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Experimental and numerical study of asperity degradation in the direct shear test

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ABSTRACT

In this paper, the shear behaviour and mechanisms of asperity degradation of rock joints under direct shear tests were studied using numerical and experimental approaches. PFC2D was used for numerical simulations, in which the intact material is simulated by a dense packing of circular particles bonded together at their contact points and by breakage of these bonds under loading regimes, the damage process is simulated. The joint interfaces were simulated by a newly developed modified smooth joint model in which micro-scale slip surfaces are applied at contacts between particles of upper and lower blocks of the shear box. In order to study the ability of this numerical approach in reproducing the shearing mechanisms and asperity degradation of rock joints in direct shear tests, a comparative study was carried out against the physical experiments. Experimental and numerical direct shear tests were carried out on saw-tooth triangular joints with the base angles of 20° and 30° under different normal stresses. Three shearing mechanisms of sliding, surface wear and asperity shearing off were observed in these experiments. The comparison of the shear behaviour and mechanisms of asperity degradation of physical and numerical experiments showed that the results of numerical models are in good agreement with physical experiments and this numerical approach can reproduce the shear behaviour of rock joints under different loading conditions.

1. Introduction

It is well understood that the mechanical behaviour of jointed rock masses is greatly influenced by the mechanical properties of joints, especially at shallow depths (Singh and Rao, 2005). Joint surface roughness has been recognised as one of the parameters having a significant impact on the mechanical behaviour of joints and numerous researchers have investigated its effect on the shear behaviour of rock joints (Asadollahi and Tonon, 2010; Barton, 1971; Barton and Choubey, 1977; Grasselli, 2001; Grasselli and Egger, 2003; Grasselli et al., 2002; Kulatilake et al., 1995; Ladanyi and Archambault, 1969, 1980; Patton, 1966).

Patton (1966) was among the first who developed a bilinear shear strength model for estimation of the shear strength of rock joints. In this bilinear model, it is assumed that when the applied normal stress σ_n is less than a specific stress σ_T, shear strength τ is controlled by sliding along the joint but when σ_n exceeds σ_T, the shear behaviour is controlled by shearing the asperities. However, in reality sliding and shearing take place simultaneously. Difficulty in determination of the joint cohesion is another shortcoming of this approach (Seidel and Haberfield, 1995). Ladanyi and Archambault (1969) developed a shear strength model, based on the work and energy principles, as follows:

$$\tau = \frac{\sigma_n(1-a_s)\left(\dot{v} + \tan\ \phi_\mu\right) + a_s S_R}{1-(1-a_s)\dot{v}\ \ \tan\ \phi_\mu} \qquad (1)$$

where $\dot{v}$ is the dilation rate, ϕ_μ is the joint friction angle and a_s is the sheared area ratio. S_R is the intact rock strength which was suggested to be estimated by the Fairhurst (1964) intact rock strength criterion, as follows:

$$S_R = \sigma_c \frac{\sqrt{n+1}-1}{n}\left[1 + n\frac{\sigma_n}{\sigma_c}\right]^{0.5} \qquad (2)$$

where σ_c and n are the uniaxial compressive strength and the ratio of tensile to uniaxial compressive strength of the intact rock, respectively. The particular problem in this model is the estimation of a_s and $\dot{v}$. Ladanyi and Archambault (1980), by undertaking a large number of

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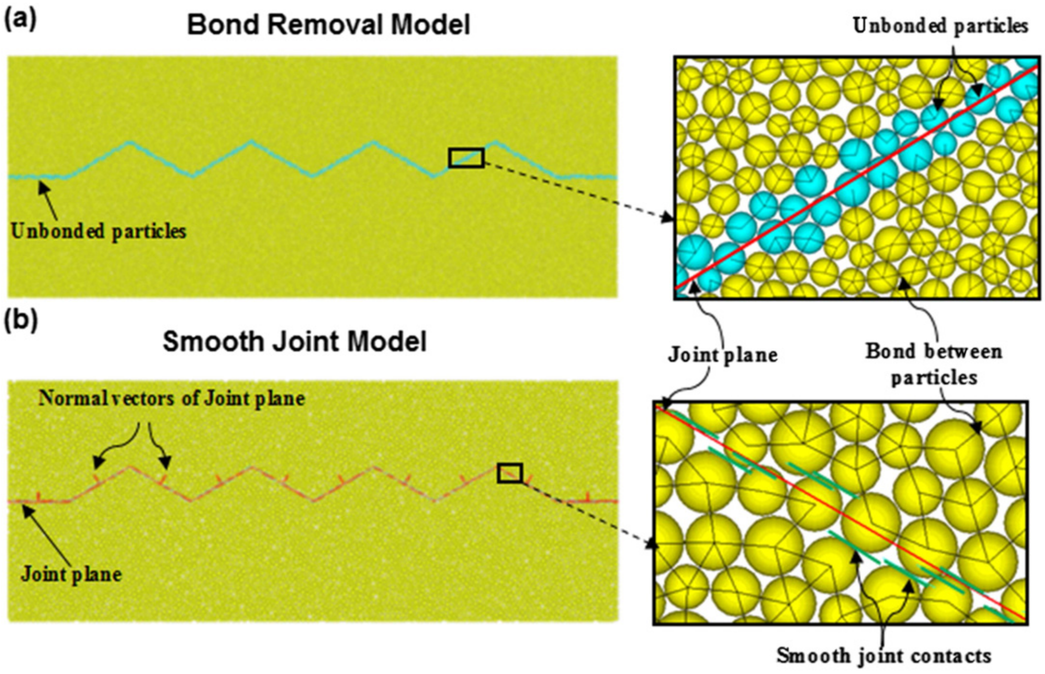

Fig. 1. Numerical simulation of rock joints in PFC: (a) Bond removal method and (b) Smooth joint model.

experimental tests on triangular joints, proposed the following empirical equations for estimation of these parameters.

$$a_s = 1-\left(1-\frac{\sigma_n}{\sigma_T}\right)^{k_1} \tag{3}$$

$$\dot{v} = \left(1-\frac{\sigma_n}{\sigma_T}\right)^{k_2} tan\ \ i \tag{4}$$

where σ_T is the transition stress at which the strength of the rock joint is equal to that of intact rock and *i* is the asperity angle. They proposed the empirical values of 1.5 and 4.0 for the constants of k_1 and k_2, respectively. However, determination of σ_T and *i* are challenging, especially for real irregular rock joints (Kodikara, 1989; Seidel and Haberfield, 1995).

The Barton model (Barton, 1973; Barton and Choubey, 1977) is the most widely used empirical model for estimation of the shear behaviour of rock joints:

$$\tau = \sigma_n\ \ tan\left[JRC\ \ log\left(\frac{JCS}{\sigma_n}\right)+\phi_r\right] \tag{5}$$

where joint roughness coefficient *JRC*, joint compressive strength *JCS* and residual friction angle ϕ_r are the parameters of Barton model. The main

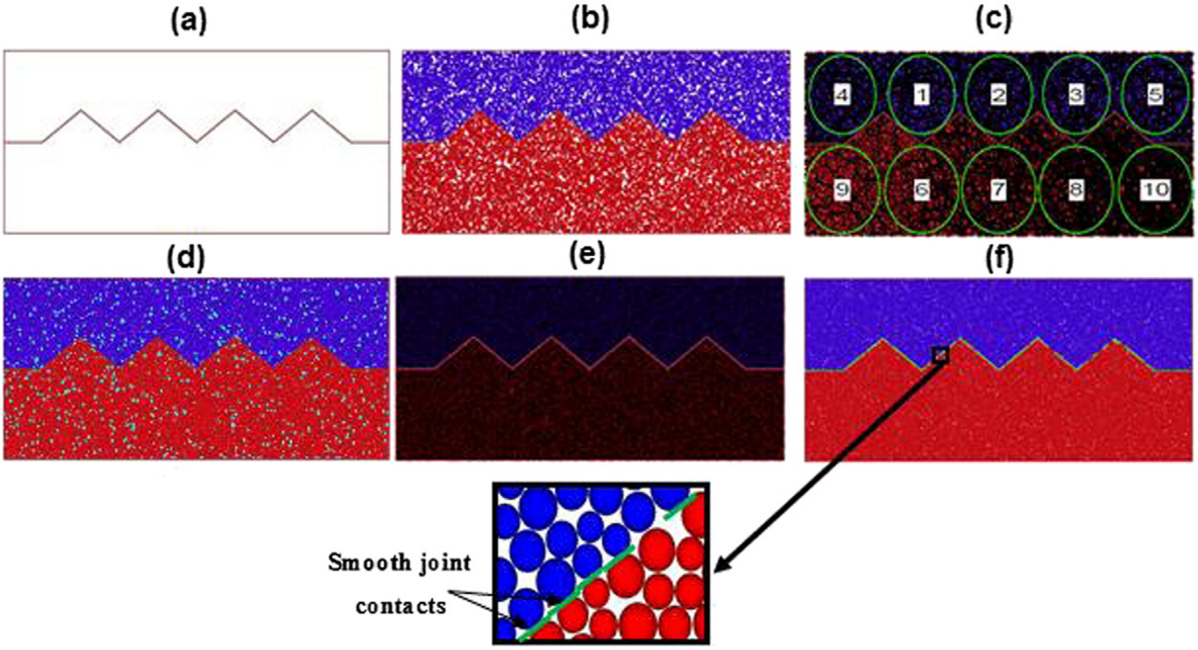

Fig. 2. Procedure of simulation of direct shear test using shear box genesis (a) Vessel generation, (b) Filling up the vessel by randomly placed particles, (c) Application of isotropic stress, (d) Elimination of floaters, (e) Installation of bonds between particles and (f) Application of smooth joint contacts (Bahaaddini et al., 2013a).