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Mechanical behavior of rock-like jointed blocks with multi-non-persistent joints under uniaxial loading: A particle mechanics approach

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ABSTRACT

By selecting appropriate micro-mechanical parameter values through a trial and error procedure, the computer code PFC^{3D} was used to study the macro-mechanical behavior of jointed blocks having multi-non-persistent joints with high joint density under uniaxial loading. The focus was to study the effect of joint orientation, size and joint mechanical properties on jointed block strength, deformability, stress–strain relation and failure modes at the jointed block level. Both the uniaxial compressive strength of the block, UCS_B, and block deformability modulus, DM_B, were found to depend heavily on the joint dip angle, β, and joint continuity factor, k. The joint particle stiffness was found to play a minor to a significant role on UCS_B depending on β and k values. The joint particle stiffness was found to play a negligible to a moderate role on DM_B depending on β and k values. The jointed blocks produced three types of stress–strain curves labeled as Type I through Type III. A relation seems to exist as explained in Section 4 of the paper between the types of curves and β and k values. The dominance of tensile failures over the shear failures was observed for all three types of curves based on the micro-mechanical parameter values used in the paper. The UCS_B, rate of bond failures and the number of bond breakages were found to decrease as the curve type moves from Type I to Type III through Type II. The jointed blocks resulted in 4 failure modes as follows: (1) splitting failure; (2) plane failure; (3) stepped path and (4) intact material failure. The main features of each failure mode and possible relations between the failure modes, UCS_B and β and k values are given in Section 5 of the paper.

1. Introduction

Most naturally occurring discontinuous rock masses comprise of intact rock interspaced with different types of discontinuities. In civil and mining engineering, the engineers face design and construction tasks associated with geotechnical systems that are in or on discontinuous rock masses. Some examples for such geotechnical systems are tunnels for hydropower and transport, dams, foundations, natural and man-made slopes, surface and underground excavations made for mineral extraction, underground caverns for oil and gas storage and hazardous waste isolation caverns. In these rock engineering systems, one comes across stability concerns of the rock structures. Rock mass strength and deformability play vital roles on stability of these structures. Rock mass strength and deformability depend on the (a) lithology, (b) discontinuity network, (c) geo-mechanical properties of the discontinuities, (d) geo-mechanical properties of the intact rock, (e) in situ stress system and (f) loading/unloading stress paths. A good understanding of rock mass strength and deformability is vital to arrive at safe and economical designs for structures built in and on rock masses. The presence of complicated discontinuity patterns, the inherent statistical nature of their geometrical parameters, and the uncertainties involved in the estimation of their geo-mechanical and geometrical properties and in-situ stress make accurate prediction of rock mass strength and deformability difficult.

Some in-situ tests have been performed to study the effect of size on rock mass compressive strength and deformability (Bieniawski, 1968; Bieniawski and Van Heerden, 1975; Pratt et al., 1972). Heuze (1980) has reviewed the work done prior to 1980 on scale effects on rock mass strength and deformability. The reported results of these investigations clearly show the reduction of rock mass strength and increase of deformability with increasing size up to a certain size, beyond which change becomes insignificant. It is important to note that the relations developed from in-situ tests in the above stated studies primarily depend on the discontinuity network of the tested rock masses. However, unfortunately, in these early investigations, no attempt had been made to map the discontinuity network before subjecting the rock mass to mechanical behavior testing. Therefore, the reported relations are highly site dependent and have qualitative value only.

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Table 1
Micro-mechanical and physical parameter values used for intact particles.

Minimum radius, r_{min} (mm)	0.85
Radius multiplier, λ	1.66
Density, ρ (kg/m^3)	1158.4
Intact particle friction coefficient, μ	0.5
Contact Young's modulus, E_c (GPa)	6
Ratio of intact particle normal to shear stiffness, k_n/k_s	2.5
Intact particle normal bond strength, S_n (MPa)	4.0
Standard deviation of normal bond strength, S_n_sdev (MPa)	0.8
Intact particle shear bond strength, S_s (MPa)	6.4
Standard deviation of shear bond strength, S_s_sdev (MPa)	1.28

Table 2
Comparison between experimental and numerical results for intact material macro-mechanical parameters.

	Experimental results	Numerical results
Uniaxial compressive strength, UCS (MPa)	8.27	8.26
Young's modulus, E (GPa)	4.04	4.03

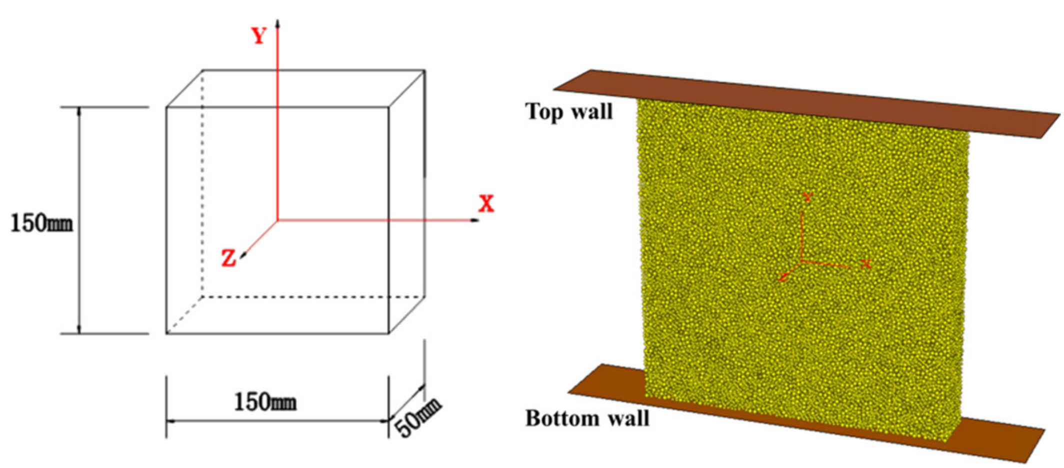
Results of laboratory model studies on rock-like materials (Heuze, 1980; Malama and Kulatilake, 2001; Brown and Trollope, 1970; Ladanyi and Archambault, 1969; Einstein and Hirschfeld, 1973; Chappell, 1974; Kulatilake et al., 1997, 2001a, 2006) show that many different failure modes are possible with jointed rock and that the internal distribution of stresses and strains within a jointed rock mass can be highly complex. Even though these jointed blocks included a significant number of joints, all the included joints were persistent joints. Only a very few experimental studies have been done using a significant number of non-persistent joints (Mughieda, 1997; Prudencio and Van Sint Jan, 2007; Chen et al., 2011, 2012). The mechanical behavior of jointed blocks having a significant number of non-persistent joints is more complicated and significantly different to that having persistent joints. The mechanical behavior depends on the number of joints, joint orientation, size, density, spacing, arrangement and whether the joints are open or closed. It is important to note that as the joint density increases, the behavior around each joint is affected by the presence of the rest of the joints in the jointed block.

Numerical simulations of jointed rock blocks (Kulatilake et al., 2004; Wu and Kulatilake, 2012; Kulatilake and Wu, 2013) based on the finite element method with Goodman's joint element (Goodman et al., 1968) and the distinct element method (Cundall, 1988; Hart et al., 1988) have shown anisotropic, scale dependent mechanical behavior for jointed rock masses. Some investigators have resorted to particle flow codes (PFC^{2D} and PFC^{3D}) (Itasca Consulting Group, 2003; Potyondy, 2007) to model jointed rock behavior under uniaxial loading (Kulatilake et al., 2001b; Koyama and Jing, 2007; Lee and Jeon, 2011; Zhang and Wong, 2012). Kulatilake et al. (2001b) performed research in providing a realistic calibration procedure for micro-mechanical parameters of PFC^{3D} for a contact bonded particle flow model. Using this model they have studied jointed rock behavior of blocks having persistent joints under uniaxial loading. They included spherical particles to model both intact material and joints. In other words they considered closed flaws. Their focus was on macro mechanical behavior of jointed blocks and possible failure modes. Lee and Jeon (2011) and Zhang and Wong (2012) have used PFC^{2D} to study crack initiation, propagation and coalescence using one or two flaws. In their models they have removed particles to simulate open flaws. They have reported about the successes, failures and difficulties they encountered in comparing their PFC results with experimental results. PFC^{3D} allows one to study the mechanical interaction behavior between intact rock and joints incorporating a significant number of joints without making unrealistic assumptions about the surrounding medium around each joint. In addition, it allows failure through both the intact rock and joints under both tensile and shear modes leading to progressive failure which usually occur in jointed blocks having non-persistent joints. Therefore, in this paper, PFC^{3D} is used to study the macro mechanical behavior of jointed blocks having multi-non-persistent joints with high joint density under uniaxial loading. The focus is to study the effect of joint orientation, size and joint mechanical properties on jointed block strength, deformability, stress–strain relation and failure modes at the jointed block level.

2. An introduction to PFC^{3D}, calibration of micro-mechanical parameters and setting up of jointed blocks for numerical simulations

2.1. A brief introduction to PFC^{3D}

PFC^{3D} models the interaction and movement of arbitrarily sized spherical particles by the distinct element method (Itasca Consulting Group, 2003; Potyondy and Cundall, 2004; Potyondy, 2007). A particle generator allows generation of particle radii of a particle assembly according to a uniform or Gaussian distribution. Two types of walls are available: (1) infinite walls, which are planes extending indefinitely in all directions; and (2) finite walls, which are convex tessellations of polygons or special surfaces, such as cylinders and spirals. Finite size boundary walls are used in creating the PFC model in this study. Properties are associated with individual particles or contacts between



(a) Experimental block (b) Numerical block

Fig. 1. Schematics of (a) experimental block and (b) numerical block.