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Effects of Rock Mass Anisotropy on Deformations and Stresses around Tunnels during Excavation

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ABSTRACT

The paper presents a short review on a modelling method for a circular tunnel excavated in the dry rock mass where the in situ state of stress is uniform. The rock mass was assumed to behave elastically and two cases were examined: whether the rock mass has an isotropic elastic property or not.

A two-dimensional plain strain elastic-plastic Jointed Rock model was used to study the response of the rock mass to excavation. The elastic behaviour of the rock mass was assured in the model by simply providing adequate cohesion. The study reveals that the distribution of excavation-induced-stresses and deformations in the space surrounding rock mass having anisotropic properties differs from that obtained under the assumption of isotropic properties. The neglect of the effect of elastic anisotropy can result in a significant underestimation of stresses and displacements in rock and thus also in the design of support measures and the final pressure tunnel linings.

Additionally, when the tunnel geometry is circular and the rock mass contains one joint set where the plane of elastic anisotropy strikes to the tunnel axis, the results obtained for one dip angle will be identical to another dip angle by rotating the x- and y-axis accordingly.

Keywords: Tunnel, Rock Mass, Anisotropy, Modelling.

1. INTRODUCTION

For deep tunnels, a rock mass is often assumed as an isotropic material. This assumption has facilitated to the understanding of the mechanical-hydraulic interaction between the lining and the rock mass (Schleiss, 1986) and furthermore has contributed to the development of the design of pre-stressed concrete-lined pressure tunnels (Simanjuntak et al., 2012; Simanjuntak et al., 2013).

However, pressure tunnels may be constructed in anisotropic rocks composed of lamination of intact rocks, such as schistosity in schists, which exhibits anisotropic strength and deformability. Determining anisotropic deformation as a result of tunnel excavation is becoming complex due to the orientation of discontinuities in the rock mass (Bobet, 2011; Hefny and Lo, 1999; Tonon and Amadei, 2002; Vu et al., 2013; Wang et al., 2012). Inevitably, designing pressure tunnel linings will depend on the response of the rock mass to excavation as well as on the behaviour of joint planes in the rock mass.

In this study, the numerical modelling of a circular tunnel excavated in an elastic rock mass having anisotropic properties is presented. The model is representative for tunnels situated above the groundwater level and embedded in the rock mass where the strike of the anisotropy planes is parallel to the tunnel axis. Hence, the plain strain conditions apply along the axis of the tunnel and the following assumptions are made: the tunnel is deep and subjected to a uniform in situ stress, the cross section of the tunnel is circular, and the development of displacements with increasing distance from the tunnel face is not covered so that results can be obtained based on two-dimensional models.

2. ROCK MASS ANISOTROPY

The anisotropic elastic model is defined with respect to the orientation of the stratification, in which a maximum three sliding directions can be distinguished in a rock mass (Fig. 1). The orientation of the plane of elastic anisotropy or transverse isotropy is defined by the dip angle, α, and the dip direction angle β. For each plane, plastic sliding will occur if the maximum shear stress is reached.

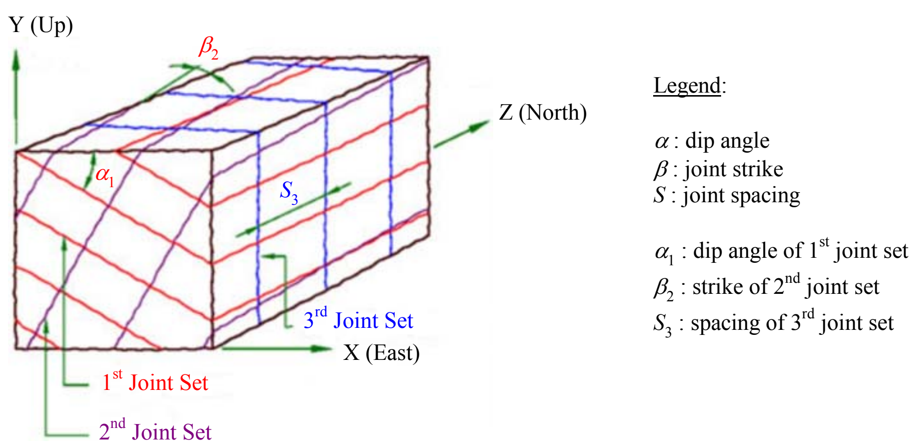


Figure 1. Configuration of Joint Sets in a Rock Mass

When the plane of transverse isotropy strikes parallel to the tunnel axis, two-dimensional analyses are adequate. However, solutions of any two-dimensional problem have to satisfy the following conditions: equilibrium, constitutive model, strain compatibility, and boundary conditions (Bobet, 2011).

Fig. 2a shows the general problem of a tunnel excavated in transversely isotropic rock. If a tunnel is excavated along the z-axis, the horizontal plane (x, z) is a plane of isotropy. In plain strain conditions, the components ε_z, ε_{yz}, and ε_{xz} vanish everywhere. The constitutive relationships can therefore be written as (Kolymbas et al., 2012; Vu et al., 2013):

$$
\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{pmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{21} & C_{22} & 0 \\ 0 & 0 & C_{33} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} \tag{1}
$$

where σ_x, σ_y, are the total stress along the x- and y-axis respectively, τ_{xy} are the shear stress and C_{11}, C_{12}, C_{22}, C_{33} are the compliance coefficients related to the material parameters and can be defined using the following relations (Kolymbas et al., 2012; Vu et al., 2013):

$$
C_{11} = \frac{1-\nu_x^2}{E_x} \tag{2a}
$$

$$
C_{12} = C_{21} = -\frac{\nu_{yx}\,(1+\nu_x)}{E_y} \tag{2b}
$$

$$
C_{22} = \frac{1-\nu_{xy}\nu_{yx}}{E_y} \tag{2c}
$$

$$
C_{33} = \frac{1}{G_{yx}} \tag{2d}
$$

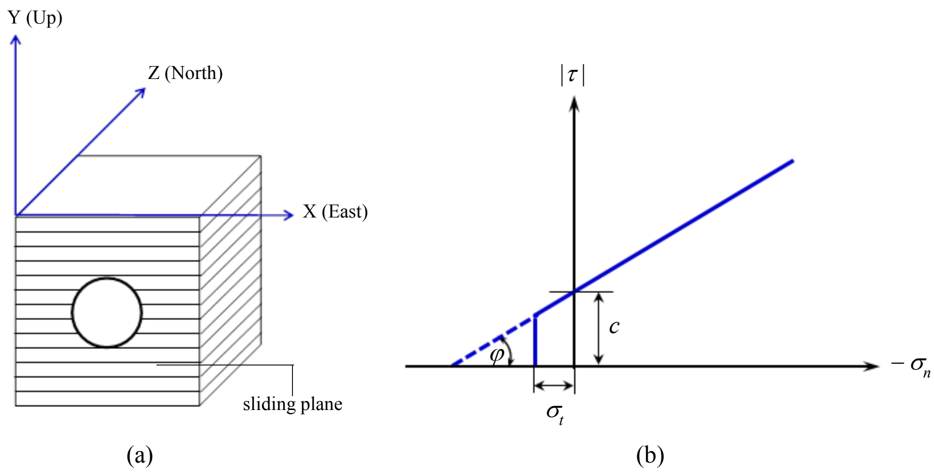


Figure 2. (a) Plane Orientation of Transverse Anisotropy, and (b) Failure Surface

The equilibrium conditions (Bobet, 2011):

$$
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \tag{3a}
$$

$$
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} = 0 \tag{3b}
$$

where x and y are the Cartesian coordinates, E_x and E_y are the elastic modulus in the horizontal and vertical direction respectively, v_{yx} is the Poisson's ratio for the effect of vertical stress on the horizontal strain, v_{xy} is the Poisson's ratio for the effect of horizontal stress on the vertical strain, v_x is the Poisson's ratio for the effect of horizontal stress on the horizontal strain and G_{yx} is the shear modulus in vertical plane.

It has to be noted that because of the symmetry of the strain tensor, the following relationship is valid (Bobet, 2011; Vu et al., 2013) and the properties in the z and x directions are the same.

$$\frac{\nu_{yx}}{E_y} = \frac{\nu_{xy}}{E_x} \tag{4}$$

A local Coulomb condition (Fig. 2b) can be applied to limit the shear stress, while a tensile strength criterion is used to limit the tensile stress. The formulation of plasticity on all planes is similar, and the corresponding yield functions for each plane, i, is given as follows:

$$f_i^c = |\tau| + \sigma_n \tan\varphi_i - c_i \tag{5}$$

$$f_i^t = \sigma_n - \sigma_{t,i} \quad (\text{where: } \sigma_{t,i} \le c_i \cot \varphi_i) \tag{6}$$

The distribution of stresses and displacements of a circular tunnel excavated in transversely isotropic or elastic anisotropy rock mass can be predicted using the Jointed Rock model implemented in the finite element software program DIANA. In this model, different values of stiffness are applied to the corresponding stratification direction so as to describe the elastic transversely material behaviour. The elastic compliance matrix is inverted and consequently multiplied with the strain increments resulting in the elastic stress increments.

For each shear failure plane, the stress conditions are checked according to the condition as depicted in Fig. 2b. When the stress point is beyond the failure surface, it is projected on the failure surface resulting in plastic deformation. When simulating the elastic-plastic behaviour of the rock mass, the model assumes associated plastic deformations resulting in volumetric expansion.

3. NUMERICAL RESULTS AND DISCUSSIONS

In this paper, the response of an anisotropic rock mass to excavation is studied by means of a finite element model. Although the Jointed Rock model is an anisotropic elastic-plastic model, the elastic behaviour of the rock mass can be simulated provided that the sliding plane has adequate cohesion. To that end, there are two cases considered: whether rock masses have isotropic elastic properties, or not.

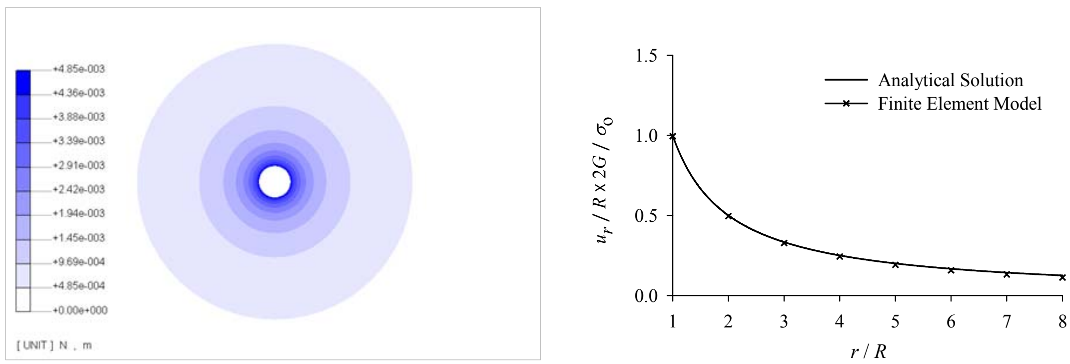
For both cases, the tunnel section was assumed circular with diameter, D, of 4 m and its axis is parallel to z-axis. The plane of transverse isotropy is horizontal or $\alpha = 0^{\circ}$, and it strikes parallel to the tunnel axis (Fig. 2a). The boundary condition corresponds to a uniform in situ state of stress, σ_o, equal to 40 MPa.

3.1. Circular Tunnel Excavated in Elastic Isotropic Rock Mass

Let us consider a rock mass, whose elastic properties are: E = 20.5 GPa and ν = 0.25. As a result of excavation works, the tunnel wall deformed radially as far as 4.85 mm inwards (Fig. 3a) and this value corresponds to the scaled radial displacement, $2Gu_r/\sigma_oR$, of 1.0.

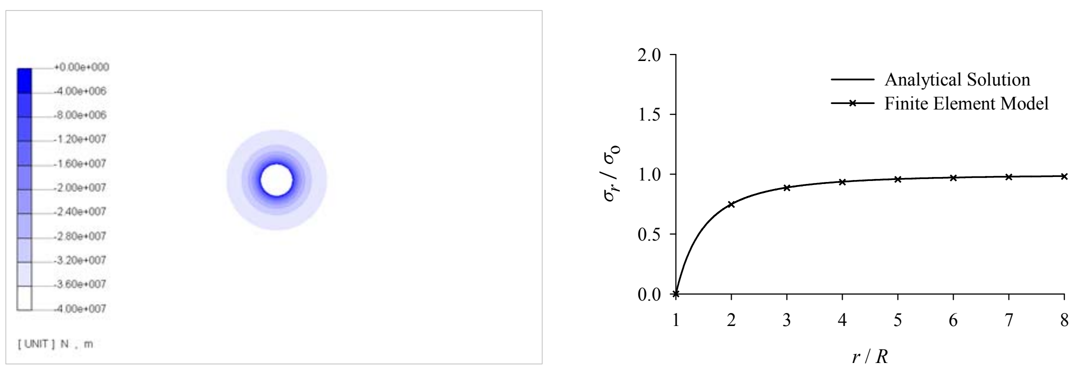
For unsupported tunnels, the radial stress along the tunnel wall was zero (Fig. 4a). The hoop stress along the tunnel wall was found as 80 MPa (Fig. 5a), which is in a compressive state of stress and corresponds to the scaled hoop stress, σ_θ/σ_o, of 2.0.

When calculated using Lame's solution (Carranza-Torres and Labuz, 2006), the radial deformation, u_r, radial stress, σ_r, and hoop stress, σ_θ, along the tunnel perimeter were found as 4.87 mm, 0 MPa and 80 MPa respectively. The good agreement between the analytical and numerical results is evident (Figs. 3b, 4b and 5b).



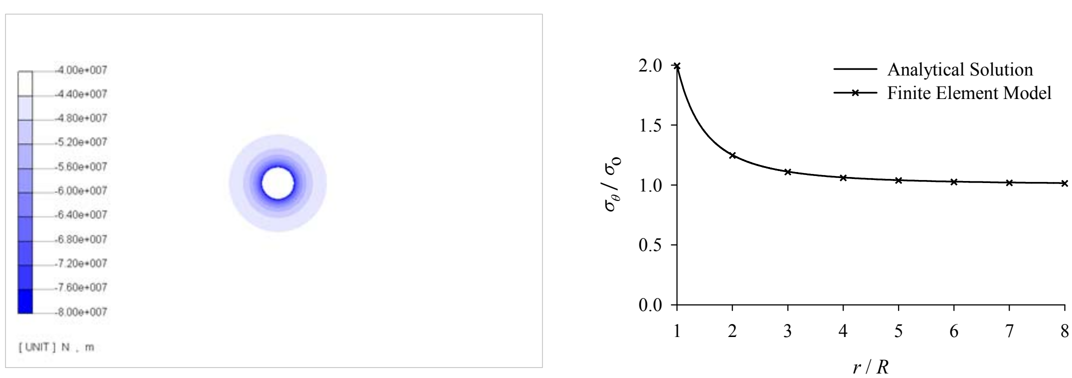
(a) (b)

Figure 3. Distribution of Radial Displacements for Elastic Isotropic Case



(a) (b)

Figure 4. Distribution of Radial Stresses for Elastic Isotropic Case

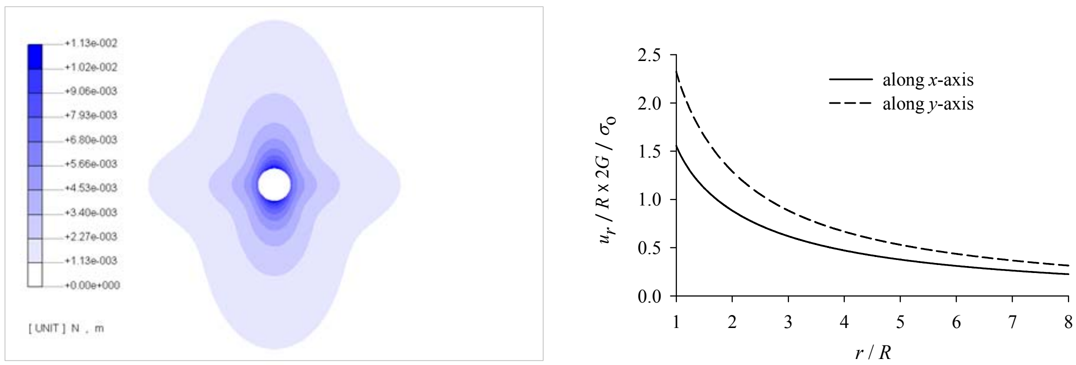


(a) (b)

Figure 5. Distribution of Hoop Stresses for Elastic Isotropic Case

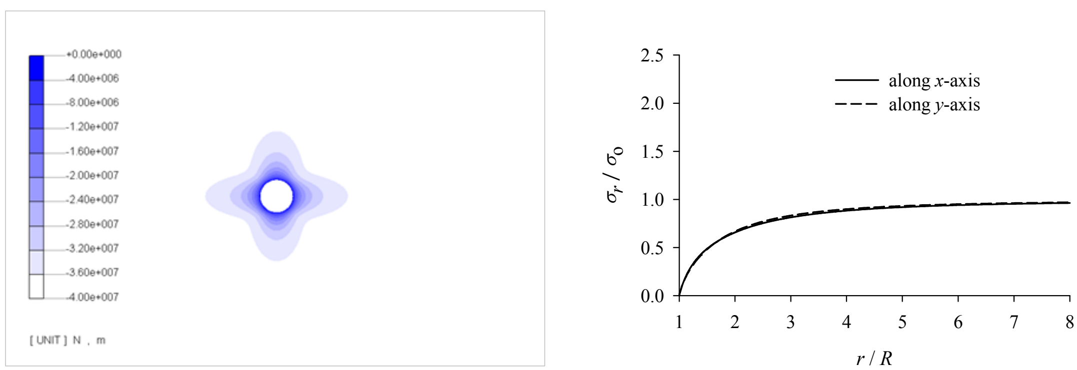
3.2. Circular Tunnel Excavated in Elastic Anisotropic Rock Mass

For cases where the tunnel is excavated in anisotropic rock masses, the following parameters were examined: $E_x/E_y = 2$, $\nu_{xy}/\nu_{yx} = 2$, and $E_x/G_{yx} = 6$. Fig. 6a suggests that when the Young's modulus parallel to the bedding plane is greater than that perpendicular to the bedding plane, the displacements at the tunnel roof and invert will be higher than those at the sidewalls. While the displacement at the tunnel roof or invert was found as 11.33 mm, the displacement at the tunnel sidewalls was obtained as 7.59 mm.



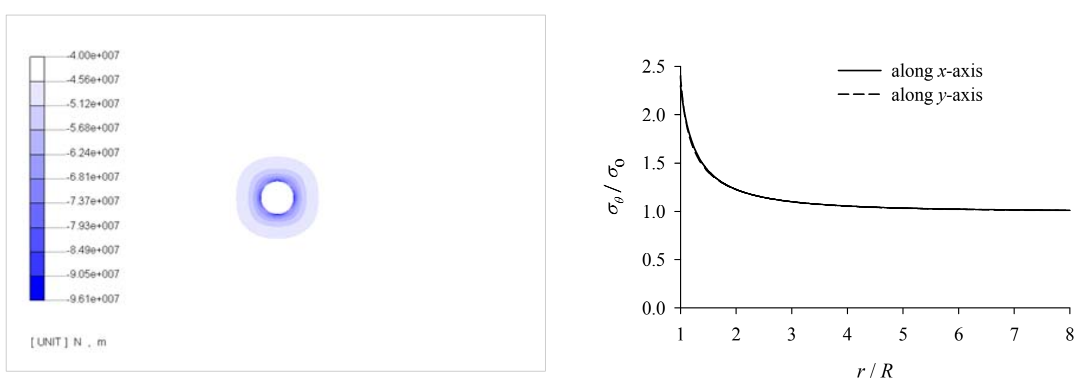
(a) (b)

Figure 6. Distribution of Radial Displacements for Elastic Anisotropic Case



(a) (b)

Figure 7. Distribution of Radial Stresses for Elastic Anisotropic Case



(a) (b)

Figure 8. Distribution of Radial Stresses for Elastic Anisotropic Case

The corresponding scaled radial displacement, $2Gu_r/\sigma_o R$, at the tunnel roof or invert and at the tunnel sidewalls were calculated as 2.32 and 1.56 respectively (Fig.9a), which indicates that the shape of the excavated tunnel is oval with its major axis parallel to the direction of the bedding planes. The response of the rock mass to excavation is comparable to those observed by Kolymbas et al. (2012) and Vu et al. (2013).

Principally, regardless the anisotropic properties of the rock mass, the distribution of radial stresses along the tunnel wall will remain zero when the tunnel is not supported. However, radial stress contours in the space surrounding the excavated tunnel will have a cross shape due to the anisotropic properties of the rock mass (Fig. 7a). The distribution of radial stresses along x- and y-axis is shown in Fig. 7b.

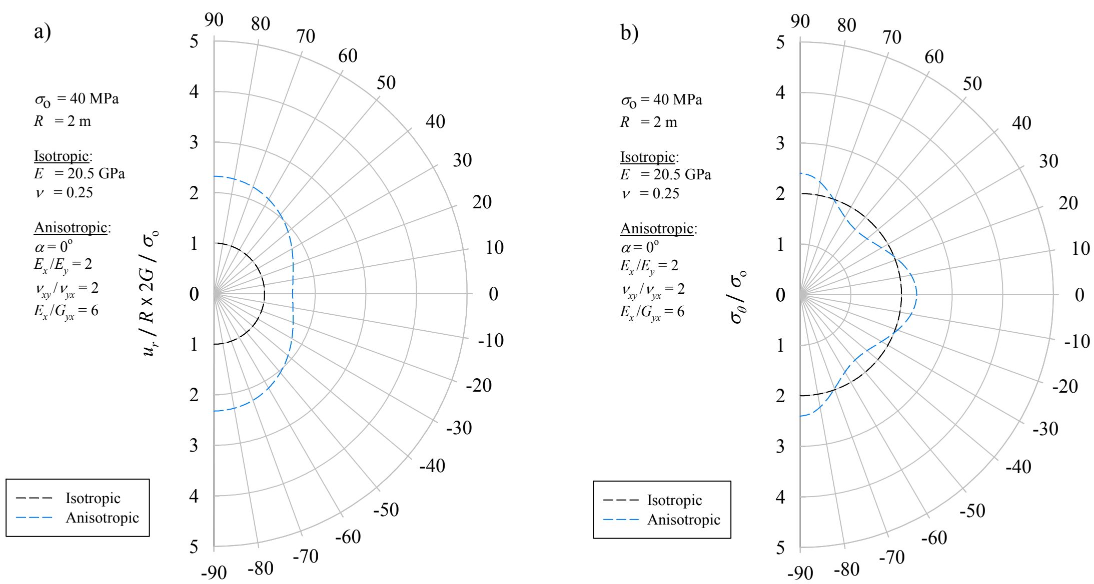


Figure 9. Isotropic and Anisotropic Case: (a) Radial Displacements, (b) Hoop Stresses

Regarding hoop stresses, the numerical results for the case of anisotropic rocks are shown in Fig. 8. While Fig. 8a shows hoop stress contours around the excavated tunnel, Fig. 8b depicts the distribution of hoop stresses along x- and y-axis. While the predicted scaled hoop stress, σ_θ/σ_o, at the tunnel roof or invert was obtained as 2.40, the scaled hoop stress at the tunnel sidewalls was found as 2.30 (Fig. 8b). However, the lowest scaled hoop stress along the tunnel wall was found as 1.69 and it was located at 50^o measured from the side-walls or at 40^o measured from the tunnel roof (Fig. 9b). This also implies that if the Young's modulus parallel to the bedding plane is greater than that perpendicular to the bedding plane, the maximum hoop stress will be concentrated at the roof or invert, while the its minimum value will be at a location around 50^o measured from the bedding plane. Similar observation can be found in Tonon and Amadei (2003) and Vu et al. (2013).

4. CONCLUDING REMARKS

In this study, the elastic-plastic Jointed Rock model was used to study the response of the rock mass to circular excavation and the elastic behaviour of the rock mass was assured by providing an adequate cohesion. Two cases are examined: whether the rocks have isotropic elastic properties or not.

As a result of circular excavation, rock masses will deform radially as long as their elastic properties are isotropic and the principal stresses are uniform. However, if the elastic properties of the rock mass are anisotropic, the displacements along the tunnel wall will be no longer radial. In such cases, the study shows that the highest deformation occurs in the direction of the lowest Young's modulus. The shape of the excavated tunnel will be oval with its major axis parallel to the bedding plane. Also, because of elastic anisotropy or transverse isotropy in the rock mass, the distribution of radial and hoop stresses in the space surrounding anisotropic rock mass will be no longer uniform. Therefore, when analyzing the response of the rock mass to excavation, the effect of elastic anisotropy or transverse isotropy cannot be neglected since it can result in a significant underestimation of stresses and displacements in the design of support measures as well as the final lining.

As long as the geometry of the tunnel is circular, the principal stress of rock mass is uniform and the plane of transverse isotropy strikes to the tunnel axis, results obtained for the case where dip angle $\alpha = 0^{o}$ will be identical to those obtained for the case where $\alpha = 90^{o}$ by rotating the x- and y-axis to 90^{o}. Studies on the effect of rock mass anisotropy in non-uniform in situ stress conditions are encouraged in the future.

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