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Tunnel roof deflection in blocky rock masses as a function of joint spacing and friction – A parametric study using discontinuous deformation analysis (DDA)

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Abstract

The stability of underground openings excavated in a blocky rock mass was studied using the discontinuous deformation analysis (DDA) method. The focus of the research was a kinematical analysis of the rock deformation as a function of joint spacing and friction. Two different opening geometries were studied: (1) span $B = h_t$; (2) $B = 1.5h_t$; where the opening height was $h_t = 10$ m for both configurations. Fifty individual simulations were performed for different values of joint spacing and friction angle. It was found that the extent of loosening above the excavation was predominantly controlled by the spacing of the joints, and only secondarily by the shear strength. The height of the loosening zone h_r was found to be dependent upon the ratio between joint spacing and excavation span S_j/B: (1) $h_r < 0.56B$ for $S_j/B \leqslant 2/10$; (2) stable arching within the rock mass for $S_j/B \geqslant 3/10$. The results of this study provide explicit correlation between geometrical features of the rock mass, routinely collected during site investigation and excavation, and the expected extent of the loosening zone at the roof, which determines the required support.

Keywords: Roof deflection; Discontinuities; Numeric analysis; DDA

1. Introduction

Most rock masses are discontinuous over a wide range of scales, from macroscopic to microscopic. In sedimentary rocks the two major sources of discontinuities are bedding planes and joints, the intersection of which form the so-called "blocky" rock mass (Terzaghi, 1946).

Excavation of an underground opening in a blocky rock mass disturbs the initial equilibrium, and the stresses in the rock mass tend to readjust until new equilibrium is attained. During readjustment of internal stresses, and consequently rearrangement of load resisting forces, some displacements of rock blocks occurs. Joints and beddings are sources of weakness in the otherwise competent rock mass and therefore large displacements and rotations are only possible across these discontinuities.

Failure occurs when the stresses can no longer readjust to form a stable, load resisting structure. This may occur either when the material strength is exceeded at some locations, or when movements of rock blocks preclude the development of a stable geometric configuration.

Terzaghi (1946) in his rock load classification scheme estimated that for tunnels excavated in stratified rock the maximum expected over-break, if no support is installed, is $0.25B$ to $0.5B$, where B is the tunnel span. For tunnels excavated in moderately jointed rock the maximum expected over break is $0.25B$. For tunnels

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excavated in blocky rock mass the expected over break is $0.25B$ to $1.1(B+h_t)$, where h_t is the height of tunnel, pending on the degree of jointing. However, no particular reference to the mechanical and geometrical properties of the discontinuities was discussed by Terzaghi.

Hatzor and Benary (1988) have used both the classic Voussoir model (Evans, 1941; Beer and Meek, 1982) and the discontinuous deformation analysis (DDA, Shi (1988, 1993)) in back analysis of historic roof collapse in an underground water storage system excavated in a densely jointed rock mass. Hatzor and Benari coined the term "laminated Voussoir beam" for an excavation roof comprised of horizontally bedded and vertically jointed rock mass. Their research showed that: (1) the classic Voussoir model is unconservative for the given rock mass structure; (2) the stability of a laminated Voussoir beam is dictated by the interplay between friction angle along joints and joint spacing.

Lee et al. (2003) showed that when two joint sets are encountered at a tunnel excavation face, the most critical joint combination is when a set of horizontal joints (bedding planes) intersects vertically dipping joints. Furthermore, they have shown that the displacement of a key block at the roof tends to increase as the block size decreases. However, no particular reference to joint spacing or tunnel dimensions is given.

Park (2001) studied the mechanics of rock masses containing inclined joints during tunnel construction using a physical trap door model. Whu et al. (2004) replicated these experiments numerically using DDA, showing very good agreement between the physical and the numerical models. The results of both models showed that the distribution of arching stresses above the opening is a function of joint inclination. Huang et al. (2002) studied the development of stress arches above large caverns and evaluated the effects of different rock bolt types upon the size and shape of the arch.

Broch et al. (1996) stressed out the importance of virgin horizontal stress on the stability of large span openings, up to 65 m, excavated in Norway. However, these high stresses are of tectonic origins which are predominantly active along convergent tectonic boundaries. In areas found at some distance from such boundary, or in different tectonic setting, the magnitude of tectonic stresses is diminished, and the arching stresses are developed due to excavation induced displacements. Which are in most cases structurally controlled.

The main objective of the study presented herein is to investigate the stability of underground openings excavated in horizontally layered and vertically jointed rock masses. The effects of joint spacing and shear resistance along joints on the height of the loosening zone above the excavation are studied using the discrete numerical model of DDA.

The focus of this study is rock mass kinematics, rather than stress distribution. Monitoring of displacements at and behind the excavation face is a routine practice in rock engineering. Displacement measurements are relatively simple comparing to in situ stress measurements, and in most cases is cheaper. Analytical models for displacements around tunnels excavated in a continuous rock-mass (e.g., Sulem et al., 1987) and numerical models for displacements around tunnels excavated in a rock-mass transected by a single fault (e.g., Steindorfer, 1997) are currently available. However, reliable models for displacements around tunnels excavated in a blocky rock-mass are less common, and those that exist still require validation. In this research, we present numerical analysis of displacements at an excavation face as a function of rock mass structure and opening geometry.

2. Outline of DDA theory

The discontinuous deformation analysis, a member of the discrete element models family, was developed by Shi (1988, 1993) for modeling large deformations in blocky rock masses. Shi presented DDA in an explicit matrix form; the following description is rather more general, and is based on recent works by Jing (1998), and Doolin and Sitar (2002).

In DDA the motion of a homogenously deformable discrete element (block) is computed using series expansion of the displacement $U = TD$. For two-dimensional formulation the displacement (u, v) at any point (x, y) in a block can be related to six displacement variables

$$[D] = (u_0 \quad v_0 \quad r_0 \quad \varepsilon_x \quad \varepsilon_y \quad \gamma_{xy})^{\mathrm{T}}, \tag{1}$$

where (u_0, v_0) are the rigid body translations of a specific point (x_0, y_0) within the block, (r_0) is the rotation angle of the block with a rotation center at (x_0, y_0), and ε_x, ε_y and γ_{xy} are the normal and shear strains of the block. Assuming complete first-order approximation of displacement, the expansion term T takes the following explicit form:

$$[T] = \begin{bmatrix} 1 & 0 & -(y-y_0) & (x-x_0) & 0 & (y-y_0)/2 \\ 0 & 1 & (x-x_0) & 0 & (y-y_0) & (x-x_0)/2 \end{bmatrix}. \tag{2}$$

By the second law of thermodynamics, a mechanical system under load must move or deform in the direction that produces the minimum total energy of the system. For a discrete element the energy balance may be written in terms of kinetic energy R and potential energy V:

$$E = R - V = \frac{1}{2}\dot{D}M_0\dot{D} - \Pi(D), \tag{3}$$

where M_0 is the mass matrix quantifying the mass distribution around the center of rotation. Body forces, loads, and displacement constraints are expressed in terms of