 1970; Lajtai, 1969). For example, Lajtai (1969) established a combined failure envelope with three parts, i.e., tension, shear failure of rock bridges, and shear failure of the crushed material matrix, under negative or low, intermediate, and high normal stresses, respectively. In his study, a mobilization factor of the joint, C_1 ($0 \leq C_1 \leq 1$), was proposed to consider the load carrying capacity of the non-persistent joints with different apertures, whose friction resistance may be fully or partially mobilized when the joints are closed, or even immobilized when the joints keep open during the tests.

Only a few physical model tests investigated the dependence of the stress-strain behavior on the joints arrangement. Tiwari and Rao (2006) studied the post-peak deformation of jointed blocks under true triaxial compression. The samples used in their tests were assemblies of cubes with one set of non-persistent joints and two sets of persistent joints, and their studies show the effect of both joint geometry and σ_2/σ_3 on the slope of post-peak stress-strain curves of the jointed rock mass. Prudencio and Van Sint Jan (2007) researched the failure modes and strength criterion of rock models with a set of non-persistent joints under uniaxial and biaxial compressive loads. It can be observed that the stress-strain curves have different features for the tested samples with different joint configurations under various confining pressures. However, the features of deformation behaviors and their relationship with the failure processes were not analyzed. What is more, the range of joint continuity factor k in their models was quite limited, $k = 0.71$ for most series of the samples and 0.63 for one series of the samples. Chen et al. (2011, 2012, 2013) set a wide range of the two geometrical parameters, joint inclination angle (0° to 90°) and joint continuity factor (0.2 to 0.8) in their physical models under uniaxial compression tests, and the stress-strain curves of the specimens show different types of deformation behaviors, depending on the combined variation of the two geometrical parameters. Compared with the conventional strain softening behavior after the single peak stress for the uniaxial compression test on the intact model, it was found that there may be one or several peaks for the jointed specimens. With different joint configurations, yielding platform or strain hardening may occur before the last peak followed by the final strain softening, i.e., the final strain softening may be delayed by different types of ductile behavior. In some other cases, there may also be one or several small peaks or oscillations during the general trend of strain softening. In this study, the term “multi-peak deformation behavior” is used to refer to this kind of deformation behaviors influenced by different joint configurations, and more detailed classification of the deformation behaviors will be described in Section 2.2. Chen et al. (2011, 2012, 2013) attempted to explain this kind of behaviors based on the damage processes, but it was mainly according to observations on the failure patterns of the samples.

In order to learn more about underlying mechanism of the deformation characteristics and failure phenomena observed in the physical model tests, numerical studies have been applied in many researches and some novel insights have been provided. With various numerical methods such as FEM (Wasantha et al., 2014; Wong et al., 2001; Zhang et al., 2006), BEM (Gehle and Kutter, 2003), DEM (Halakatevakis and Sofianos, 2010; Jiang et al., 2009; Kulatilake et al., 1992; Park et al., 2004), NMM (An et al., 2014) and hybrid FEM/DEM approach (Karami and Stead, 2008; Morris et al., 2006), the numerical models can be built to simulate and analyze the stress redistribution and fracturing mechanism, which cannot be easily measured or characterized in the physical model tests. However, it should be noted that, the crack initiation and propagation direction around the joint tips are very complex and are always simplified in these numerical simulations.

In recent years, PFC (Particle Flow Code), a DEM method developed by Itasca Co. Ltd., has shown many advantages in damage mechanism analyses of rock mass. A PFC model is generated by a group of particles with varied size, deformation modulus, normal or shear bonding strength, etc., which can be bonded together or broken up dependent on the strength of each bond, therefore no macro constitutive law or strength criterion is required while yielding, strain softening, fracture

initiation and propagation can all be simulated. It has been widely employed to build models of rock mass with non-persistent joints (Bahaaddini et al., 2013b; Fan et al., 2015; Ghazvinian et al., 2012; Park et al., 2004; Scholtès and Donzé, 2012). Especially with the development of smooth joint contact model (Bahaaddini et al., 2014, 2013a, 2013b; Chiu et al., 2013; Esmaili et al., 2010; Hadjigeorgiou et al., 2009; Lambert and Coll, 2014; Mas Ivars et al., 2011), PFC modeling has been proved to be a promising method to make a better understanding on the mechanism of mechanical behavior of jointed rock mass. However, most of the previous PFC studies on rock mass with non-persistent joints focused on the mechanical parameters such as peak strength, Young's modulus and Poisson's ratio, as well as the failure patterns, while the stress-strain behaviors and the corresponding micromechanical mechanism, especially the opening or closing of joints, were not considered effectively.

By PFC3D, Fan et al. (2015) and Yang et al. (2016) gave a successful simulation on the strength behavior and failure modes of the jointed specimens researched by Chen et al. (2011, 2012, 2013). They also presented the calculated stress-strain relationships, however, the damage mechanism was not studied. In this study, intending to understand the damage mechanism on multi-peak deformation behavior of these jointed specimens under uniaxial compression, smooth joint contact model in PFC is found to be suitable for some quantitative analyses. It is noted that these jointed specimens have geometries of plate, hence PFC2D is applied in this work for saving computer memorize. With numerical analysis, the multi-peak deformation behaviors of rock masses dependent on joint orientation, continuity factor, and aperture are studied.

2. Laboratory physical model experiments

2.1. Geometry and properties of the specimens

The geometry of specimen, geometrical parameters of joints and the photograph of a sample are presented in Fig. 1. The specimen has the geometry of plate with a size of 150 mm × 150 mm × 50 mm, and a single set of non-persistent joints penetrates through the thickness of the specimen. A global coordinate system $ox_1x_2x_3$ is related to the specimen dimension, where x_2 is direction of thickness. In addition, a local coordinate system $o\zeta_1\zeta_2\zeta_3$ is related to the arrangement of non-persistent joints, where ζ_2 shows the direction of specimen thickness and cannot be plotted in Fig. 1(b), while ζ_3 presents the direction of joint plane.

For the non-persistent joints, s is joint spacing; c is the joint center distance, which is the distance between the centers of two neighboring joints in a joint plane; L_j is the length of each single joint; β is the joint inclination angle, defined by the angle between the joint plane ($o\zeta_3$ direction) and the horizontal plane (ox_3 direction); and k is the continuity factor, defined by the ratio of the length of a single joint to the joint center distance, i.e., $k = L_j/c$. In this study, joints are regularly arranged with constant joint spacing $s = 30$ mm and constant joint center distance $c = 30$ mm. The combined variation of the continuity factor k ($k = 0.2, 0.4, 0.6$, and 0.8) and the joint inclination angle β ($\beta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$, and 90°) is considered, and the corresponding joint length L_j is 6 mm, 12 mm, 18 mm, and 24 mm. For comparison, the intact specimen is also studied, which is presented as $k = 0$.

The mixture of plaster and water with a ratio of 1:0.6 by weight was casted into the mold made of PMMA (polymethyl methacrylate) to prepare the specimens. To form the pre-existing non-persistence joints, a group of 0.3 mm-thick nickel steel sheets were inserted into the mixture through the pre-cut slots in the upper and bottom PMMA plates, and then were removed after the setting of the liquid mixture started. The specimens were cured for 21 days in room temperature before being subjected to mechanical testing. In order to observe repeatable results, the mixing, molding and curing of the material were carefully controlled, and at least three samples with the same joint configuration

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