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An Investigation into the Effect of Foliation Orientation on Displacement of Tunnels Excavated in Metamorphic Rocks

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ABSTRACT

Rocks show a different behavior towards excavation due to their continuity or discontinuity, elastic or inelastic behavior, isotropy or anisotropy and homogenous or heterogeneous nature and the response behavior of tunnels has always been a concern for geotechnical engineers during excavation operations in a variety of stones. Anisotropic rocks have different properties in different directions and also in different locations. In the present study, the effect of foliation orientation on the displacement of tunnels excavated in metamorphic rocks is evaluated. Hence the tunnel excavation is modeled for a metamorphic rock medium in different directions of foliation plane. The results show that the vertical displacement of tunnel crown is seen at a distance of 4 to 6 m from the critical tunnel face in all samples, where more than 60% of deformations occur. It should be noted that 20% of deformations are reported at a distance of 6 to 15 m along the excavation face section.

Key words: Tunnel, Excavation, Metamorphic rock, Foliation orientation.

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1. INTRODUCTION

In the design of tunnels and underground spaces, an important issue is the awareness of strength and deformability properties of the rock mass where the tunnel is drilled. In jointed and fractured rocks, the recognition of these properties requires the application of strong theoretical and empirical foundations (1). Many hard rocks have an elastic behavior in laboratory samples; but most of the rocks do not show a fully elastic behavior on a field scale due to cracks, fractures, laminations, contact surfaces, metamorphic areas and clay with plastic properties (2). The geologic structure typically has a great influence on the rock mass properties, e.g. its strength and deformability properties. In some cases, the discontinuities form weak planes along which biaxial slides or deformations are observed, resulting in the failure of rock mass (3). When flat minerals such as mica, talc, chlorite and serpentine are parallel within the rock or when the direction of long minerals such as amphibole is in such a way that their longitudinal axes are parallel to each other, the rocks behave as cross-isotropic materials and, in fact, their horizontal stresses are equal in two directions. These rocks are metamorphic and have a laminar appearance (4). These rocks exhibit a cross-isotropic behavior, so the foliation orientation in these rocks strongly influences their behavior under applied loads or their reaction to unloading due to excavation. Given the complex and diverse nature of rock and soil masses, researchers have carried out extensive studies about tunnel excavations in such mediums. Investigations on the importance of anisotropy in the estimation and measurement of in situ stresses in rock mass indicated that rock properties, its formation process within the earth's crust and existing in situ stresses affect various parameters of rock and stresses, particularly compressive stresses, tend to close small joints or create discontinuities in the rock mass. As a result, the structure of rock mass behavior is nonlinear and depends on anisotropy pressures in rock mass (5). Also, the deformability and tensile strength analysis of anisotropic rocks showed that the results depend on the angle between the anisotropy planes in the rock and the direction of diagonal loading (6). Given the results of behavior of transversely isotropic rocks, the three-dimensional analysis must be conducted when transversely isotropic conditions are observed and the two-dimensional analysis and stress release modeling are not lonely adequate. The transversely isotropic behavior must be modeled for a foliated rock mass under uniform stress conditions; otherwise, the assumption of isotropic behavior of these rocks may result in damage to the support system (7). Investigations into anisotropy parameters of jointed rock masses in a mine in China showed that the damage and stress region are affected by the joint orientations and the orientation of joint plates has a significant effect on the behavior of anisotropic rocks in comparison to homogeneous rocks (8). Investigations into square tunnels in non-homogeneous soils demonstrated that the parameter of soil cohesion greatly influences the pressure on the tunnel and the stress applied on the tunnel decreases linearly as cohesion increases (9). Studies on the instable kink zone in fractured rock masses suggested that the kink zone instability develops when the main joints are at an angle of 5° to 30° to the major principal stresses under a confining pressure of less than 5 MPa (10). The heterogeneous behavior of tunneling in stratified rock masses indicated that the convergence of heterogeneous development mainly depends on asymmetric profiles in the stress-related behavior, except for tectonized rock masses that have a quasi-isotropic behavior (11). In a study on the effect of relative orientation of anisotropy planes to tunnel axis on the magnitude of tunneling displacements, it was found that the tunnel should be drilled in the opposite direction of dip if possible, because most displacements occur in the tunneling behind the tunnel face in heterogeneous earth conditions; thus, it is possible to reduce surface subsidence using stiffer linings (12, 13). In studies on tunneling in anisotropic rocks, it was found that the horizontal stress caused by tunneling in horseshoe tunnels is much less than that for circular tunnels and the horseshoe tunneling is more suitable for anisotropic rocks (14). The theory of elasticity has substantially contributed to the estimation of deformations and stresses in tunnel excavations. Given the crucial role of isotropic and anisotropic behavior assumption for rock materials in tunneling simulations, a wide range of parametric studies were done on isotropic and anisotropic rocks (15). Moreover, studies were carried out about tunneling in metamorphic rocks and its impact on surrounding structures, e.g. existing dams in tunnel construction sites (11). The results of investigations into the anisotropic behavior of stratified rock masses in tunneling showed that the interaction between rock mass layers increases the convergence, which is mainly due to bending in the rock mass stratums; so that the stratums are tangential to the tunnel section. This increase depends on the geological strength index (GSI) of rock mass encompassing the tunnel and the status of surface discontinuities (16-18).

2. RESEARCH METHODOLOGY

In this study, the effect of foliation orientation on tunneling response is evaluated using the finite element method (FEM). As explained, the foliated rocks exhibit a cross-isotropic behavior, so the foliation orientation in these rocks strongly influences their behavior under applied loads or their reaction to unloading due to excavation. Figure 1 schematically shows the elastic parameters in foliated rocks.

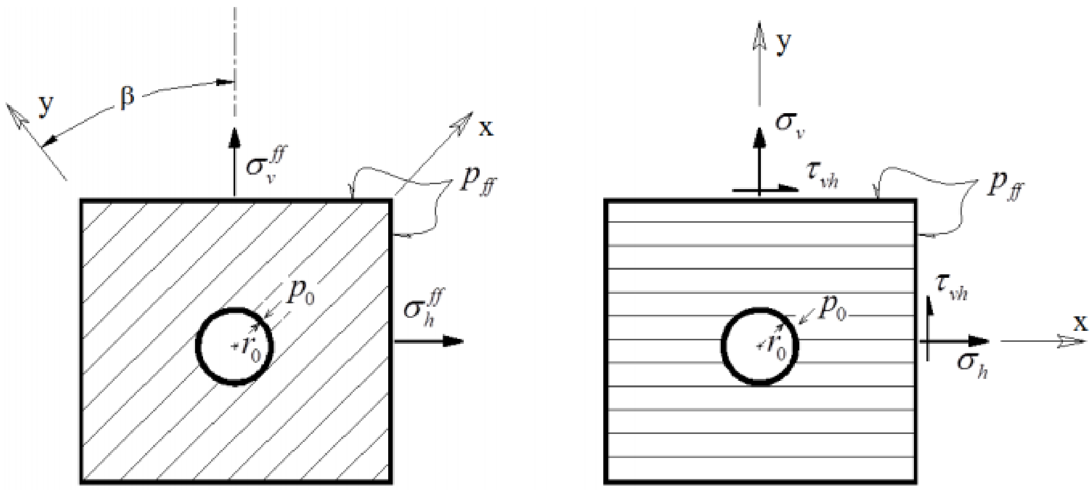

Figure 1. Elastic parameters of foliated rocks (19)

Dip angle and dip direction angle are used to introduce the orientation of foliation layers in rocks. In this study, two dip direction angles perpendicular and parallel to the tunnel axis are used and each one is evaluated using different dip angles. It should be noted that both positive and negative directions are used for selection of dip angle of foliation layers in order to examine the effect of layers along and against the tunnel excavation. Moreover, the results of different foliation orientations are compared with the tunneling response of rock model without foliation layers. It should be noted that non-laminated rocks have the same general properties as laminated rocks in this situation and stratification orientation and strength properties are not available for these layers in this model.

Table 1 shows the samples in this study that include two dip directions of 0° and 90°, each modeled using dip angles of +30°, +45°, +60°, +90°, -60°, -45° and -30°. In Table 1, the letter D is used to refer to the dip direction and the letter A is used to denote the dip angle. It is worth mentioning that the dip angle shows the stratification slope and the dip direction angle indicates the direction of foliation layer versus the tunnel axis; so that if this direction is parallel to the tunnel axis, it equals 90° and if this direction is perpendicular to the tunnel axis, it equals 0°. It should be noted that the model without stratification is referred to as “elastic”.

Table 1. Introduction of numerical samples

Name	*Dip directions angle (degrees)*	*Dip angle (degrees)*
D0-A(+30)	0	+30
D0-A(+45)	0	+45
D0-A(+60)	0	+60
D0-A(+90)	0	+90
D0-A(-60)	0	-60
D0-A(-45)	0	-45
D0-A(-30)	0	-30
D90-A(+30)	90	+30
D90-A(+45)	90	+45
D90-A(+60)	90	+60
D90-A(+90)	90	+90
D90-A(-60)	90	-60
D90-A(-45)	90	-45
D90-A(-30)	90	-30
Elastic	-	-

An elastic behavior model with Mohr-Coulomb yield surface is used to model the tunnel shotcrete lining. This behavior model includes five input parameters: Poisson’s ratio ν and Young’s modulus E (for introduction of elastic behavior), c and φ (for introduction of yield surface) and dilation angle ψ. A jointed rock behavior model is employed to introduce the behavior of foliated rock, which is an anisotropic elastoplastic behavior model used to simulate the behavior of stratified rock layers and specific fault directions. In this behavior model, plasticity can only be determined for specific directions, not for the entire elastic mass; hence these layers have their own specific parameters of c and φ. Therefore, in this behavior model, it is assumed that the origin rock has a fully elastic behavior with constant stiffness properties (E and ν) and reduced elastic properties can be defined for the stratification orientation. The plastic volume expansion caused by shear can be also expressed by dilation angle at the surface of rock layer. In order to validate the software functionality and numerical models made in this study, the results of tunnel displacement presented by Logar (12) are compared with the results of a similar numerical model developed and evaluated by the software in this research. The characteristics of tunnel modeled by logar are given in Figure 2.

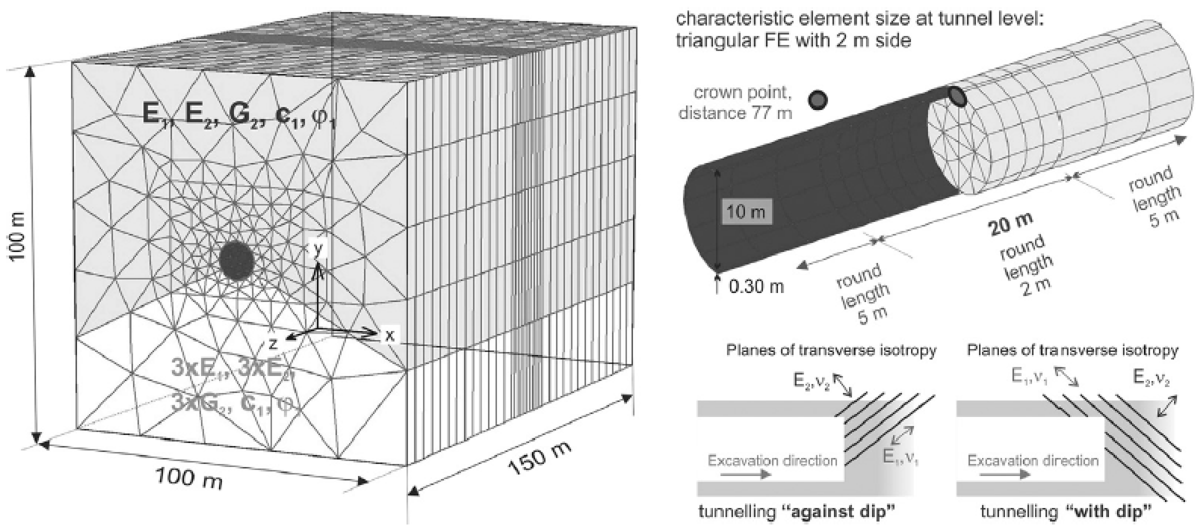

Figure 2. Geometry of tunnel modeled by Logar (12)

In this study, the geometry is modeled similar to that used by Logar. The results of study and comparison of tunnel displacements (Figure 3) show that the selection of material specifications, behavior models and other characteristics of the model are appropriate and the reliability of results can be ensured. As seen in Figure 3, the difference between displacements is very low in both models, which indicates the proper selection of tunnel specifications and reliability of software performance.

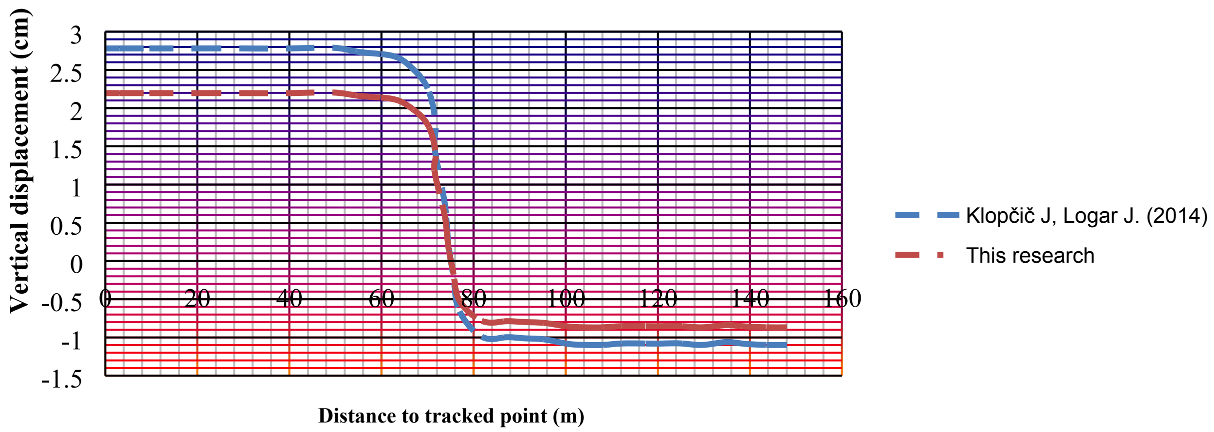

Figure 3. Comparison of results with Logar's research

The Logar's numerical model is used to introduce the characteristics of foliated rock and tunnel shotcrete. Table 2 represents the parameters used for the jointed rock modeling and Table 3 presents the parameters used for the lining specifications.

Table 2. Rock characteristics

Amount	*Parameter*	
26.5	$\gamma(kN/m^3)$	Density
600	$E(GPa)$	Young's modulus
0.25	$v_1 = v_2$	Poisson's ratio
61663	$d_1(Pa)$	Cohesion
34.6	$\beta_1(deg)$	Friction angle

Table 3. Shotcrete specifications

Amount	*Parameter*	
25	$\gamma(kN/m^3)$	Density
8	$E(GPa)$	Young's modulus
0.2	v	Poisson's ratio
5000	$c(kPa)$	Cohesion
20	$\emptyset(deg)$	Friction angle

A continuous wedge mesh with degrees of freedom 15 (C3D15) is used for modeling of the rock and a continuous 8-node cubic mesh with incompatible modes is utilized to simulate the lining (C3D8I). The appropriate boundary distance is calculated 5 times the diameter of tunnel using the convergence analysis and the average size of elements is determined 5 m according to the mesh dimensional convergence analysis.

3. DISCUSSION AND ASSESSMENT

Both directions of 0° and 90° are employed to investigate the effect of rock foliation layers, which are located perpendicular and parallel to the tunnel axis, respectively. Each foliation direction is investigated at different dip angles (β) of +30, +45, +60, +90, -60, -45 and -30. The results are evaluated at different levels by the comparison of vertical displacement of crown points for the first panel of tunnel and the assessment of effect of foliation orientation and dip. Figure 4 shows a contour of deformations around the tunnel for different foliation angles.

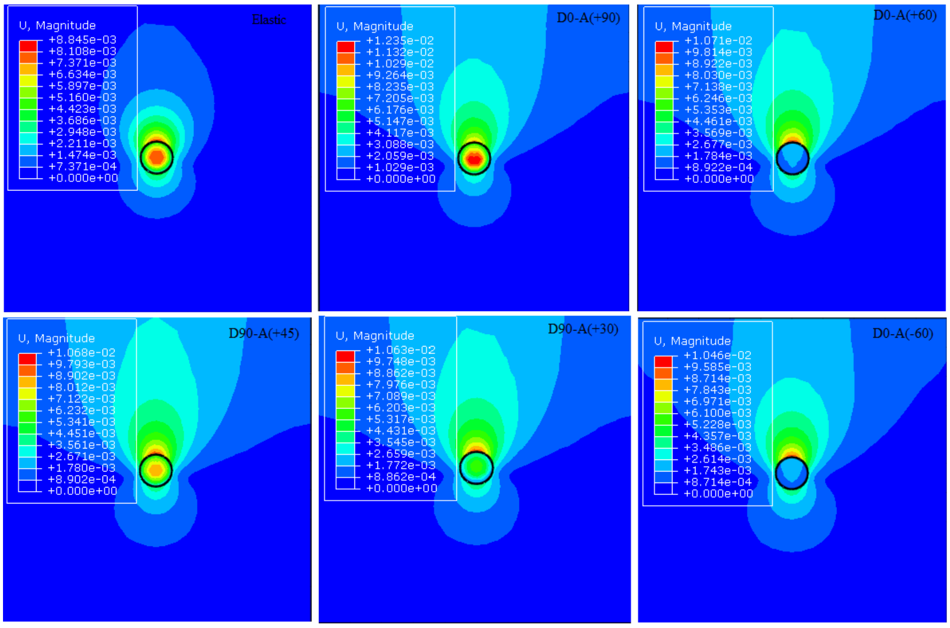

Figure 4. A contour of deformations around the tunnel for different foliation angles

The tunnel crown displacement is evaluated to study the effect of foliation direction and dip. In the charts of Figure 5 and Figure 6, the tunnel crown displacement is shown for dip directions of 0° and 90° and the dip angles of +30°, +45°, +60°, +90°, -60°, -45°, and -30°, respectively. According to the results of all charts, the maximum deformations occur at the end of excavation face, so that more than 60% of displacements happen only at a distance of 4 to 6 m from the excavation face in all charts. Moreover, 20% of displacements occur at a distance of 6 to 15 m from the tunnel face and 20% of displacements happen at a distance of first 62 m of tunneling. Therefore, the anisotropy of foliated rocks and their orientation has a significant effect on displacements (especially within a distance of 6 m from the excavation face). Thus, the deformations of the end panel should be carefully observed during tunneling in foliated rocks and drilling should be done at a lower distance along the panels in critical conditions. The maximum critical end distance is observed for dip direction of 90° and the minimum critical end distance is observed for dip direction of 0° with less dip angles (+30° and -30°). Obviously, the results of crown displacement are approximately the same along dip direction of 90° for identical dip angles in positive and negative directions, so the tunneling response is the same along or against the dip.

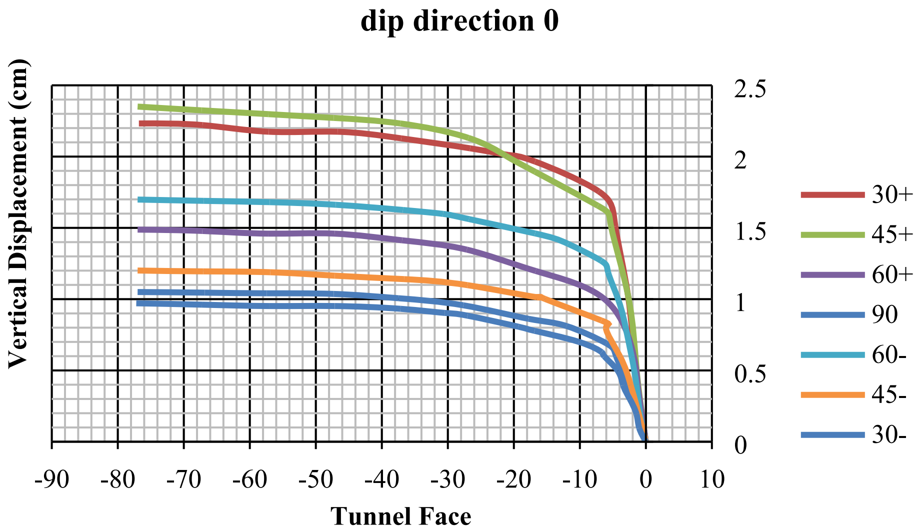

Figure 5. Vertical displacement of tunnel crown for foliation along dip direction of 0° and different dip angles

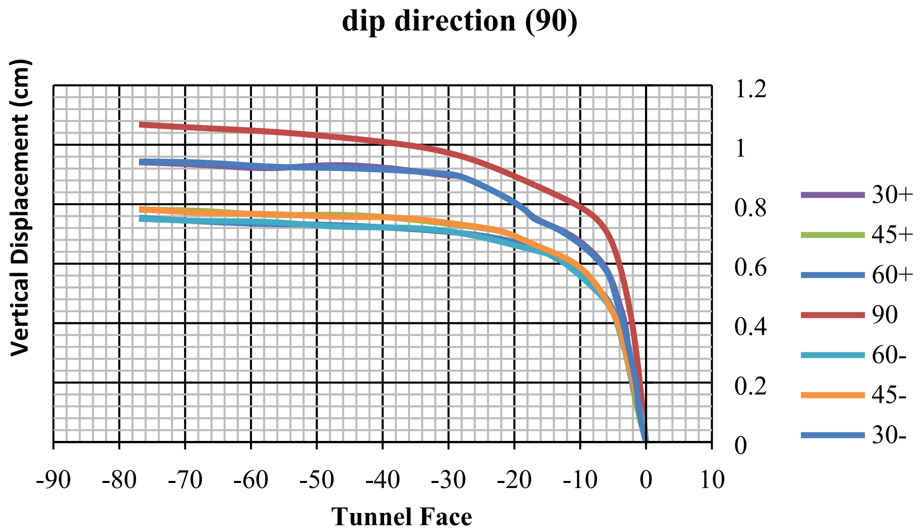

Figure 6. Vertical displacement of tunnel crown for foliation along dip direction of 90° and different dip angles

In foliated rocks, anisotropy characteristics are extremely dependent on stratification orientation and cause redistribution of stress during excavation. Therefore, significant deformations occur in unexcavated sections and panels due to the excavation of previous panels and anisotropy characteristics of these rocks. The parameter Q_1 is used according to Equation 1 to assess the effect of foliation orientation and dip, where d_1 and d_2 are the relative vertical displacement in front of the tunnel face and the relative vertical displacement behind the tunnel face, respectively. In fact, Q_1 shows the contribution of previous displacements in the tunnel face versus total displacements.

$$Q_1 = \frac{d_1}{d_1 + d_2} \quad (1)$$

In Figure 7 and Figure 8, values of Q_1 are specified for both dip directions of 0° and 90°.

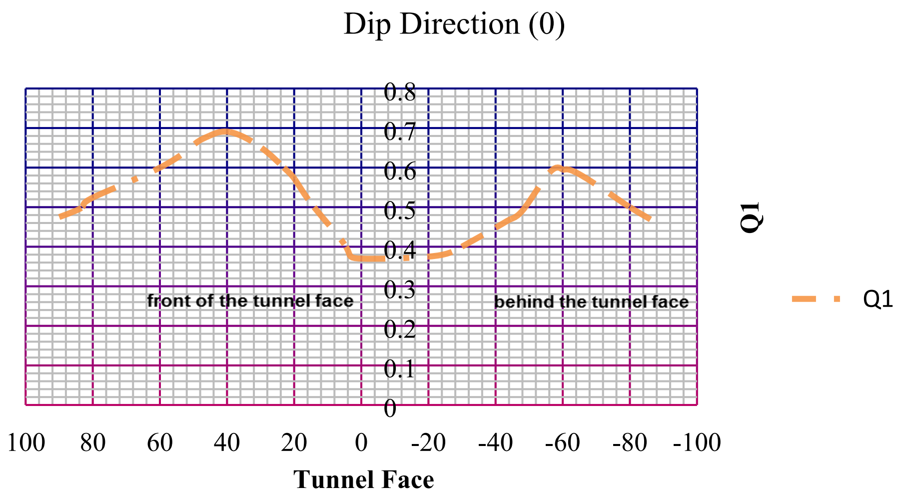

Figure 7. Values of Q1 for dip direction of 0° and different dip angles

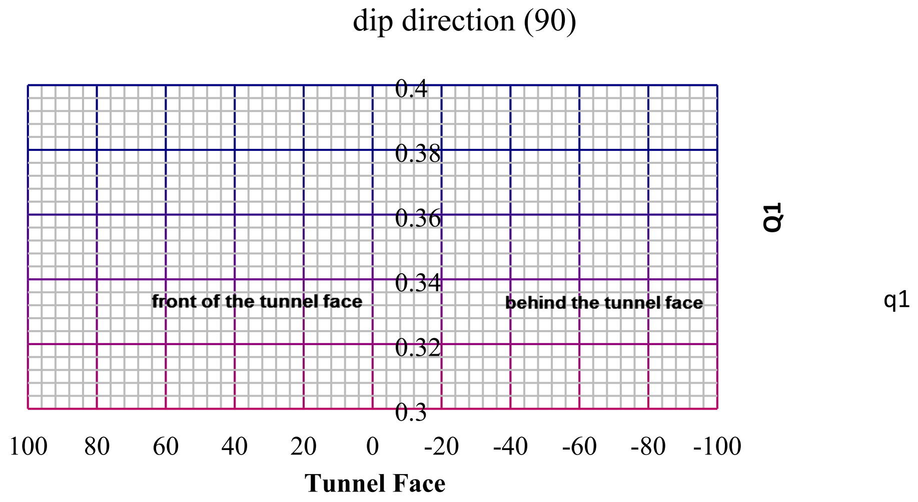

Figure 8. Values of Q1 for dip direction of 90° and different dip angles

A comparison of the results shows that when the direction of foliation is 0°, the values of Q_1 are the same for different dip angles but have different signs for excavation along and against the dip. In other words, if the foliation orientation is perpendicular to the tunnel axis and the tunnel is excavated along the dip, most deformations occur before the section of excavation face. However, if the excavation is started in the opposite direction of dip, most displacements happen before the excavation face (behind the tunnel face). This is a very practical issue that affects the choice of excavation direction in pragmatic problems and the excavation direction must be chosen according to regional conditions, e.g. low or high depth of excavation, proximity to densely populated areas and structures susceptible to settlement, etc. This function along the foliation dip direction of 0° is due to the fact that if the excavation is carried out in the direction of slope, the rock mass deformations occur toward the excavation site and the subsidence is affected by the speed of lining, but the conditions are completely different for tunneling in the opposite direction of slope and the rock mass deformations happen toward the excavation face. The slope leads to the same results for the dip direction of 90° along or against excavation dip and the Q_1 is not affected by the dip angle of layer.

4. CONCLUSION

In the present study, the effect of foliation orientation on the displacement of tunnels excavated in metamorphic rocks is evaluated. Foliation is the most important structural characteristic of metamorphic rocks, resulted from the preferential orientation of the rock minerals. Investigations show that the strength and deformability behavior and the failure mode of these rocks depend on the angle of loading direction, foliation rate and amount of lateral pressures; so that as lateral pressures increase, the effect of foliated surfaces is reduced and the rock behavior becomes more uniform in different directions. To investigate the vertical displacement of crown section for the first panel of tunnel and to assess the effect of foliation direction and dip in tunnel displacements in this study, different samples are evaluated for two foliation directions of 0° and 90° at dip angles of +30°, +45°, +60°, +90°, -60°, -45° and -30°. The results of this research are as follows:

1. In all samples, the vertical displacement of tunnel crown occurs at a distance of 4 to 6 m from the critical face, so that more than 60% of deformations happen in this area. It should be noted that 20% of deformations are reported at a distance of 6 to 15 m from the excavation face section. For the foliation direction of 90°, the excavation direction does not affect the tunnel excavation response.
2. In all studied samples, the tunnel crown displacement for the same excavation panel in foliated rocks is higher than the tunnel crown displacement of the tunnel crown in non-foliated rocks with the same general properties, which indicates a decrease in strength properties and stiffness of these rocks.
3. If the foliation direction is perpendicular to the tunnel axis and the tunneling is done along the dip direction, most deformations occur behind the tunnel face. However, if the excavation is started in the opposite direction of dip, most displacements occur in front of the tunnel face.
4. In samples with a dip direction of 0°, changes in the layer properties affect the Q_1 value. However, in samples with a dip direction of 90°, no significant effect on Q_1 values is observed.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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