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Directional projection in stereographic representation of three-dimensional stress redistribution during tunnelling

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ABSTRACT

The three-dimensional principal stress mutation of surrounding tunnel roof rocks can cause devastating disaster during excavation process. The mechanism of stress redistribution thus becomes critically important to implement the rock bolt support and enhance the safety and stability. This research focuses on the effect of rock bolt installation relative to the optimal orientation alternatives. There are deficiencies in contemporary analytical literature for that purpose. This shortcoming not only increases the construction expenditure unnecessarily but also impacts the engineering stability. The problem with 3D principal stress rotation is that uncertainty in finding the optimal bolt rock implementation during tunnelling. The stereographic projection technique that 3D is transformed to the 2D chart with the benefits of simplicity and brevity. This algorithm allows tunnelling practitioner better understanding and firmer grasp of complexity affiliated with the 3D principal stress rotation process. First we use FLAC^{3D} to simulate the unsupported tunnelling excavation process, to produce the stress redistribution and orientation mutational data of surrounding tunnel roof rocks. We then take the modeling result to generate Stereographical Projection. The result clearly shows the progressive principal stress rotation during tunnelling, and renders the optimal rock bolt orientation.

1. Introduction

Localized stability in a rock medium during tunnelling may alter depending on the stress transformation by the surrounding material composition, which is associated with the critical stress states of the rock medium. In the past, there are many research topics on this specific stress redistribution issues for tunnel excavation based on two-dimensional (2D) representation. Classical solutions involved in stress analysis of tunnels such as the Kirsch's equations (1898), which solved analytically the distribution of stress and displacement in unsupported circular tunnels, are readily available. Kirsch's solutions rely upon elasticity theory using plane stress conditions with different K0 values. Panet and Guenot (1982) discovered the tunnel convergences that are interrelated with overall stress redistribution and support. Poulos and Davis (1991) mentioned that the tunnelling problem can be classically viewed as the magnitude of stress distribution around a hole in the ground under plane stress condition and has been summarized in works. Ren et al. (2005) investigated the stress states involved in optimal underground excavation shapes. 2D analysis is suitable for tunnel complete excavation and cannot offer the stress redistribution mechanism during tunnelling. Rajankar and Sitharam (2015) created a two dimensional model by using a finite element method software package, ABAQUS/CAE to understand its effect on Stress Distributions around the Tunnel in Underground Bangalore Metro Project, and the results are presented to understand the difference in stresses in the presence and absence of dowels present around the tunnel excavation. Cai (2008) provided for choosing appropriate tools and modeling strategies for tunnel excavation and also illustrated the importance of honoring the true stress path in tunnel excavation response simulation. For linear elastic tunnel excavation problems, different codes FLAC and Phase2 provide the same result and stress path is unimportant. However, for tunnel excavation in elasto-plastic materials using long-round drill and blast method, there is significant difference in terms of yielding zone distribution. Chen and Huang (2007) provided an algorithmic procedure which stably evaluates stress adjustment of a bench excavation with respect to the three-dimensional state of stress, and the evaluation of a safety factor at the tunnel face during advancement was performed following the stress path and principal stress space. The stress redistribution of a tunnel during construction should be three-dimensional condition. Galli et al. (2004) used a 3D finite element model to simulate tunnel excavation and evaluated the stress distributions involved in the lining-soil interaction. Eberhardt (2001) explored near-field stress paths during the progressive advancement of a tunnel face which results a detailed three-dimensional finite-element study.

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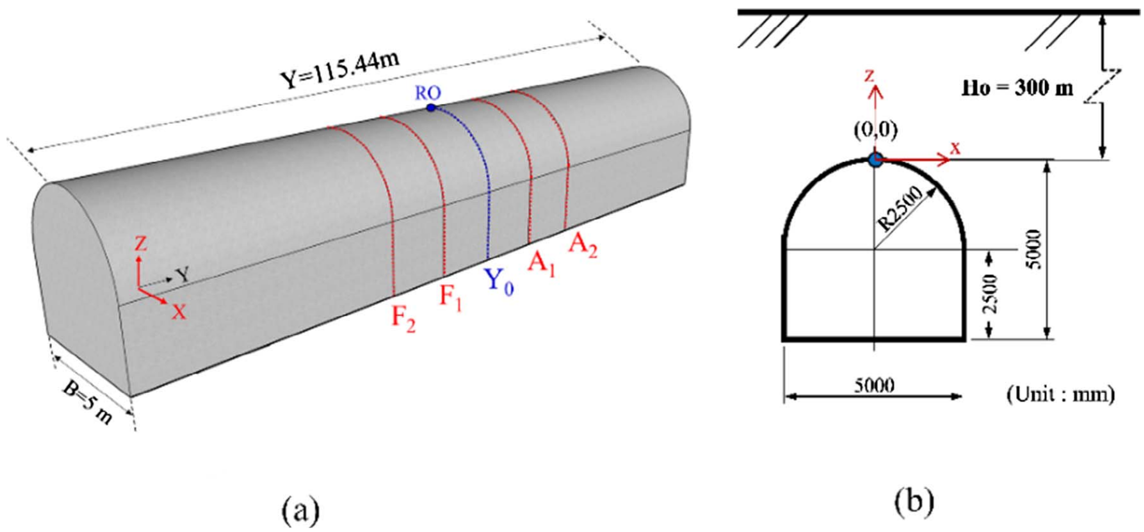

Fig. 1. Numerical tunnel shape and dimensions.

Cantieni and Anagnostou (2009) investigated the interaction between yielding supports and squeezing ground by means of spatial numerical analyses that take into account the stress history of the ground. Innaurato et al. (2011) provided some useful considerations and suggestions on the forecasting of the behavior of TBM discs during advancement in deep tunnels.

However, the Plunge and Trend of each principal stress σ_i cannot read clearly by illustrative graphics and is hard to capture rotation angle of σ_i with sequential advance length. Especially, how far from working face that the minimum principal stress can rotate to vertical direction is very important for rock bolts efficacy assessment. This can be obtained by stereographic projection and is used in the paper.

The major function of rock bolts is to increase the shear strength and suspension of the surrounding rock of excavation surface. Hence, it is very important to know the supporting mechanism of the rock bolts during tunnelling. Further literatures revealed several relevant discussions on the use of rock bolt support. Spang and Egger (1990) developed for the evaluation of the bearing capacity of fully grouted bolts and for the prediction of the required shear displacements, and also checked the test observations and to furnish complete information for all stages of the shear tests with 3D Finite Element model. Ladanyi (1974) presented stress distribution around a circular opening in a hydrostatic stress field, and used the Mohr–Coulomb elastic–plastic theory to determine the failure criteria for the annular rock at the periphery of a tunnel during excavation. To increase the stability and reduce the costs of tunnel support. Rabcewicz and Golser (1973) showed support systems installed with shotcrete, rock bolts and anchors in contact surrounding rock, will result in supports that can lead to the lowering of overall construction costs and contribute positively towards tunnel stability. Gao and Kang (2008) indicate that pre-tensioned rock bolts have a significant effect on stress redistribution which can greatly increase vertical stress and result in a greater capacity of bearing a large horizontal stress in the roof. Bobet and Einstein (2011) indicate that rock bolts solution is strongly depending on the relative stiffness between the rock bolts and the deformed rock. The best results are obtained by placing the rock bolts while the rock undergoes plastic deformations. Ahmad Fahimifar and Ranjbarnia (2009) assumed that grouted rock bolts increase internal pressure within a broken rock mass, and the result show that decreasing rock bolts spacing increase the support system stiffness rather than preloading of rock bolts. Low and Einstein (2013) applied the circular tunnel supported with elastic rock bolts in a homogeneous and isotropic elasto-plastic ground with the Coulomb failure criterion with the first-order reliability method (FORM) and the second-order reliability method (SORM). The result can be performed to obtain the length and spacing of rock bolts for a target reliability index.

The rock bolt system is one of the most commonly used support during tunnel excavation, and the optimal installed orientation also affects the excavation stability and project cost. However, it seems no further study has been conducted on how the progressive efficiency of radial rock bolts is established after installation. In order to provide the optimum supporting position of the design and the best economical tradeoff, this paper takes the smooth excavation as the objective study and expects to complements the progressive efficiency of radial rock bolt and its optimal installed orientation by using the stereographic projection which can be analyzed from the stress magnitude and orientation before rock bolt installation.

2. Numerical simulation of tunnelling

2.1. Numerical mesh and boundary condition

To generate 3D stress redistribution during tunnelling, a numerical mesh of the Horseshoe shaped tunnel is generated by using the numerical code FLAC^{3D}. The model is to be investigated on the mechanical behavior of a horseshoe shaped tunnel with full face excavation. The shape, dimensions and boundaries of the tunnel model are shown in Fig. 1, where the respective lengths along the X, Y, Z directions of the model are longer than 20B, where B is the tunnel width (B = 5 m). The overburden depth Ho of the tunnel is 300 m. The coordinate system is shown in Fig. 2a, where Y-axis is parallel to the tunnel driving direction and Z-axis is the vertical direction and is perpendicular to the tunnel. The numerical boundary constraints are shown in Fig. 2b.

2.2. Monitoring station and key rounds of numerical model

Due to the fact that some of rock bolt implementations are radiant, we can focus on the rock bolt position near roof, and extrapolate to its proximity to obtain the principal stress magnitude and orientation of surrounding rocks to derive the optimal results. And the overall rock bolt efficiency and tunnelling stability can be achieved.

Stress redistribution and displacement within the working face during tunnelling are the most important design considerations for the tunnel stability. Hence, it is necessary to carefully select and configure the monitoring stations in the model. The monitoring station location is shown in Fig. 3. A monitoring station at tunnel roof (RO) is set at the location Y = 0 m. The stress redistribution and orientation variant during the tunnelling process towards the monitoring station is then