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Research paper

Studying the effect of some parameters on the stability of shallow tunnels

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A B S T R A C T

Several factors have crucial impact on the serviceability of underground openings including: the quality of rock mass; the presence of rock joints and their geometrical properties; the state of in-situ stress ratio; the depth below surface and opening geometry. This paper only investigates the effect of two parameters on the stability of underground shallow tunnels, namely: the presence of rock joints in the rock mass matrix and the shape of the excavation. A series of two-dimensional elasto-plastic finite-element models has been constructed using rock-soil, RS^{2D}, software. Consequently, parametric stability analysis has been conducted for three different tunnel shapes (e.g. circular, square and horseshoe) with/without joint inclusion. Four reference points have been assigned in the tunnel perimeter (e.g. back, sidewalls and floor) to monitor the state of stress-displacement in the rock mass around them. The results indicate that the weak performance of a tunnel opening occurs with a square-shaped opening and when joints exist in the rock mass. In addition, the normal stress along joints sharply drops in the vicinity of a tunnel opening. Moreover, the direction of shear stress is reversed. Thus, it causes inward shear displacement.
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1. Introduction

Tunnels are constructed to serve several purposes (e.g. irrigation, sanitary drainage, conveyance, and hydro-electrical power stations) in geotechnical, civil and mining engineering. They have become an essential component of modern societies particularly in big cities (Madkour, 2012; Elshamy, Attia, Fawzy, & Abdel Hafez, 2013; Panjia, Koohsari, Adampira, Alielahi, & Marnani, 2016). Therefore, their performance during their service/entire life is of major concern. This performance is primarily influenced by the characteristics of rock mass (e.g. strength, quality) and the state of in-situ stresses. The failure mechanism of rock mass is mainly ruled by the behaviour of discontinuities (e.g. faults, joints, bedding planes, shear zones, dykes, etc.). In rock mechanics, joints usually refer to any type of discontinuities (Ghorbani, Zahedi, & Asaadi, 2015; Kulatilake, Qiong, Zhengxing, & Fuxing, 2013; Piyal & Konietzky, 2016).

Rock joints are regularly spaced and usually occur in a parallel set of joint networks. However, sometimes they may exist at various dip directions. Therefore, rock mass is broken up into a blocky structure (Jia & Tang, 2008). In-situ stress ratio has a significant effect on the stability of underground tunnels (particularly at great depths). Therefore, in high stress environments the stability of tunnels is controlled by the induced-stresses and joints that grow parallel to the tunnel boundary (Martin, Kaiser, & McCreath, 1999; Raju, 2013).

The construction of tunnels in a terrain with mixed lithology (e.g. incompetent, quasi-elastic with faults, folds, weak, fragile rocks, presence of a considerable amount of clay minerals, etc.) and varied ground conditions (e.g. tectonically active, thrusts of different magnitudes or a trapped water reservoir) is a big challenge for engineers particularly at great depths with high overburden pressures. Consequently, several problems are encountered in the supporting of tunnels, due to squeezing, swelling, water existence, poor rock state, and excessive temperatures and gases in rocks. Tunnel squeezing is a result of the plastic behaviour of rock mass under high overburden stresses, particularly when a considerable amount of clay/micaceous minerals are presented and there is low swelling capacity. Therefore, to optimize the costs of a support system and avoid instability problems, the tunnel which experiences squeezing conditions must be allowed to deform. Such

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deformation has to be considered when planning the size of an excavation. Experience with different support systems (e.g. steel ribs, compressible backfill, and shotcrete) in such terrain reveals that empirical methods do not provide reliable evaluation of the design parameters (Jethwa, Dube, Singh, & Singh, 1984; Saini, Dube, & Singh, 1989).

Different tools can be employed to assess the stability of underground tunnels, such as: analytical, empirical and numerical modelling methods. The analytical methods comprise of equations which are used to estimate the stresses and deformation around simple openings (e.g. circular openings). They are primarily developed by Kirsch (1898), Ladanyi (1974), Brady (1977), Brady and Lorig (1988). However, these methods cannot provide adequate solutions for complex geometries.

The empirical methods (e.g. stability graph method) are based on past experiences, reported case studies and rock mass classification systems. Such methods use the geomechanical properties of rock mass to provide an estimate for the rock design support system. However, these methods do not account for all factors influencing the stability of underground openings. Therefore, they are widely replaced by numerical modelling methods. Numerical methods are reliable, robust and efficient at providing a complete solution and can handle very complex geometries. They can also be adopted ahead of time, before actual excavation, to select the optimum design/sequence (Berisavljević, Dušan, Čebašek, & Rakić, 2015; Maleki, Mahyar, & Meshkabadi, 2011; Soren, Budi, & Sen, 2014). Numerical modelling analyses have been conducted by many researchers to investigate the effects of rock joints on the performance of underground tunnels. A basic scale-model has been developed by Barton (1972) to examine the performance of rock support installed into jointed rock mass. The behaviour of rock mass deformation around the tunnel has been analysed by Goodman, Heuze, and Bureau (1972). The impact of a fault on the tunnel has been investigated by Jeon, Kim, Seo, and Hong (2004).

A sensitivity analysis was carried out by Yeung and Leong (1997) using discontinuous deformation analysis (DDA) to study the effect of the attribute of joints in a rock mass matrix. Two-dimensional discrete element code (UDEC) was employed by Hao and Azzam (2005) to examine the effect of some fault parameters on the stability of a tunnel. The geometrical properties of rock joints (orientation, dimensions) have been studied by Jiang, Tanabashi, Li and Xiao (2006). The stability of underground openings in blocky rock mass has been investigated by Goodman and Shi (1985). Although many researchers have investigated analytically and experimentally the impacts of stress state and rock joints on the stability of underground openings, rock failure mechanism of underground openings under complex geological conditions is not fully explained in the literature. Eberhardt (2001) examined the impact of rock joints and stress regime on tunnel behaviour, due to stress rotation ahead of the tunnel, using three-dimensional analysis. This paper aims to evaluate the impact of different tunnel shapes and presence of rock joints on the performance of underground shallow tunnels in terms of the state of stress-displacement. The following section briefly discusses various stability indicators used in this parametric stability analysis to assess the serviceability of a tunnel opening.

2. Stability indicators

A range of failure evaluation criteria could be adopted to assess the stability of underground openings. In this study, the state of stress-displacement around a tunnel opening is monitored and introduced in terms of induced-stress, stress concentration, strength of rock mass, convergence ratio of tunnel shoulders, ratio of roof sag and floor heave, and the depth of yielding zones into the rock mass surrounding tunnel opening. The following subsection briefly presents these evaluation criteria.

2.1. Induced-stress

Eq. (1) represents the induced-stress as the difference between pre- and post-excavated stress, as per Eq. (1).

$$\text{Induced} - \text{stress} = \sigma_1 - \sigma^0 \tag{1}$$

where:

σ_1 – stress results after excavating the tunnel, and
σ^0 – in-situ stress (virgin stress).

2.2. Stress concentration

Stress concentration regions around tunnel opening are measured using the stress concentration factor, *SCF*. As shown in Eq. (2), *SCF* is defined as the ratio of post-excavated stress, σ_1 to pre-excavated stress, σ^0 (Zhang & Mitri, 2008).

$$SCF = \frac{\sigma_1}{\sigma^0} \tag{2}$$

2.3. Rock mass strength

The strength of rock mass, after excavating a tunnel opening, is monitored using strength factor (*SF*). This factor is analogous to the factor of safety which may have several formulations based on different assumptions (Sheorey, 1997) In Eq. (3), the *SF* is defined as the ratio of unconfined compressive strength of intact rock (*UCS*) to post-excavated stress (σ_1). Thus, the serviceability of a tunnel opening will be considered unsatisfactory if $SF < 1.0$.

$$SF = \frac{UCS}{\sigma_1} \tag{3}$$

2.4. Potential stress failure (PSF)

Another factor called potential stress failure (*PSF*) can be used to assess the stability of underground tunnels, as shown in Eq. (4). The, *PSF* is calculated at the boundary of the tunnel, where minor principal stress (σ_3) vanishes (Mitri, 2007).

$$PSF = \frac{\sigma_1}{UCS_{rm}} \times 100 \tag{4}$$

where:

σ_1 – maximum computed boundary stress due to excavation, and
UCS_{rm} – uniaxial compressive strength of rock mass and is estimated as per Eq. (5).

$$UCS_{rm} = UCS\,\sqrt{s} \tag{5}$$

where:
s – Hoek-Brown constant, $\sqrt{s} \geq 0.50$, and
UCS – lab uniaxial compressive strength of intact rock.

PSF is only adopted when the Hoek-Brown failure criterion is employed (e.g. elasto-plastic brittle shear failure analysis)

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