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Technical Note

Wall displacement prediction of circular, D shaped and modified horseshoe tunnels in non-hydrostatic stress fields

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ABSTRACT

The prediction of the magnitude and development of the expected displacements has an important impact on a large number of issues during tunnel construction. Convergence confinement method (CCM) is based on the analysis of the stress and strain state that develops in the rock around a circular tunnel capable of determining wall displacement. The radial displacement given by RocSupport that is based on convergence-confinement method (CCM) is valid for the tunnel circular cross section driven in the hydrostatic state of stress. In this paper several equations and graphs are presented using numerical modeling (FLAC3D) to obtain corrective coefficients to be applied to the values of wall displacement of circular tunnels in hydrostatic state of stress given by analytical method (RocSupport) for the prediction of maximum wall displacement and displacements of different parts of circular, D shaped and modified horseshoe tunnels in non-hydrostatic stress fields.

1. Introduction

Excavation and support methods are influenced by the magnitude of displacements. The over excavation has to be adjusted to the expected displacements to guarantee the clearance after stabilization. To allow for a safe and economic construction, the prediction of displacements is essential.

Convergence confinement method (CCM) is based on the analysis of the stress and strain state that develops in the rock around a tunnel. It was developed initially in the1930s, was further refined by various researchers and has been comprehensively reviewed by Carranza-Torres and Fairhurst (Alejano et al., 2010). Convergence confinement method is useful in the preliminary design of support and reinforcement structures, determination of the thickness of the plastic zone around the tunnel, estimation of final convergence and radial displacement.

The convergence confinement method is based on four main assumptions (Oreste, 2009):

1. The state of stress is hydrostatic and constant with depth.
2. The tunnel cross section is circular.
3. Rock mass is continuous, homogeneous and isotropic.
4. Stress field is planar and problem is bi-dimensional.

Assume that a circular tunnel of radius r_o is subjected to hydrostatic stresses p_o and a uniform internal support pressure p_i. If the internal support pressure p_i is greater than the critical support pressure p_{cr}, no failure occurs and the magnitude of displacements associated with elastic behavior of the rock mass surrounding the tunnel can be determined from the Kirsh Solution. Otherwise, failure occurs and the radius r_p of the plastic zone around the tunnel is given by Eq. (1) (Hoek, 1999):

$$r_p = r_0 \left[\frac{2(p_0(k-1) + \sigma_{cm})}{(1+k)(k-1)p_i + \sigma_{cm}} \right]^{\frac{1}{k-1}} \quad (1)$$

where σ_{cm} is the uniaxial compressive strength of the rock mass and k is the slope of the σ_1 versus σ_3 line in Mohr–Coulomb criterion and can be obtained by Eq. (2).

$$k = \frac{1+\sin\varphi}{1-\sin\varphi} \quad (2)$$

where φ is the friction angle.

For plastic failure, the total inward radial displacement of the walls of the tunnel is (Hoek, 1999):

$$u_{ip} = \frac{r_0(1+\upsilon)}{E}\left[2(1-\upsilon)(p_o - p_{cr})\left(\frac{r_p}{r_0}\right)^2 - (1-2\upsilon)(p_0 - p_i)\right] \quad (3)$$

Critical support pressure (p_{cr}) can be obtained by the following equation (Hoek, 1999):

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$$p_{cr} = \frac{2p_o - \sigma_{cm}}{1+k} \tag{4}$$

It is possible that some of the conditions required in the convergence confinement method (CCM) differ from real conditions that may end to significant error in the final results of this approach. Different authors have done many attempts to describe and modify convergence confinement method and applied CCM for different purposes. Panet (1995) proposed the analytical equation of the trend of the radial displacements on the tunnel perimeter both ahead and behind the excavation face for the particular case of a tunnel and without supports. Carranza-Torres and Fairhurst (2000) showed application and limitations of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek–Brown failure criterion. Antiga et al. (2007) considered limit of application of the closed form solution compared with numerical models for the CCM and presented a corrective coefficient to be applied to the values obtained with the analytic solution for circular tunnels. Gonzalez-Nicieza et al. (2008) presented a modification to CCM method that would account for the effect of depth and tunnel cross-sectional shape when predicting the radial convergence of a lined tunnel. Oreste (2009) presented roles and limits in modern geomechanical tunnel design for the CCM. Alejano et al. (2010) examined application of the convergence confinement method to tunnels in rock masses exhibiting Hoek–Brown strain-softening behavior.

RocSupport is a quick and simple to use program for estimating the deformation of circular tunnel in an elasto-plastic rock mass under a hydrostatic stress field. The analysis method used in RocSupport is based on convergence confinement method. RocSupport uses Kirsh's equations for the elastic displacements and stresses in the elastic state, while it uses two solutions based on the incremental theory of plasticity for the plastic range (Duncan Fama for the Mohr–Coulomb or the Carranza-Torres solution for the Generalized Hoek–Brown failure criterion).

In this paper several equations and graphs are presented using numerical modeling (FLAC3D) to obtain corrective coefficients to be applied to the values of wall displacement of unlined ($p_i = 0$) circular tunnels in hydrostatic state of stress given by analytical method (RocSupport) for the prediction of maximum wall displacement and displacements of different parts of circular, D shaped and modified horseshoe tunnels in non-hydrostatic stress fields.

2. Methodology

A fair quality rock mass according to RMR classification range was chosen and wall displacement of circular tunnel of 3 m radius driven in this rock mass was calculated using RocSupport program for different excavation depths (50, 100, 150, 200, 250, 300, 350 and 400 m). The rock mass chosen for discussion is characterized by the parameters summarized in the Table 1. Three tunnel cross-section shapes including circular, D shaped and modified horseshoe were considered for the numerical modeling using FLAC3D. Shape and dimensions of each type of the tunnels cross-section are shown in Fig. 1 along with the origin of the angles θ that allow situating any point on the perimeter of the tunnel. Several numerical modeling were carried out considering different tunnels shapes, depths and horizontal to vertical stress ratios (0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2) by FLAC3D. Due to the symmetry of the problem only half of the model was considered and for circular cross section quarter of the model was considered. Fig. 2 shows the boundary condition and FLAC3D mesh for circular tunnel in quarter symmetry. Boundary conditions of D shaped and modified horseshoe cross-sections are exactly the same. Mohr–Coulomb model was used to define properties of rock mass parameters summarized in Table 1. In each case, the radial wall displacements at several points situated on the perimeter of the cross-section were recorded and maximum wall displacements in different parts of the tunnels (circular part, sidewall and bottom) were determined. The position of maximum displacements of different parts of tunnels (points 1–10) are shown in Fig. 1 that depend on the stress ratio value which are explained in Section 3. The ratio of recorded maximum wall displacement of different parts of the tunnels in different depths and different horizontal to vertical stress ratios (K) by numerical modeling to analytical method result (RocSupport) for the same depth in hydrostatic state of stress were considered and specified with symbols shown in Table 2. Average of recorded wall displacement of circular, D shaped and modified horseshoe tunnels for a specific value of angle θ in different depths and a same stress field by numerical modeling to RocSupport results considered as ξ_c, ξ_D and ξ_{mh} respectively. Table 3 shows the ratios of the recorded maximum wall displacement of circular tunnel by numerical modeling to RocSupport results (Δ_c) and the average of them for different depths and different stress fields as an example. $\Delta_{cK=1,H=100}$ means the ratio of obtained numerical maximum displacement to analytical method results (RocSupport) for a circular tunnel in hydrostatic state of stress and depth of 100 m. As can be seen from the Table 3 obtained values of maximum displacements by numerical modeling in hydrostatic state of stress are exactly the same with analytical method results ($\Delta_{cK=1} = 1$). Then the averages of Δ_c, Δ_D, Δ_{mh}, Δ_D, Δ_{mh}, ω_D, ω_{mh} for a specific stress ratio (K) and different depths and the values ξ_c, ξ_D and ξ_{mh} for different horizontal to vertical stress ratios, several equations and graphs were presented applying curve fitting tool of MATLAB program to predict maximum displacement of different parts of the mentioned tunnels and wall displacement along with the origin of the angles θ in non-hydrostatic stress field according to analytical method results used in convergence confinement method (RocSupport) for circular tunnels in hydrostatic stress field.

Table 1
Parameters of the rock mass chosen for discussion.

RMR	55
Modulus of deformation (E)	10 GPa
Compressive strength of rock mass (σ_{cm})	22.5 MPa
Poisson's ratio (υ)	0.25
Cohesive strength (c)	5.847 MPa
Friction angle (ϕ)	35.08°

3. Results and discussions

Fig. 3 shows the average of Δ_c, Δ_D and Δ_{mh} graphs for different horizontal to vertical stress ratios (K). As shown in Fig. 3 in circular tunnels and circular part of D shaped and modified horseshoe tunnels for $K \leqslant 1$, increasing K results in decreasing the ratio of numerical maximum displacement to analytical maximum displacement (RocSupport result) non-linearly. These changes are more severe for D-shaped cross section. For $K \geqslant 1$ in all cross sections the ratio of maximum displacements increases with increasing the K approximately linear. Fig. 4 shows the average of δ_D and δ_{mh} graphs for different horizontal to vertical stress ratios (K). According to Fig. 4 for D shaped and modified horse shoe tunnels, increasing K ends in decreasing the ratio of the bottom numerical maximum displacements of the tunnels to the analytical result (RocSupport result) up to 1.75 and for greater values of K the ratio increases. Fig. 5 shows the average of ω_D and ω_{mh} for different horizontal to vertical stress ratios (K). It indicates that maximum displacements of the sidewall of D shaped tunnel increase with the increasing of the K so that this increasing is more severe for $K > 0.5$. This ratio is ascending for modified horseshoe tunnel up to 0.65 and