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Research Paper

Projected area-based strength estimation for jointed rock masses in triaxial compression

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ABSTRACT

Reliable evaluation of the strength of rock masses is required for failure analysis in rock engineering. This paper describes the failure of rock mass specimens under triaxial compression via numerical testing based on the Discrete Element Method (DEM). It investigates the fracturing phenomena in rock masses with pre-existing joint sets and outlines a simple yet practical method for estimating compressive strength under complex joint geometric and loading conditions. The simulations capture different failure regimes, including intact, sliding and orthogonal failure, as joint geometric parameters are varied. Sensitivity studies demonstrate that the joint orientation, joint radius and continuity factor are essential geometrical terms affecting the material strength. The results reveal a linear relationship between the projected area of joint transections – which is introduced as a proxy to represent the three geometrical parameters – and the vertical strength. Based on this finding, a hypothesis for failure of jointed brittle materials is proposed, prescribing the influence of two factors: the complexity of the joint configuration and the spacing between the sample surface and the joint network. Such an approach, if validated, provides practitioners with a simple method for rapid estimation of compressive strength of rock-like materials via measurements of the joint geometry.

1. Introduction

The main aim of fracture mechanics is to investigate material resistance to fractures. Fractures within rock masses dominate failure processes and the mechanical properties of rock. The lower strength of rock masses as compared with intact rock is caused by the weaker component – joints, the most common discontinuities – transecting the rock into pieces. Understanding the fracture mechanics of rock masses is essential to the design and performance prediction of constructions built in and on rock masses. It has significant effects on mining [1], mineral processing [2,3], civil engineering [4–6] and many other disciplines of science and engineering [7,8]. Although the evidence for complex behaviours of rock masses under loading is overwhelming, the dynamics of rock masses under triaxial compression is still obscure. While it has long been known that fracture networks produce complexity, the propagation of fractures and their influence on the rock strength remain poorly understood.

The complex arrangement of joints makes it extremely difficult to determine the mechanical properties of jointed materials [9]. The mechanical response of rock masses under different applied loads has different sensitivities to various geometrical parameters such as joint persistence, orientation, continuity, etc. [10]. Due to the large number of potential interactions among these parameters, it can prove difficult to quantitatively determine their effect on rock failure and strength.

Applications of current failure criteria in rock strength estimation are not convenient. Usually, practitioners need to identify the discontinuity types using a particular system of rock mass classification and determine the parameter values required by the criterion. During this process, manual errors often arise in rock mass classification, often caused by subjective definitions or a wide value-range for each joint type. Moreover, specific failure criteria can only be used for particular forms of rock conditions from which they were deduced; sometimes being misused beyond their original intended application range [11,12].

Estimating material strength based on the discontinuity geometry enjoys many benefits. Firstly, this approach is objective because the strength assessment is based on measurable properties, which eliminates the manual errors associated with subjective rock mass

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classification. Secondly, the geometry-based strength estimation could be applied to a range of jointed materials; eliminating the need to deduce specific failure criteria for certain materials.

Much effort has been made to reveal the mechanical properties of jointed rocks via laboratory experimentation and numerical simulation. Effects of persistent joints on the material properties have been widely studied in the literature [13–17]. However, understanding of the behaviour of non-persistent jointed materials is limited. Although, some scholars demonstrate the influence of the joint geometry on material features [18–21,10], most specimens used in these studies are thin slices which lead to results similar to those obtained in a 2D environment.

Although laboratory experiments have been broadly used to understand the complex mechanical features of rock masses, they are difficult to assemble and conduct. Preparing specimens with artificial joints is challenging. Furthermore, the direct observation and measurement of fracturing phenomena within most materials is laborious due to the rapidity of crack propagation and physical opaqueness. Also, stress field perturbations caused by sample grips or boundaries cannot be ignored. Equipment use, experiment configurations and sample preparation are also relatively costly. In all, current practical impediments limit data acquisition for analysis of the failure behaviour of jointed rock masses.

Numerical modelling, on the other hand, overcomes the shortcomings of laboratory experiments and provides an alternative avenue to reveal the insights into the factors governing the strength and fracturing response of jointed rock masses. Numerical methods permit direct observation and measurement of fracturing phenomena with systematically varying parameters. In addition, simulations provide adequate flexibility in dealing with complex material features involving inhomogeneity, anisotropy and boundary conditions [22]. Moreover, the cost of conducting numerical studies is negligible compared with corresponding laboratory tests.

Herein, a bonded particle model is employed to investigate deformation processes in jointed material under triaxial compression. The DEM enables simulation of unconstrained nucleation and propagation of cracks and can model complicated material features such as heterogeneities and voids without prohibitive increases in computational complexity [23].

2. Numerical method and model arrangements

2.1. Discrete element method

The DEM is a numerical technique used to simulate the behaviour of composite materials formed mainly of granular components, wherein the specimen macroscopic behaviour is depicted as an assembly of microscopic motions of individual particles [24,25]. The force interactions on and between discrete elements depend upon the particular physical scenario to be simulated. Simulations herein were performed using ESyS-Particle (https://launchpad.net/esys-particle), a general-purpose and open-source DEM software package.

ESyS-Particle represents the solid material as an assembly of discrete spherical particles linked to adjacent particles with bonds that are spring-like connections. The macroscopic properties of the DEM specimen are governed by the micromechanical parameters regulating the strength and elasticity of bonds [26]. When the specimen deforms under external loading, individual bonded interactions break when the accumulated stress within the interaction exceeds a limitation governed by a prescribed failure criterion. These interactions, subsequently, are replaced with repulsive frictional interactions, simulating crack onset and subsequent frictional sliding. This approach has proven to be suitable for modelling deformation processes in brittle discontinuous materials subjected to a variety of external loading conditions.

2.2. Particle interactions and loading mechanisms

The interactions between two adjacent DEM particles involve six degrees of freedoms – tension, compression, shearing, torsion and bending – which can be expressed by four Hookean elastic interactions; under the isotropic assumption for shearing and bending deformation [26]. The failure of such elastic beam interactions is governed by a generalized Mohr-Coulomb failure criterion:

$$\sigma_s \geqslant c + \sigma_N \tan\theta, \tag{1}$$

where σ_s and σ_N are the shear and normal stress within the elastic beam; c and θ are respectively the cohesion and the friction angle of the interaction. The bond adjoining particles i and j breaks forming a macroscopic fracture surface. The normal stress (σ_N; positive under tension) and shear stress (σ_s) are computed in each time step as follows

$$\sigma_N = \frac{F_N}{A} + \frac{|M_B|}{I} R_{ij}, \tag{2}$$

$$\sigma_s = \frac{|F_S|}{A} + \frac{|M_T|}{J} R_{ij}, \tag{3}$$

where F_N and F_S mean normal force and shear force between the particle i and j, M_B and M_T represent bending moment and torsion moment, A, I and J denote cross-sectional area, moment of inertia and polar moment of inertia of the interaction, and R_{ij} is the half length between the two centers of the adjacent particles i and j.

Six rigid platens are placed and bonded to the six surfaces of cubic samples to apply boundary forces. Compression or tension within the DEM specimen is generated by platen movement towards or away from the specimens respectively. For simulations of triaxial compression tests, six platens initially accelerate uniformly to a prescribed stress. The four lateral platens thereafter maintain the compression stress at a prescribed value via a servo control mechanism. The two platens atop and below the specimen continue the compression at a constant rate until the specimen fails macroscopically.

2.3. Model description

2.3.1. Intact rock

A rock mass usually comprises intact rock pieces transected by discontinuity planes. Via a geometrical space-filling sphere packing algorithm, around 110,000 non-overlapping spheres are packed into a 30 mm × 30 mm × 30 mm cubic region with beveled edges, as shown in Fig. 1. The radii of spheres range between $r_{min} = 0.2$ mm and $r_{max} = 0.6$ mm. Microscopic model parameters for this specimen are listed in Table 1. The uniaxial compressive strength of the intact specimen is $\sigma_U = 127.71$ MPa, measured via simulations with zero lateral stress.

For the simulation of triaxial compression, the samples are compressed vertically and laterally by six movable platens. During the simulations, the six platens are initially moved with a stress increasing linearly for 20,000 time steps. After that the four lateral platens are fixed at a stress of 22.68 MPa and the top and below platens vertically compress specimens with a constant velocity.

2.3.2. Joint configuration

A conceptual model is used to represent a non-ubiquitous rock mass with a single joint set distributed fracture network (DFN) [27,28]. All joints are penny-shaped and non-persistent. The geometrical parameters of the joint system follow the definition by Prudencio and Van Sint Jan [21]. β is the joint orientation relative to the σ_1-direction; γ is the joint step angle; α is the joint tip to tip angle; r is the radius of the penny-shaped joint; L_r is the length of the rock bridge; d is the spacing between joint layers. Additionally, L_b is the boundary spacing between the specimen surface and the joint network and n_j is the number of joint layers. The continuity factor k represents the ratio of the joint