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Evaluation of the anisotropy and directionality of a jointed rock mass under numerical direct shear tests

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ABSTRACT

The characteristics of the anisotropy and directionality of jointed rock masses are the key to simplifying it as a transversely anisotropic material. Experimental direct shear tests were performed on stratified rocks cored from granulite rocks. The influence of normal stresses and joint orientations was tested and the anisotropy and directionality of the shear strength were evaluated. Numerical shearing tests on stratified rock models and discrete fractures network (DFN) models were subsequently conducted. In addition, the shear anisotropy and directionality in the DFN models were tested and discussed. The results demonstrate that the peak shear stress was more sensitive to the inclination angles than the normal stress. The stratified rocks in the experimental test showed apparent shear anisotropy and directionality. The maximum value of directionality coincided with the direction of the strike of the bedding plane. The more apparent the anisotropy was, the higher the directionality became. The failure patterns of stratified rocks exhibited more complex characteristics under higher normal stress. Significant variation of the shear strength distribution occurred due to the different orientations of fractures relative to the directions of the shear load. The failure patterns of DFN models of varied scales differed, and no apparent convergence was discovered. The shear strength of the DFN model showed an apparent principal direction. The numerical results presented in this paper are valuable for evaluating the prediction of the failure behaviour of rock masses, and can be further applied to the study of the failure mechanism of surrounding rock in engineering.

1. Introduction

Anisotropy is one of the principal mechanical properties of various types of rocks. Weak planes can cause large deformation and low shear strength and contribute significantly to the anisotropic behaviour of rocks (Cho et al., 2012; Kim et al., 2012; Bahaaddini et al., 2014; Jiang et al., 2014; Park and Min, 2015). Therefore, the effect of discontinuities on the anisotropic behaviour of a jointed rock mass, such as the compressive and shear strength and, failure pattern, needs to be evaluated as part of safety assessments for any rock engineering project.

Transverse anisotropy studies can be easily applied to engineering problems (Fortsakis et al., 2012; Yu et al., 2013; Li, 2013) when the rocks are bedded or layered. In terms of the mechanical properties of these types of rocks, anisotropic characteristics are usually studied by conducting laboratory tests (Lei et al., 2013; Labiouse and Vietor, 2014; Chen et al., 2014; Khanlari et al., 2014) and simulation tests (Sun and Zhao, 2010; Sun et al., 2011; Li, 2013; Saeidi et al., 2013; Yu et al., 2013; Labiouse and Vietor, 2014). Deformation (Sagong et al., 2011; Kim et al., 2016) and failure patterns (Vietor et al., 2010; Seeska et al., 2011; Xia et al., 2013) are typically analysed to discuss the anisotropic characteristics. Among such studies, Liang et al. (2005) investigated the mechanical properties and the failure process of stratified rocks using numerical code RFPA. They noted that the layer orientation had a large influence on the failure process, such as the peak strength, failure modes and deformation characteristics. Tavallali and Vervoort (2010) found that the layer orientation determined both the strength and failure modes of the rock samples. Moradian et al. (2010) conducted experimental tests on natural joints cored from an in situ rock mass to study the shear behaviour of rock joints. The dominating influence of joints on the shear behaviour of a rock mass was emphasized. The influence of strength anisotropy in rocks was also numerically investigated by Dinh et al. (2013). They concluded that the degree of anisotropy has a strong influence on the tensile strength. Ghazvinian et al. (2013) studied the shear strength response of inherently anisotropic rocks. According to their research, the anisotropic effect of the weak plane orientation is a significant occurrence that must be noted in analyse and failure mechanism studies.

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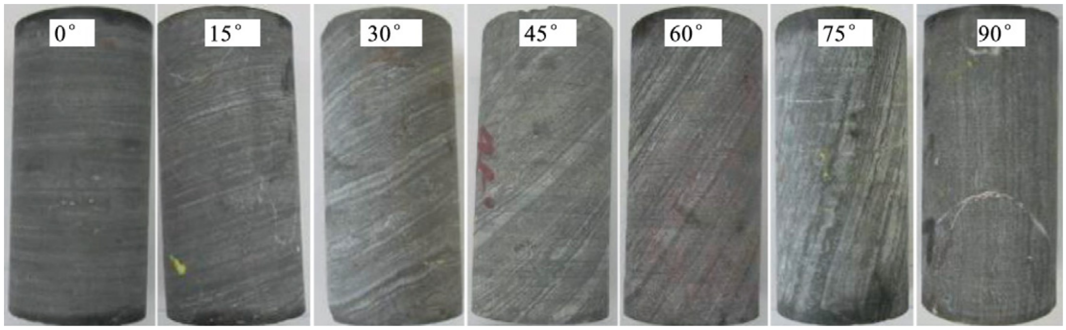

Fig. 1. The layered rock samples with different dip angles.

A large number of studies have been carried out to investigate the anisotropic behaviour of a jointed rock mass under compressive tests (Kulatilake et al., 2001; Zhang et al., 2011a,b; Lisjak et al., 2014a; Lisjak et al., 2014b; Wang et al., 2016), whereas studies of anisotropic shear behaviour remain limited. Many researchers have studied the shear behaviours of rock samples with a single rock joint (Bahaaddini et al., 2013; Bahaaddini et al., 2014; Bahaaddini et al., 2016) or one set of rock joints (Yun et al., 2013; Wasantha et al., 2014; Cheng et al., 2016). However, the anisotropy of the shear behaviour of a jointed rock mass with discrete fractures is controlled by the complex interactions of joints and intact-rock bridges. In addition, the geometry of discontinuities can exert a controlling influence on the distribution of fractured zones (Li, 2013; Yu et al., 2014; Labiouse and Vietor, 2014). Theories or modelling methods related to the evaluation of a natural rock mass with randomly distributed discontinuities are still limited. Yang et al. (2015) proposed an efficient technique to evaluate the mechanical characteristics of a natural rock mass. The constitutive relationship and failure mechanisms were introduced, and the proposed model was verified using a case study. This approach is suitable for the stability analysis of rock engineering based on numerical simulations. The key of their research is to evaluate the scale effects (Min and Jing, 2003; Chen et al., 2008), anisotropy and directionality of the representative elementary volume (REV) of a fractured rock mass. The mechanical properties in their model were investigated by numerically conducting a uniaxial compressive test using the RFPA code. Shear behaviour is also one of the most important properties of a jointed rock mass. Thus, the anisotropy and scale effect of shear behaviours should also be discussed.

Some efficient numerical methods have been developed to study the rock failure process, such as RFPA (Tang, 1997; Tang et al., 2000); to study the crack propagation and fracture patterns of rock materials under stress, such as the particle flow code (PFC) by Cundall and Strack (1979); and to analyse the crack growth of complex crack patterns, such as the cracking-particle method (Rabczuk and Belytschko, 2004; Rabczuk and Belytschko, 2007; Rabczuk et al., 2010), dual-horizon peridynamics (Ren et al., 2016) and dual-support smoothed particle method (Dai et al., 2016). These numerical methods have many advantages in the modelling of rock masses that possess the ability to fracture and break apart under stress. For the purpose of a quantitative description, numerical analyses are carried out using PFC2D version 3.0, which has been shown to have advantages in the simulation of mechanical behaviours of rocks (Lambert et al., 2010; Zhang et al., 2011a,b) and discontinuities in fractured rock masses (Potyondy and Cundall, 2004; Park and Min 2015; Potyondy 2015; Wang et al., 2016). PFC2D models the movement and interaction of circular particles by the distinct element method. The code represents a rock as an assemblage of circular disks confined by planar walls and models the forces and motions of the particles within this assembly. The particles move independently and can interact at contact with others. Two basic bonding models are adopted in PFC2D, viz., a contact-bond model and a parallel-bond model (Itasca Consulting Group, Inc., 2004). Both bonds can be envisioned as a kind of glue joining two particles. The parallel bond model can effectively characterize the transmission of moments between particles and can thus describe the constitutive of cementitious materials such as concrete. However, this model needs more parameters to be calibrated. In the contact bond model, the contact bonds could be envisaged as a pair of elastic springs with constant normal and shear stiffness acting at the contact point. Hazzard and Young (2000) verified the feasibility of the contact bonded particle models to reproduce the mechanical behaviours on different rock types. Thus, PFC2D is a logical choice for modelling the anisotropy and scale effect of shear behaviours.

The aim of the work is to introduce an experimental and numerical investigation of the effect of the joint geometrical parameters of a rock mass on the anisotropy of shear behaviour using PFC2D. First, the effects

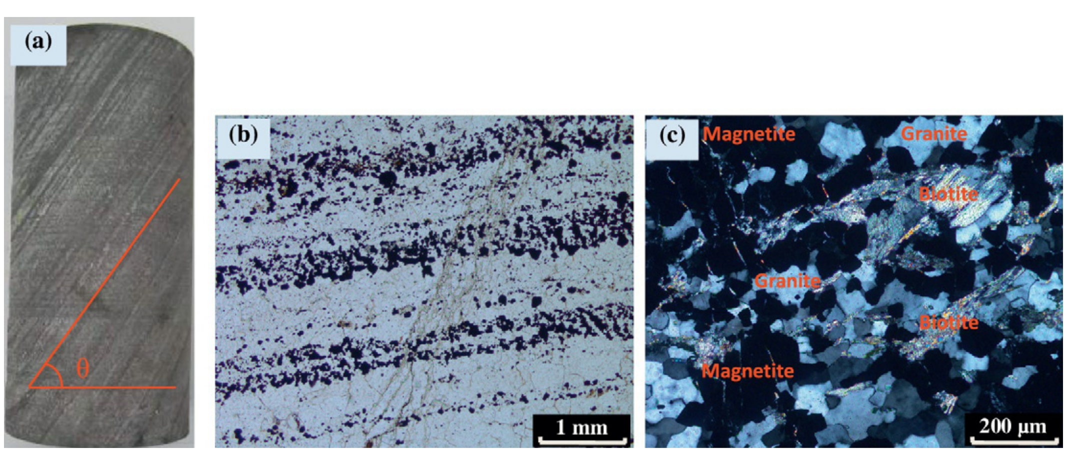

Fig. 2. Cored rock samples and thin sections of layered granulite. (a) is the cored rock samples. (b) and (c) show the thin sections of rocks.