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Technical Note

Discrete element modeling of anisotropic rock under Brazilian test conditions

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1. Introduction

Anisotropy is one of the most distinct features that must be taken into account in rock engineering as many rocks exposed near the Earth's surface show well-defined fabric elements in terms of bedding, stratification, layering, foliation, fissuring or jointing. Such rocks are said to be inherently anisotropic as their properties (physical, mechanical and hydraulic) vary with direction. Rock anisotropy affects different geotechnical operations like rock cutting performance, hydraulic fracture propagation in shale reservoirs, and development of excavation-induced damage around underground structures.[1] Therefore, an accurate understanding of anisotropic properties is required for the design and construction of related rock engineering projects.

Among the many mechanical parameters, tensile strength is a key one because rocks are in nature much weaker in tension than in compression. Many rock mechanics applications like stability of underground excavations, rate of rock blasting and propagation of hydraulic fractures are highly dependent on the tensile strength. The Brazilian tensile test (diametrical compression of circular discs)[2] has been widely adopted in laboratory to determine the tensile strength of rock materials.[3–7] The effect of anisotropy on the mechanical responses of rock discs under Brazilian test conditions has been investigated by various approaches.

The theoretical relation between stresses and strains within a disc of anisotropic material under diametrical loading was proposed by Lekhinitskii.[8] Based on this solution, Amadei et al.[9] presented a comprehensive analytical solution to measure the tensile strength of anisotropic rocks. Chen et al.[10] presented an analytical procedure to determine the deformability and tensile strength of anisotropic rocks from the results of Brazilian tests. However, this solution is implicit and numerical techniques are needed to calculate the stress field.

In the laboratory, the effect of anisotropy on the indirect tensile strength and failure patterns under diametrical loading conditions has been investigated by conducting Brazilian tests on various types of rocks.[11–15] In general, the failure of anisotropic rocks under diametrical compression is very complex in terms of fracture mode and direction. Vervoort et al.[16] generalized the experimental results of nine different anisotropic rocks into four trends of the Brazilian tensile strength (BTS) which are normalized by the strength for loading perpendicularly to weak planes versus anisotropy angles as illustrated in Fig. 1.

- Trend 1: constant value over the entire anisotropy angles (Fig. 1(a));
- Trend 2: constant value between 0° and 45°, followed by a linear decrease (Fig. 1(b));
- Trend 3: systematic decrease of Brazilian tensile strength over the entire interval (Fig. 1(c));
- Trend 4: decrease of strength from very low anisotropy angles (between 0° and 30–40°) and followed by a leveling off (Fig. 1(d)).

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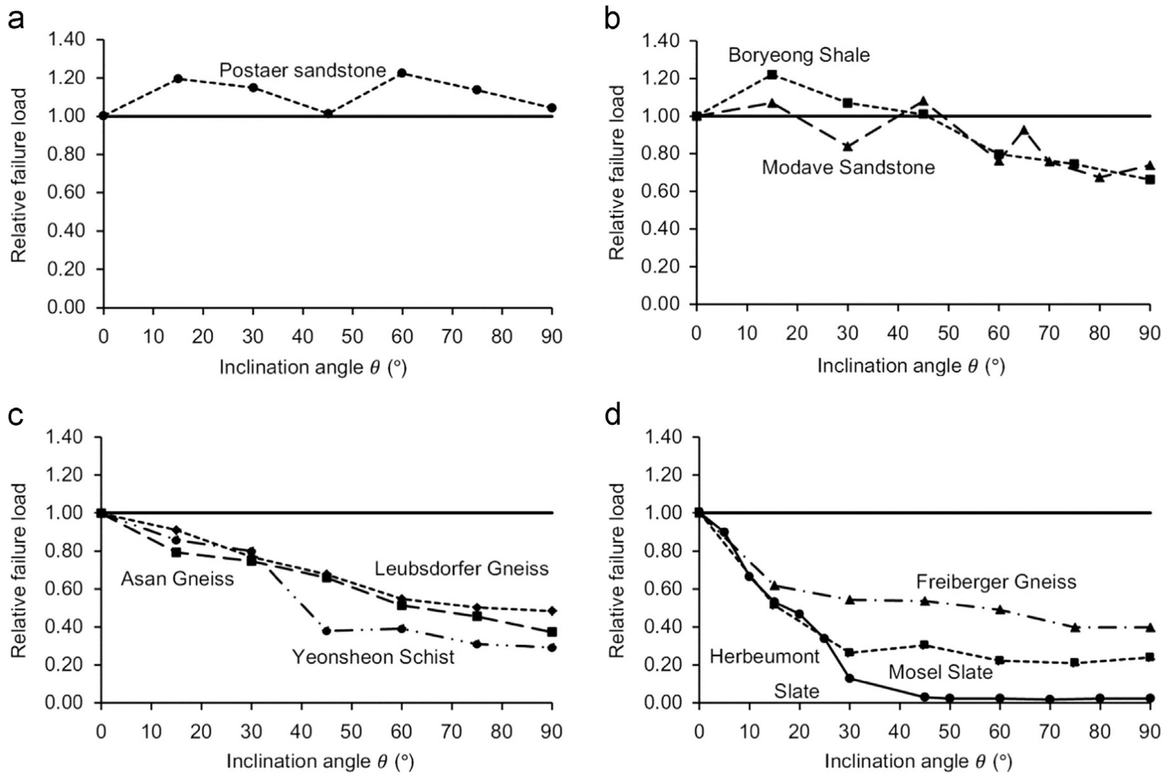

Fig. 1. Variation of average failure load, relative to the failure load for loading perpendicular to weak planes (a) trend 1; (b) trend 2; (c) trend 3; and (d) trend 4.[16]

The fracture types along the weak layers and inside rock matrix were also investigated for these four different trends in Ref. 16. However, possible important parameters (including the strength of weak layers, ratio between tensile strength and cohesion, and anisotropic Young's modulus) and the ways in which they can affect variations of strength and fractures were not investigated in detail.

Numerical simulations have been performed to understand the crack initiation and propagation process of anisotropic rocks. The anisotropic mechanical behaviors of Opalinus Clay in Brazilian test and compression test have been studied through combined finite-discrete element method (FEM/DEM).[17,18] In this model, a transversely isotropic elastic constitutive law was implemented to describe the elastic response, while DEM algorithms and non-linear fracture mechanics principles were employed to capture rock fracturing. The fracture behavior of slate rock has been modeled in Ref. 19 based on two-dimensional discrete element (UDEC) where the schistosity is conceptualized as a set of parallel continuous weak layers. Most recently, the particle based DEM was adopted to simulate the behaviors of transversely isotropic rock by employing also continuous smooth joints to represent weak planes.[20] However, with careful examination of microstructure of intact anisotropic rocks such as sedimentary or metamorphic rocks, the inherently anisotropy is not necessarily be straight and continuous at microscopic scale.[13] Therefore, there is a challenge to develop a more realistic numerical approach to explicitly represent the existence of weak layers in micro-scale.

In this study, a new numerical approach is proposed to represent the weak layers in inherently anisotropic rocks more realistically.[21] The effect of strength, stiffness and number of weak layers with different loading direction will be examined in detail. The numerical results are compared with previous experimental results quantitatively and failure mode and fracture direction are investigated. The numerical simulations link the strength anisotropy, deformation behaviors and fracture patterns on sample scale to the micro-properties of weak layers.

2. Numerical methodologies

DEM has been successfully used in modeling the behaviors of rocks under different stress conditions.[22–27] Moreover, DEM models provide an avenue to investigate the effect of microscopic properties on the macro-scale response, like role of grain interlocking on strength,[28] effect of porosity on the deformability and strength,[29,30] effect of pore size and pore distribution.[31] The advantage of DEM over other continuum methods is its ability to explicitly model the initiation and propagation of cracks from micro-scale to macro-scale without applying complex constitutive laws.[32] In this study, DEM models will be generated to represent inherently anisotropic rocks based on the bonded particle model (BPM) and smooth-joint model provided by PFC2D.[33] Here, a brief introduction of these two models is provided.

2.1. The bonded particle model (BPM)

In PFC models, rock is represented as an assembly of discs (2D) or particles (3D) bonded at their contacts.[22] These discrete elements can move with respect to each other and the bonds between them can break once the stress induced by applied load exceeds the corresponding bond strength. Once a bond fails, the stress will be redistributed which may further induce new bond breakage. In this way, meso- or macro-fracture can form as coalescences of micro-cracks.

Detailed introduction of the algorithm and related force-displacement relationship for BPM can be found in Ref. 33. The