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Effect of joint spacing and joint dip on the stress distribution around tunnels using different numerical methods

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ABSTRACT

Different conditions may affect the stability of tunnels by the geometry (spacing and orientation) of joints in the surrounded rock mass. In this study, by comparing the results obtained by the three novel numerical methods i.e. finite element method (Phase2), discrete element method (UDEC) and indirect boundary element method (TFSDDM), the effects of joint spacing and joint dips on the stress distribution around rock tunnels are numerically studied. These comparisons indicate the validity of the stress analyses around circular rock tunnels. These analyses also reveal that for a semi-continuous environment, boundary element method gives more accurate results compared to the results of finite element and distinct element methods. In the indirect boundary element method, the displacements due to joints of different spacing and dips are estimated by using displacement discontinuity (DD) formulations and the total stress distribution around the tunnel are obtained by using fictitious stress (FS) formulations.

1. Introduction

Since tunnels can shorten the routes and pass through valleys, mountains and other difficult geological conditions, they are considered as one of the main ways of transportation in modern life. On the other hand, the stability, economic justification and safety of manmade structures in rocks are of major concerns in all rock engineering projects. Due to complexity of large underground structures, several numerical modeling techniques have been developed for analyzing and getting a better insight into rock mechanics projects. Some progressive efforts have been made to enhance the efficiency of these numerical techniques. Finite difference method (FDM), finite element method (FEM) and boundary element method (BEM) are three of the most popular numerical methods which were used for analyzing the behavior of rock mass around the rock tunnels. They can provide some good measures of rock reinforcements and rock supports for stability and sustainability of tunnels (Jing and Hudson, 2002).

During tunnel construction, rock discontinuities significantly affect the behavior of a rock mass around it. FDM can be used in both continuous (e.g. FLAC (Fast Lagrangian Analysis of Continua) soft wares (Itasca Consulting Group, 2002)) and discontinuous (e.g. UDEC (Universal Distinct Element Code) soft wares (Itasca Consulting Group, 1989)) rock environments. BEM is mainly used for intact rock in a continuous environment and also for jointed rocks in a semi-continuous environment. A large number of studies have been carried out for analyzing the effect of geometrical features of rock joints (e.g. spacing and orientation of joints in a rock mass) on tunnel behaviors by using these numerical methods (Button et al., 2006; Jia and Tang, 2008; Palassi and Asadollahi, 2007; Tsesarsky and Hatzor, 2006; Wang et al., 2003).

Button et al. used district element method to study the effect of orientation of layering in the general behavior and displacement of tunnel wall (Button et al., 2006). Jia and Tung used RFPA (Rock Failure Process Analysis) studied the effect of joint slope angle on the stability of tunnel in jointed rocks by numerical code. RFPA code is a two-dimensional model of FEC that is based on damage mechanism and static theory (Jia and Tang, 2008). In order to estimate the deformation around tunnel as a function of joint spacing, Tsesarsky and Hatzor studied cinematic analysis of rock blocks by using the discontinuity deformation analysis (DDA) and concluded that the height of the loosed zone above the excavation may

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predominantly be controlled by joint spacing and joint shear strength (Tsesarsky and Hatzor, 2006). Wang et al. performed the stability of rock slopes by using PFC^{2D} (Particle Flow Code) software (Wang et al., 2003). Palassi and Asadollahi studied the effect of joint orientation in tunnel supporting system using discrete element method (Palassi and Asadollahi, 2007).

Tonon and Amadei used finite element method to investigate the influence of joints dip angles and their boundary conditions on the behavior of rock mass around tunnels by taking the orthotropic and isotropic rock environments into account (Tonon and Amadei, 2003). Wittke studied the results of three-dimensional numerical methods using finite element method for 4 different anisotropic joint orientations and studied joints effect on the induced stresses, displacements and cohesion in a jointed rock mass(Wittke, 1990).

The three dimensional elastic anisotropic behaviors of rocks were studied by a boundary element and finite element code (BEFE) (Tonon, 2000). The results of this study were obtained by using the advanced assessment methods to recognize the changes in the quality of rock mass in anisotropic material and also to distinguish the effect of anisotropy on support load. The influence of joint orientation of rock masses in tunnel behavior was studied by using DEM^{3d} (Lee et al., 2003). Goricki et al. studied the anisotropic effect of rock mass on displacement and induced stress in tunnels and in the combination of rock mass with layered rocks where continuity of joints is high by using district element method (Goricki et al., 2005). Boundary Element (BE) models are widely used in geomechanics issues for computing stresses and displacements around underground excavations. Most of these models assume that the rock mass is homogeneous, isotropic, linearly elastic solid; although inhomogeneity and anisotropy can also be analyzed by the boundary element method (Napier and Ozbay, 1993; Banerjee and Butterfield, 1982; Crouch and Starfield, 1983).

Many researchers carried out studies on the fracture and discontinuity around the tunnel using boundary element method. Displacement discontinuity method (indirect boundary element method using the displacement discontinuities (fictitious cracks) over an element) is particularly appropriate for modeling rock discontinuities (Chan et al., 1990). Shou used the 3D boundary element method to investigate impact of the weak zone adjacent the tunnel (Shou, 2006; 2000). Higher order DDM is more suitable for the solution of BVPs (Boundary Value Problems) with displacement boundary conditions and where discontinuities and cracks are presented in the elastic body (Fatehi Marji and Hosseini-nasab, 2005; Fatehi Marji, 2014; Ritz et al., 2012). A lot of studies have been devoted to the use of indirect boundary element method in rock fracture mechanics, most of which worked on the formulations (Fatehi Marji et al., 2006; Fatehi Marji and Dehghany, 2010; Fatehi Marji, 2013; 2014). Recently, Haeri et al. have also investigated the crack propagation in rock like specimens containing pre-existing cracks (Haeri et al., 2014, 2015a, 2015b, 2015c and Haeri, 2016). The effects of joints in rocks have been investigated by some researchers such as Nikadat et al. (2015) who have investigated the behavior of jointed rock mass by a hybridized indirect boundary element method (TFSDDM). (Nikadat, 2014; Nikadat and Fatehi Marji, 2016; Nikadat et al., 2015).

In this study, the FDM, FEM and a 2D hybrid boundary element method (TFSDDM[1]) have been used for the analysis of joint set behavior around rock tunnels considering the effect of joints spacing and joints dips. The hybrid BE model adopts the fictitious stress method (FSM) for the simulation of underground excavation and the DDM for joint set.

[1] Two fictitious stress displacement discontinuity method.

2. Numerical methods

The main idea of any numerical method is to replace the problem with an approximate problem which is easier to be solved, with the solution as close as possible to the original solution.

In numerical methods, a continuum is usually subdivided into a finite number of domains (elements, block-averaged nodes etc.) with finite degrees of freedom and simplified mathematical behavior. To solve the discretized problem numerically, the following criteria should be satisfied properly:

- The physical statement of the problem as expressed by the governing partial differential equations.
- The continuity condition at interfaces between adjacent elements.

Two different approaches have been used in the literature, continuous (FEM, BEM and FDM) and discontinuous (DEM such as UDEC, 3DEC and PFC codes, and DDA) methods.

In this research, the influences of the joint spacing and joint orientation on the stress distribution around the circular tunnel are investigated by using various numerical methods i.e. FEM, FDM and the combined indirect BEM (combination of FSM and DDM).

2.1. Finite Element Method (FEM)

Finite Element Method (FEM) is based on a piecewise representation of the solution in terms of specified basic functions. FEM consists of the fundamental steps; domain discretization, local approximation, global matrix assembly and solution. The domain of the problem discretized into a finite number of subdomains with a regular shape and fixed number of nodes known as “finite elements”. The field variables are then written as trial functions of its nodal value in a polynomial form (i.e. weak form). Appropriate test functions are multiplied by the weak form of the governing equations, and then integrated over each element. The results are then assembled into a global matrix, and by solving the linear system of equations therein, the value of field variables at each integration point is determined (Jing, 2003).

For the case of jointed rock masses, Goodman et al. proposed a zero thickness “joint element” in which the normal and shear stresses and the deformation normal to and along the discontinuity are related through constant normal and shear stiffness values (K_n and K_s), respectively (Goodman et al., 1968). The zero thickness assumption (i.e. large aspect ratio) may lead to some numerical ill-conditioning. Ghaboussi and Wilson implemented plasticity theory in a finite thickness FEM fracture element and Desai et al. proposed a “thin-layer” element that used a special constitutive law for contact and frictional sliding (Desai et al., 1984; Ghaboussi and Wilson, 1973). Buczkowski and Kleiber implemented an interface element model in contact mechanics with an orthotropic friction, based on the theory of plasticity (Buczkowski and Kleiber, 1997).

However in this study, the finite element code, Phase2 (Rocscience Corporation, 2011) is used for the analyses of stress distribution around rock tunnels. The version 8.0 of this software uses a 2-dimensional elasto-plastic advanced FEM for the stability analyses of underground or surface excavations in rock or soil.

2.2. Discrete Element Method (DEM)

Finite Difference Method (FDM) is used to solve many problems in discontinuous rock masses in a discrete form. Therefore, this version of FDM is known as Discrete Element Method (DEM). Two types of mechanical behavior can be considered by DEM; those of the discontinuities and those of the solid materials. The analyzing