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Hydro-mechanical behavior of sandstone with interconnected joints under undrained conditions

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In rock masses containing multiple joint sets the joints will intersect. The geometric nature of such joint intersections can influence the hydro-mechanical response of jointed rock. An undrained experimental study was performed on fully-saturated, doubly-jointed sandstone specimens. Testing considered a variety of joint orientations and interconnected joint configurations, and various values of confining and initial pore-water pressure. Test results revealed three failure mechanisms: (1) shearing (through intact material); (2) crushing failure in the vicinity of the joint junction point (with associated sliding on joints), and (3) sliding along a preferred joint plane. Using these results, a 'failure mode matrix' was developed to assist in prediction of failure mechanisms for different joint angles and intersection configurations, at different confining pressures. Greater peak induced pore-water pressures were observed for symmetric interconnected joint configurations than skew-symmetric configurations, for all confining pressures, though the difference was significantly more pronounced at higher confining pressures. Greatest peak strength values were obtained for joint geometries in which both interconnected joints were at a low angle. When both joint angles were greater than the friction angle of the joints, peak strength did not show a noteworthy difference between symmetric and skew-symmetric joint configurations for relatively low confining pressures. However, at higher confining pressures, skew-symmetric joint configurations showed considerably higher peak strength than symmetric joint configurations. These behaviors were attributed to differences in failure mechanism (between symmetric and skew-symmetric specimens) and the influence of failure mechanism and confining pressure on end friction and specimen response.

1. Introduction

Rock masses are often highly heterogeneous, owing to the presence of discontinuities (i.e. joints) within them. Joints form the weakest component of rock masses (i.e. are weaker than the intact rock bridges they intersect) and thus their presence can result in a marked decrease in the strength of a rock mass (Terzaghi, 1965; Hoek, 1983). The degree of this strength reduction, and the effects of joints on other mechanical properties of rock, is influenced by the mechanical (cohesion, friction angle, etc.) and geometrical (orientation relative to loading direction, persistence, degree of interconnectivity, surface roughness, etc.) properties of the joints.

Laboratory testing approaches are widely used to determine design properties required for engineering projects in rock, including open-pit mines, road and rail cuttings, tunnels, rock caverns, etc. However, joints in rock in the field are often too large and too numerous for a representative sample of the jointed rock mass to be obtained for the purpose of laboratory testing (Min and Jing, 2003, Esmaieli et al., 2010, Oda, 1988, Kulatilake et al., 1994). In other words, the specimen dimension required for full characterization of the pattern and distribution of macro-scale joints within a rock mass is generally too large to be considered for laboratory testing. Therefore, it is common practice for laboratory experiments to use rock specimens containing only one or two (or rarely more than three) typical joints/joint sets. The results obtained from such testing are generally extrapolated to larger rock volumes using numerical modelling approaches (e.g. Marache et al., 2008).

In jointed rocks, the deformation behavior of the rock mass can be heavily influenced by joint configuration. There are three scenarios of interest regarding the influence of joints on the mechanical behavior of rock: (1) two or more joints/joint sets occur; (2) only one joint/joint set occurs, or (3) the rock mass is entirely intact. For Scenario 1, above, the nature of interconnectivity of the various joints/joint sets will affect overall rock mass behavior.

Joints in heavily jointed rock masses often intersect. Intersecting joints/joint sets can take one of two broad patterns, with each defined by the relative orientation of the two intersecting joints/joint sets when viewed in 2D. When the orientation of the joints/joint sets are such that both have the same dip (from the horizontal), but different

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dip directions, the interconnectivity is termed symmetric (Fig. 1). When the intersecting joints/joint sets have different dips, the interconnectivity is termed skew-symmetric (Fig. 1). Two intersecting, fully-persistent joints will delineate four discrete blocks. One edge of each of these blocks will meet at the 'joint junction point'. Throughout this manuscript we denote this edge as the 'tip' of the block.

A thorough understanding of the expected mechanical response of rock to loading under intact, singly- and multiply-jointed rock scenarios (including the two scenarios depicted in Fig. 1) is extremely important for the design of rock structures. Moreover, deformation of rock can be simulated under one of two hydrogeological conditions (drained or undrained). Under drained conditions, liberal movement of pore water within the rock mass will allow dissipation of pore-water pressures that would otherwise develop during loading (i.e. pore-water pressure remains constant during loading). Under undrained conditions, movement of pore water within the rock mass is restricted (and total volume of pore water is fixed during deformation), such that pore-water pressures are able to fluctuate in response to loading. In general, permeable rocks undergo drained deformation. However, when the boundaries of a permeable rock mass are sealed, their deformation response may be better characterized by the undrained scenario. In jointed rocks with low permeability in the intact rock bridges, fluid flow will occur predominantly through joints, and thus sealing of joints (with infill, cement, etc.) can also lead to undrained conditions. In situations where saturated rock is subjected to dynamic loading (such as earthquakes) undrained conditions may also be expected, because stress changes occur at such a rapid rate that the pressures that develop cannot be effectively dissipated by porous flow. In addition, man-made alterations to rock masses (e.g. shotcreting of rock surfaces without provision of adequate drainage, etc.) can produce undrained conditions for rock deformation. It is clear that undrained conditions can occur in several situations of interest for understanding of rock response, from the point of view of both the engineer and geologist.

This paper investigates the effect of joint interconnectivity on the hydro-mechanical properties of rock, through simulation of undrained triaxial conditions in the laboratory. The section that follows briefly highlights some important outcomes of previous studies relevant to jointed rock mass behavior with interconnected rock joints. Following the brief literature review, details are provided on experimental method and results, and the potential origins of the observed behaviors and implications for engineering/geology are discussed. The experimental work presented in this manuscript does not capture the character of every multiply-jointed rock likely to be encountered by the engineer/geologist, and nor does it claim to (no single experimental study could). The purpose of this experimental study is to produce results that may one day inform numerical models capable of reproducing

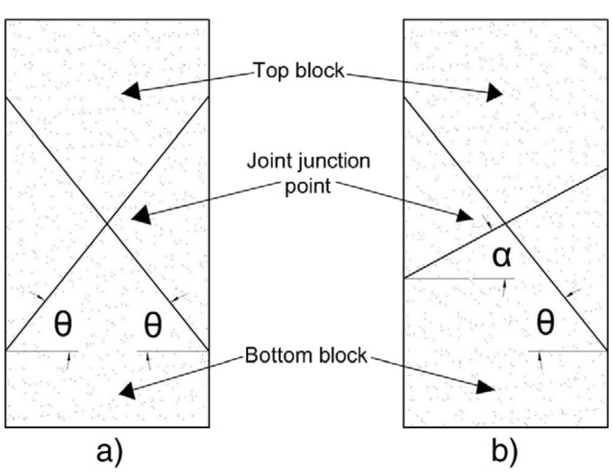

Fig. 1. Joint configurations for a doubly-jointed specimen with (a) symmetric interconnectivity, and (b) skew-symmetric interconnectivity.

large-scale mechanical behavior of jointed rock, or constitutive equations used in engineering design. Such numerical models/constitutive relationships offer a flexible platform for field-scale characterization of the expected mechanical response of jointed rock.

2. Previous studies

The mechanical behavior of jointed rock has been a topic of research for many decades (e.g. Brown and Trollope, 1970; Sheorey et al., 1989; Reik and Zacas, 1978; Jaeger, 1959; Xu et al., 2013; Wasantha et al., 2014a) and numerous experimental studies have addressed the effect of joint orientation on the strength of rock containing a single joint, or joint set, under both unconfined and confined conditions (e.g. Singh et al., 2002; Kumar and Das, 2005; Ranjith et al., 2004; Yang et al., 1998; Tiwari and Rao, 2004; Asef and Reddish, 2002; Ramamurthy and Arora, 1994; Einstein and Hirschfeld, 1973; McLamore and Gray, 1967; Ladanyi and Archambault, 1972; Wasantha et al., 2014b). The results of these studies have generally been consistent with sliding plane of weakness theory, which is summarized in 2D (in the plane perpendicular to the intermediate principal stress) in Eq. (1) (Jaeger et al., 2007).

$$\sigma_1 = \sigma_3 + \frac{2(S_w + \mu_w \sigma_3)}{(1-\mu_w \cot\beta)\sin 2\beta} \tag{1}$$

Where, σ_1 is the major principle stress, σ_3 is the minor principal stress, S_w is joint cohesion, μ_w is joint friction coefficient ($\mu_w = \tan\phi_w$, where ϕ_w is the joint friction angle) and β is joint orientation measured from the minor principal stress direction.

Though many studies have been carried out for rock with a single joint or joint set, a few studies have considered rock masses with multiple, interconnected joints/joint sets (e.g. Yang et al., 1998; Kulatilake et al., 2001; Chong et al., 2013).

Yang et al. (1998) tested rectangular prismatic specimens made of a plaster–sand mixture that contained rough joint sets in systematically varying orientations across the specimen set. Their specimens were 125 × 100 × 300 mm in size and specimens with two and three joint sets were considered (Fig. 2). Their testing considered only uniaxial compression. Eight different combinations of interconnected joint set orientations were used, of which five considered symmetric interconnectivity (i.e. 0°/90°, 15°/−15°, 30°/−30°, 40°/−40°, 45°/−45°, 60°/−60°, 15°/−30°, 15°/−45°). They identified three different failure modes from the results of testing with two joint sets, which were observed to relate to orientation of the joint set. These were: splitting (for joint orientations of 0°–30° and 90°), sliding (for joint orientations of 50°–75°) and mixed (for joint orientations of 40°–45°). For the specimens with multiple interconnected joint sets (i.e. with three joint sets) and symmetric interconnectivity, they observed that compressive strength was similar to the strength of specimens containing only two joint sets at corresponding orientations, for tests in which specimen failure occurred by splitting or sliding. For splitting failure, they postulated that failure is controlled by intact material properties. For sliding failure, they suggested that interaction between joint sets was negligible. On the other hand, for specimens that displayed mixed mode failure, they observed an appreciable strength reduction when three joint sets (two of them symmetrically interconnected) were considered rather than two. They considered this strength reduction to be related to greater interaction between joint sets for the specimen with more joint sets. For specimens with skew-symmetric interconnectivity, Yang et al. (1998) found that if all joint sets in a doubly-jointed specimen had orientation for which sliding could not occur (i.e. failure must occur by splitting), the strength obtained was not different to that for the doubly-jointed specimens with symmetric connectivity, or the specimens with three joint sets. However, if the angle of at least one joint set allowed mixed mode failure (i.e. was 40°–45°), the strength was lower than that for specimens with two joint sets at 40°–45° and