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Assessing the ability of rock masses to support block breakage at the TBM cutter face ☆

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ABSTRACT

In order for tunnel boring machines to efficiently cut or break rock, it is necessary that the block of rock in contact with the cutter be adequately supported by the surrounding rock mass. This support is provided by the interlocking of blocks and the friction of the surfaces. If blocks are inadequately supported or become free without breakage the result can be jamming at the TBM face. Such blocky ground conditions are typically assessed according to the spacing and orientation of discontinuities (including joints) within the rock mass, typically using a rock mass classification system. In laboratory tests on cuttability or abrasivity of rocks, test samples are typically supported securely in a frame or jig. Numerical models of rock breakage also assume boundary conditions in which the sample is completely supported. Therefore the applicability of the results from laboratory and numerical studies depends on the same degree of support of blocks in the ground. The conditions required to adequately support a block for breakage are investigated and related to rock mass parameters, in particular, the three-dimensional patterns of discontinuities. A rock mass can be capable of providing adequate support to a block of rock such that the cuttability is adequately described by conventional methods. However, there are some rock mass conditions where support of blocks is not well developed, potentially resulting in otherwise unexpected poor TBM progress or jamming of TBM with loose blocks. Three-dimensional discontinuity patterns can be assessed using stereographic methods or borehole (α–β) methods. It is proposed that problematic conditions may occur where: two or more oblique (α between 20° and 70°) discontinuity sets are present (and over-represented relative to a uniform distribution); one or more of these discontinuity sets are dipping into the opening ($\beta = 180° \pm 90°$) and additional discontinuities (in sets or randomly oriented) are present to form complete tetrahedral wedge blocks.

1. Introduction

Blocky and raveling ground conditions have been recognised as potentially difficult ground for excavation by TBM (e.g. Zhao et al., 2007). The presence of joints and other discontinuities that can form blocky ground can be identified by conducting rock mass characterization, in particular, by recording the spacing and orientation of discontinuities (Gong and Zhao, 2009). A range of interactions of joint patterns and stress conditions have been identified as relating to deformation mechanisms at a TBM face including buckling and sliding (Delisio et al., 2013).

Laboratory tests used to assess resistance of rock to excavation by TBM are conducted on well constrained samples (Chang et al., 2006; Gertsch et al., 2007; Acaroglu et al., 2008). Laboratory testing of cutter effectiveness has become increasingly sophisticated, but understandably continues to require well constrained test samples (Cho et al., 2010, 2013; Moon and Oh, 2012; Balci and Tumac, 2012; Zhang et al., 2012a,b). Data derived from these tests is then commonly used in models of cutter wear (Wang et al., 2012a,b; Zhou and Lin, 2013).

Research into controls on TBM penetration rate has included the orientation of discontinuities (Hamidi et al., 2010; Bejari and Hamidi, 2013; Delisio and Zhao, 2014). That research investigated the orientation of a single set of discontinuities. The orientation of a discontinuity is defined by the angle α between the tunnel axis and the discontinuity surface, such that a discontinuity perpendicular to the tunnel axis has an α value of 90°. Multiple sets of discontinuities are typically assessed by identifying a critical discontinuity for the analysis. The critical discontinuity would be the one most likely to cause problems for the excavation due to its orientation or other characteristics. This approach is common in rock mass classification methods of stability analysis

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Fig. 1. TBM heading face with blocky rock mass which appears to have moved on discontinuities (arrow) after boring. Image courtesy of The Robbins Company (Home, 2009).

(Bieniawski, 1989; Barton, 2000). Calculation of average α values from a population of discontinuity orientations has also been used (Hamidi et al., 2010). Numerical modelling studies have shown that, in general, oblique discontinuities can be the most favourable for TBM penetration (e.g. Hamidi et al., 2010). Models of rock mass strength account for discontinuities but typically assume an isotropic distribution of discontinuity orientations (Hoek and Brown, 1997; Zhao and Cai, 2010). More complex treatments of multiple discontinuity orientations have typically been applied to an analysis of the perimeter walls of a tunnel (Jiang et al., 2006; Ramoni and Anagnostou, 2010; Wang et al., 2012a,b) or cavern faces (Zhang et al., 2012a,b) but less commonly in studies of TBM cutter face processes.

A review of large diameter TBM face stability concluded that "In all but homogeneous sedimentary formations, there is a very high degree of rock fallout at the face... Small to large blocks of rock are wedged out, causing openings or voids culminating in larger blocks and larger voids... As the diameter increases, the increase in face fallout goes up exponentially" (Home, 2009, p. 2.4, Fig. 1).

2. Support of blocks during breakage

The breaking of rock by direct impact requires the ability to transmit force into the rock. It is not sufficient simply to apply the force from the cutting tool to a block of rock, it is equally necessary that the block is held in a secure manner to generate sufficient stress to cause breakage. Without such support the block is liable to move rather than break as was intended. The stability of blocks in a rock mass will be affected by the spacing of the discontinuities, the orientation of the block faces relative to the applied force and the in situ and excavation-induced stress conditions in the rock mass. These factors and their combination have influence on the behavior of a block of rock as it is impacted by a TBM cutter (Table 1). The effectiveness of TBM cutters has typically been considered in terms of breaking intact rock without reference to discontinuities (Fig. 2A) or with reference to the influence of only a single discontinuity set (Fig. 2B). The common occurrence of multiple discontinuity sets is generally appreciated but is yet to be fully integrated into TBM penetration assessments. This paper highlights one aspect of the influence that multiple discontinuity sets have on rock breakage by TBM cutters. An example data set is used to illustrate three-dimensional discontinuity patterns.

3. Orientation of multiple discontinuity sets

3.1. Stereographic method

The stereographic method is commonly used to represent discontinuity orientations (e.g. Holcombe, 2014). Structural discontinuity surfaces such as bedding, joints, foliations and faults can be represented as points on the stereograph. Each point, known as a pole, marks the orientation of the plane perpendicular to the marked pole (e.g. Holcombe, 2014). Contouring of the poles allows identification of clusters with similar orientations known as sets (e.g. Fig. 3, Table 2). In the example data, the dominant orientation is Set 1 which is approximately vertical and strikes northwest–southeast. The second most prevalent orientation is Set 2 which dips moderately toward the southeast. A third concentration is present which is Set 3 oriented with a gentle dip to the west. Set 4 dips moderately toward the northeast. Other orientations are present and the occurrence of "random" discontinuities not belonging to the dominant sets should not be ignored.

The stereograph in Fig. 3 has also been labelled with some zones (small circles) according to the orientation relative to the tunnel axis. The actual distribution of discontinuities within a given range of orientations can be compared to a uniform distribution by using spherical geometry:

$$A = 2\pi(1 - \cos\theta) \quad (1)$$

where A is the area on a spherical surface and θ is the angle of a cone relative to its axis.

A small circle (a cone in three-dimensions) with an angle of 20° from the tunnel axis is shown on the stereograph (Fig. 3). Any pole within this small circle represents a discontinuity plane which is within 20° of the tunnel face (i.e., the plane is perpendicular to

Table 1
Summary of factors influencing support of a block during cutter impact.

Characteristic	May promote block breakage	May inhibit block breakage	Potential for difficult ground
Spacing of discontinuities/size of blocks	Wide spacing/large blocks	Close spacing/small blocks	Blocks too large for TBM but small enough to come loose. Blocks may unravel or self-cave from face without adequate breakage
Orientation of block interfaces relative to applied force	Perpendicular to line of force	Oblique to line of force (sensitive to friction of interface)	Applied force causes sliding on discontinuity not breakage
Friction on block interfaces	High friction	Low friction	Blocks slide away from cutter force on low friction interfaces
Stress in rock mass	High confining stress on favourably oriented discontinuities	High confining stress on unfavourably oriented discontinuities or low confining stress	Blocks undergo slow displacement (squeezing) or rapid displacement such as ravelling or self-caving from face
Combined	Orientation and friction of discontinuities is favourable to holding blocks of a suitable size for loading to breakage	Orientation and friction of discontinuities is unfavourable to holding blocks of a suitable size for loading to breakage	Unstable wedges formed by multiple discontinuities