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Tunnel reinforcement in columnar jointed basalts: The role of rock mass anisotropy

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ABSTRACT

The extent of the loosening zone in tunnels excavated through columnar jointed basalts is studied with the numerical discontinuous deformation analysis (DDA) method. The structure of the rock mass and tunnel geometry are modeled on the basis of a real field case study of deep tunneling performed in such a rock mass in south west China. Slender prismatic keyblocks formed by the intersection of broadly-spaced, gently-dipping breccia layers and closely-spaced, orthogonally oriented, steeply dipping columnar joints result in a highly anisotropic rock mass structure and give rise to sliding and toppling failure modes in the sidewalls and to an excessive height of loosening zone in the roof, the geometry of which is shown to be controlled by the orientation of the steeply inclined columnar joints. Results of displacement monitoring performed during tunnel excavation in a similar rock mass with multiple point borehole extensometers confirm the numerically obtained depth of the loosening zone both in the sidewalls and the roof. We find that the height of the loosening zone in the roof as obtained with DDA is greater than would have been predicted by Terzaghi's empirical rock load classification for "blocky" rock masses, and show that its shape and orientation are controlled by the anisotropy of the rock mass structure. Moreover, we demonstrate that dimensioning rock bolt reinforcement using well-established empirical criteria without consideration of the anisotropic nature of the rock mass may lead to un-conservative design.

1. Introduction

Rock masses consisting of columnar basalts pose difficult challenges to the design of underground mining and excavation operations because of the intensity of the jointing pattern. Typically rock mass structures are characterized by well-defined joint sets (e.g. Hudson and Priest, 1979) each with representative spacing and length distributions (e.g. Priest and Hudson, 1976, 1981; Zhang and Einstein, 1998). The intersections of discrete joints in the rock mass give rise to three dimensional blocks of various shapes and sizes (Kuszmaul, 1999; Shi and Goodman, 1989) the interaction of which can be studied numerically using discrete element approaches such as DEM (Cundall, 1987) or DDA (Shi, 1993). The same is true for rock masses consisting of columnar basalts, but here the mean spacing of the columnar joints is extremely small and their length is constrained by upper and lower boundaries of lava flows (Hetényi et al., 2012), which typically manifest in the field as bedding plane like partings, giving rise to a structure that has been referred to in sedimentary rocks as mechanical layering (Bai and Gross, 1999; Bakun-Mazor et al., 2009; Narr and Suppe, 1991; Ruf et al., 1998). The spacing between the upper and lower lava flow boundaries, or the thickness of a single columnar joint stack (elsewhere referred to as colonnade (Hetényi et al., 2012)), is controlled by the volcanic conditions at time of the eruption but is typically in the order of several meters. The spacing between the columnar joints, however, is typically limited to several to tens of centimeters only (Goehring and Stephen, 2008) with a characteristic homogeneous spacing distribution, giving rise to orderly shaped prisms of a typically pentagonal or hexagonal cross section (Saliba and Jagla, 2003). Since essentially the stacks of columnar joints are bounded between the gently dipping upper and lower boundaries of lava flows (elsewhere referred to as basal and upper breccia layers (see Hetényi et al., 2012)), and are typically oriented normal to those boundaries, the inclination of the

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prismatic blocks tends to be rather steep, causing stability problems around underground openings excavated through such rock masses. An example of steeply inclined columnar joints oriented normal to the boundary planes is shown in Fig. 1. This particular relationship between the columnar joints and the breccia planes gives rise to a highly anisotropic rock mass structure, the tunneling challenges of which are explored in this paper.

In this paper we model the deformation of a rock mass consisting of columnar jointing using the numerical discontinuous deformation analysis (DDA) method (Shi, 1993) with two modifications:

1. Non-reflecting boundaries around the jointed domain are introduced following the recent development of Bao et al. (2012) and initial *in situ* stresses are imposed from the beginning of the numerical simulation, thus allowing us to minimize the size of the modeled domain and focus our analysis near the underground opening.
2. To simulate the response of the rock mass to tunneling as accurately as possible we model the excavation sequence using a recent development that was originally introduced into the numerical manifold method by Tal et al. (2014).

Naturally, in the more mature DEM and certainly in the FEM these modifications have been standard practice for some time, but application of these improvements in DDA is fairly new.

Following introduction of the rock mass structure and considerations in mesh generation, we first demonstrate the application of sequential excavation modeling in DDA and then show the modes of failure and depth of loosening zone that are expected to develop in the sidewalls and roof, respectively. We show that because of the strong rock mass anisotropy, the initial principal stresses rotate after the excavation is formed and become aligned with the orientation of the principal joint sets. This of course controls the shape and orientation of the loosening zone which develops around the opening following the excavation. Our DDA results are validated and confirmed by means of *in situ* displacement monitoring data obtained with multiple point borehole extensometers during tunneling in a similar rock mass structure. Finally, using the bolt element in DDA we test the applicability of the empirical rock bolting guidelines recommended by Lang (1961, 1972) with respect to the required bolt spacing and length.

2. The DDA model

2.1. The modeled rock mass structure

The modeled rock mass structure is based on field mapping performed during tunneling in columnar jointed basalts in south west China. It consists of easterly, gently dipping, breccia planes which are truncated by westerly, steeply dipping, columns of basalts. The axis of tunnel used for analysis in this paper is horizontal trending N–S. This gives rise to the E–W cross section shown in Figs. 2 and 3. The columnar joints and breccia planes are labeled J_1 and J_2 respectively, and the statistical characteristics of each joint set are provided in Table 1. Note that in reality every column is comprised of a polygon of joints as shown in the inset in Fig. 1. Since the analysis here is two dimensional the entire column is treated as a joint set (J_1) which is steeply dipping to the west as it is not possible in a two dimensional approach to represent the polygonal structure of the prisms.

A detail of the block system around the modeled underground opening obtained with the statistical joint trace generation code of DDA is illustrated in Fig. 2. Note the uneven distribution of spacing in both sets due to the applied degree of randomness in the statistical joint trace generation code (see Shi and Goodman, 1989) as detailed in Table 1. Also, note the continuity of the trace lines due to the imposed zero bridge length. Since the mean spacing between the upper and lower breccia planes (J_2) is 5 m and the mean trace length for the columnar joints (J_1) in the cross section is 20 m, all columnar joints are truncated by and terminated against the breccia planes, a structure similar in essence to mechanical layering typically observed in sedimentary rocks (e.g. Narr and Suppe, 1991), although the formation mechanism here

Fig. 1. Steeply inclined columnar joints oriented normal to a breccia plane. In the inset a cross section through the lava flow shows the polygonal geometry of the columns (see Jiang et al., 2014).