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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
The response behavior of tunnels has always been a concern for geotechnical engineers during excavation operations in a variety of stones due to the differences in excavation behavior exhibited by rocks with different degrees of continuity, discontinuity, elastic behavior, isotropy, and heterogeneity. The composition of anisotropic rocks varies in different directions and at different points. This research measures how tunnel excavations in metamorphic rocks change in position as a result of foliation orientation. As a result, the tunneling process is simulated for a metamorphic rock medium with varying foliation planes. More than 60% of the deformations in all samples occur between 4 and 6 meters away from the key tunnel face, where the vertical displacement of the tunnel crown may be observed. Sixteen to twenty meters out along the excavation face section is where the majority of recorded deformations occur (20%)..

Keywords: Tunnel, Excavation, Metamorphic rock, Foliation orientation.

1. INTRODUCTION

Being cognizant of the rock mass's strength and deformability qualities is crucial in tunnel and subterranean space design. Recognizing these characteristics in jointed and fractured rocks calls for the use of robust theoretical and empirical foundations (1). However, most rocks do not display a fully elastic behavior on a field scale due to cracks, fractures, laminations, contact surfaces, metamorphic zones, and clay with flexible qualities (2), even if many hard rocks exhibit an elastic behavior in laboratory samples. Properties of the rock mass, such as its strength and deformability, are often heavily influenced by the geologic structure. For example, biaxial slides or deformations along the planes formed by the discontinuities might cause the rock mass to collapse (3). Rocks behave as cross-isotropic materials, with equal horizontal stresses in both directions, when flat minerals like mica, talc, chlorite, and serpentine are aligned parallel to one another within the rock, or when the direction of long minerals like amphibole is such that their longitudinal axes are parallel to each other. These rocks have a laminar look and are metamorphic in nature (4). Since these rocks have a cross-isotropic behavior, their response to applied stresses or unloading due to excavation is very sensitive to the orientation of their foliation. Researchers have studied tunneling through rock and dirt extensively because of the difficulty of doing so. Compressive stresses, in particular, have been shown to close small joints or create discontinuities in the rock mass, and studies on the significance of anisotropy in the estimation and measurement of in situ stresses in rock mass have revealed that rock properties, its formation process within the earth's crust, and existing in situ stresses affect various parameters of rock. Consequently, the behavior structure of rock masses is nonlinear and is affected by anisotropy pressures (5). When analyzing the deformability and tensile strength of anisotropic rocks, it was found that the findings change depending on the angle between the anisotropy planes and the direction of stress applied to the rock.

a six-grid payload of gb. Because two-dimensional analysis and stress release models are insufficient when transversely isotropic circumstances are encountered, a three-dimensional study must be performed. Assuming isotropic behavior of these rocks might lead to structural failure (7), thus it's important to simulate their transversely isotropic behavior under uniform stress circumstances. Anisotropy parameter studies conducted on jointed rock masses in a Chinese mine revealed that the orientation of joint plates significantly affects the behavior of anisotropic rocks when compared to homogeneous rocks (8). Recent research into square tunnels in heterogeneous soils has shown that the parameter of soil cohesion considerably affects the pressure on the tunnel, with the stress exerted on the tunnel decreasing linearly with increasing cohesion (9). According to research on the unstable kink zone in brittle fractured rock masses, the instability sets in at a confining pressure of less than 5

MPa (10), when the main joints are at an angle of 5° to 30° to the major primary stresses. In contrast to tectonized rock masses, which exhibit a quasi-isotropic behavior (11), the heterogeneous behavior of tunneling in stratified rock masses suggests that the convergence of heterogeneous development mostly rely on asymmetric profiles in the stress-related behavior. The size of tunneling displacements may be affected by the orientation of the anisotropy planes with respect to the tunnel axis, and it was determined that the tunnel should be As most displacements happen in the tunneling below the tunnel face conditions, surface subsidence can be reduced by drilling in the opposite direction of dip (12, 13). Studies of tunneling in anisotropic rocks have shown that horseshoe tunneling is better appropriate for anisotropic rocks due to the significantly lower horizontal stress incurred while digging compared to circular tunnels. Deformation and stress estimate in tunneling has benefited greatly from the theory of elasticity. Numerous parametric investigations on isotropic and anisotropic rocks (15) were conducted due to the importance of these behavior assumptions for rock materials in tunneling simulations. Further, research has been done on the effects of tunneling through metamorphic rocks on nearby infrastructure such existing dams during tunnel construction (11). Studies of the anisotropic behavior of stratified rock masses in tunneling have revealed that the convergence is exacerbated by the contact between rock mass layers, which is mostly attributable to bending in the rock mass stratums. This boost is conditional on the GSI of the rock mass around the tunnel and the condition of any surface discontinuities (16-18).

2. RESEARCH METHODOLOGY

Using the finite element technique (FEM), this research examines how foliation orientation influences the tunneling response. For the reasons stated, the foliation orientation in these rocks has a significant impact on how they respond to weights or how they deform when unloaded, such as during excavation. Figure 1 is a simplified illustration of foliated rocks' elastic characteristics.

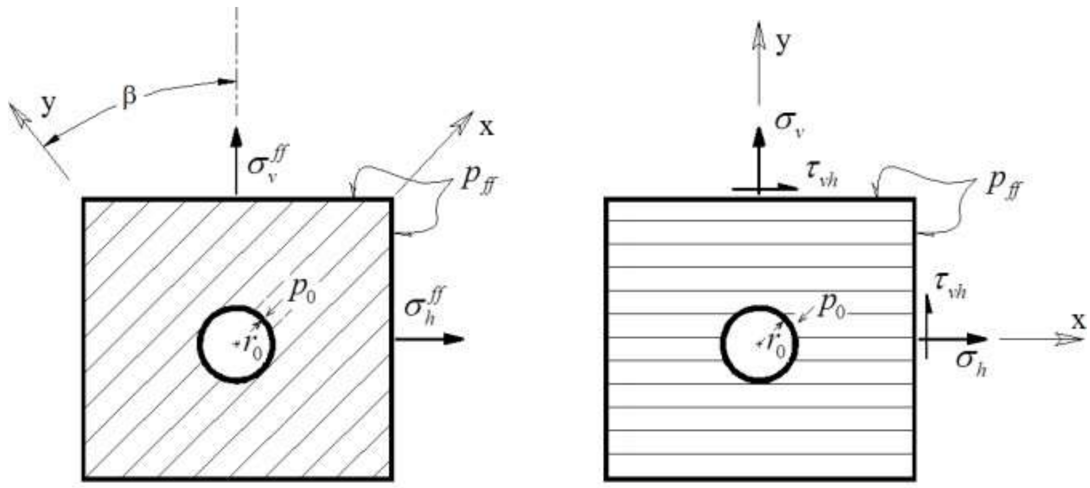

Figure 1. Elastic parameters of foliated rocks (19)

In rocks, foliation layers are oriented according to the dip angle and the dip direction angle. separate dip angles are used to assess two separate dip directions: one perpendicular to the tunnel axis and the other parallel to it. In order to compare the impact of foliation layers running with and against the tunnel's axis of excavation, the dip angle of these layers is chosen in both the positive and negative polarities. In addition, the tunneling response of a rock model devoid of foliation layers is compared to the findings obtained from various foliation orientations. Stratification orientation and strength qualities are not provided for these layers in this model, however it is important to remember that non-laminated rocks have the same overall properties as laminated rocks in this case.

In Table 1, we see that the samples in this study were modeled with dip angles of +30 degrees, +45 degrees, +60 degrees, +90 degrees, -60 degrees, -45 degrees, and -30 degrees, with two dip directions of 0 degrees and 90 degrees. In

In Table 1, the dip direction is denoted by the letter D and the dip angle by the letter A. The stratification slope may be seen in the dip angle.

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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	-	-

To simulate the shotcrete lining's performance in a tunnel, an elastic behavior model is employed, complete with a Mohr-Coulomb yield surface. Poisson's ratio v and Young's modulus E (for introducing elastic behavior), c and (for introducing a yield surface), and the dilation angle are the five input parameters for this behavior model. An anisotropic elastoplastic behavior model, which is utilized to mimic the behavior of stratified rock layers and particular fault orientations, is used to introduce the behavior of foliated rock. Plasticity in this behavior model is direction-dependent rather than elastic-mass-dependent, therefore each layer has its own unique values for c and. As a result, the origin rock is considered to be fully elastic, with constant stiffness characteristics (E and), and stratification-oriented reductions in elasticity are described in this behavior model. The shear-induced increase in plastic volume may also be described in terms of the dilation angle at the rock's surface. The tunnel displacement findings reported by Logar (12) are compared with the results of a comparable numerical model generated and analyzed by the software in this investigation to validate the software's functioning and the numerical models made in this study. The tunnel features were model

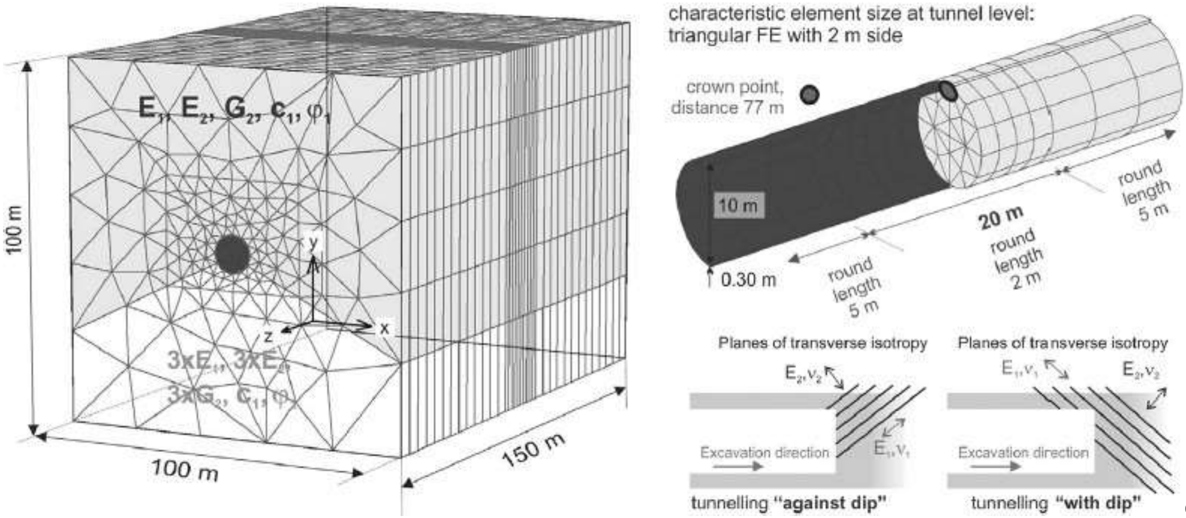

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Figure 2. Geometry of tunnel modeled by Logar (12)

The geometry is represented in a way that is analogous to what Logar did. Analysis and comparison of tunnel displacements (Figure 3) demonstrates that the model's parameters and assumptions are well-founded, guaranteeing the accuracy of the findings. Figure 3 shows that the difference in displacements between the two models is small, confirming that accurate tunnel parameters were chosen and that the software's results may be trusted.

Table 2. Rock characteristics

Amount	Parameter	
26.5	$\gamma(kN\ m^3)$ /	Density
600	$E(GPa)$	Young's modulus
0.25	$\nu_1 = \nu_2$	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	ν	Poisson's ratio
5000	$c(kPa)$	Cohesion
20	$\emptyset(deg)$	Friction angle

3. The rock is modeled using a C3D15 continuous wedge mesh, while the lining is simulated using a C8D8I continuous 8-node cubic mesh with incompatible modes. Convergence analysis is used to define a border distance equal to five times the diameter of the tunnel, and the average element size is set at five meters.

4. DISCUSSION AND ASSESSMENT

5. Rock foliation layers are studied in two orientations, either perpendicular to the tunnel axis (0°) or parallel to it (90°). Different dip angles () of +30, +45, +60, +90, -60, -45, and -30 are explored for each foliation direction. The influence of foliation orientation and dip is assessed, and the vertical displacement of crown points in the first tunnel panel is compared. Figure 4 shows a contour of deformations around the tunnel for different foliation angles.

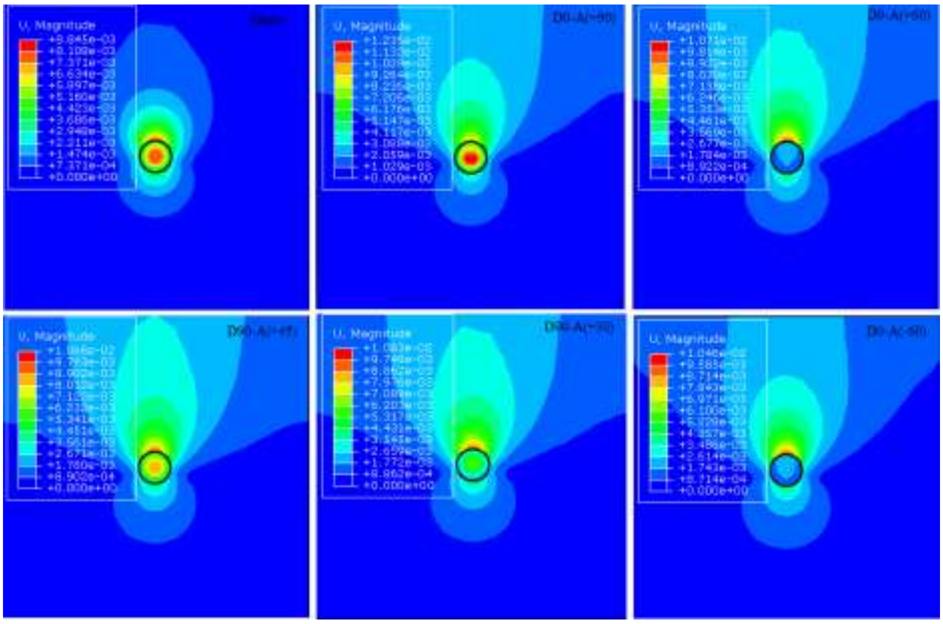

Figure 4. A contour of deformations around the tunnel for different foliation angles

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 fordip 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

The influence of foliation direction and dip is analyzed using the tunnel crown displacement. Figure 5 and Figure 6 illustrate the tunnel crown displacement for 0 and 90 degree dip directions, as well as for 30 and 45 degree dip angles, 60 and 90 degree dip angles, -60 and -45 degree dip angles, and -30 and -45 degree dip angles. Maximum deformations, as shown by all charts, occur towards the end of the excavation face, with more than 60% of all displacements occurring within a radius of 4–6 m of the face. In addition, the first 62 meters of digging saw 20% of all displacements, with another 20% happening between 6 and 15 meters from the tunnel face. Thus, foliated rocks' anisotropy and orientation play a

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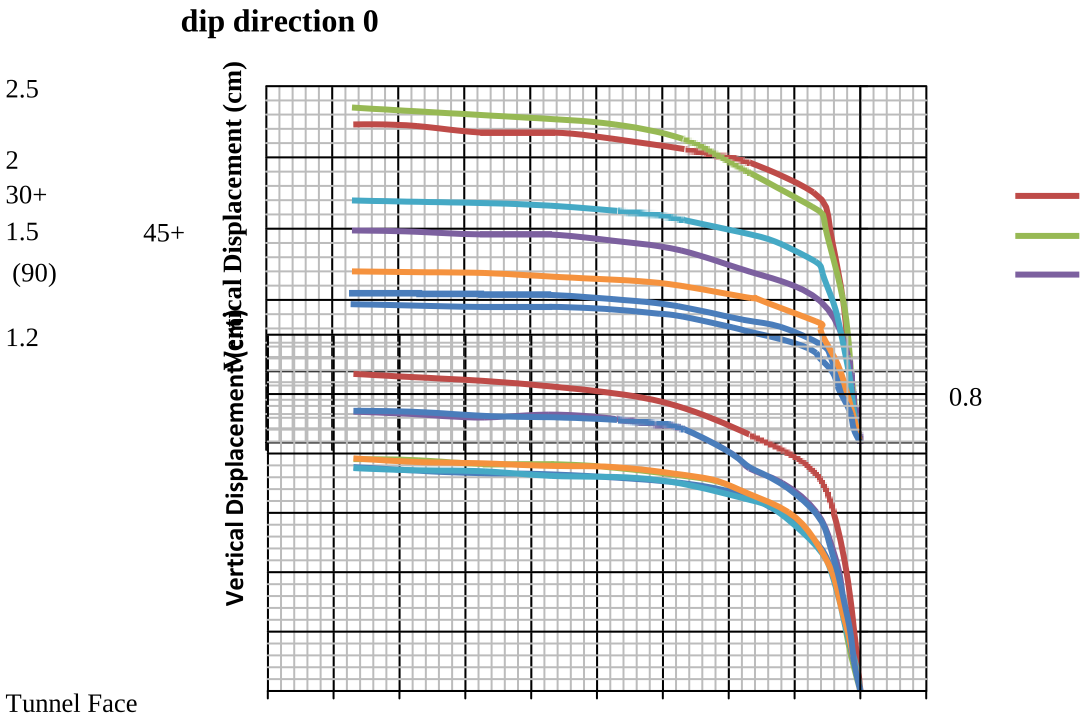
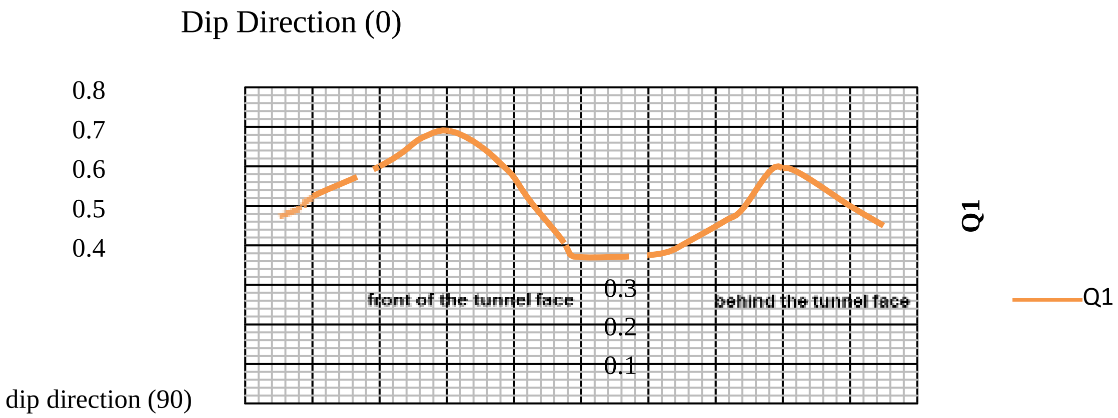


Figure 6. Vertical displacement of tunnel crown for foliation along dip direction of 90° and different dip angles

Anisotropy features in foliated rocks generate stress redistribution during excavation and are highly reliant on stratification orientation. Unexcavated areas and the relative vertical displacement behind the tunnel face undergo substantial deformations as a result. In reality, Q1 illustrates the relative importance of past tunnel face displacements to overall displacements.

panels because of the anisotropy of these rocks and the excavation of prior panels. The influence of foliation direction and dip may be evaluated with the use of the parameter Q1 by plugging d1 and d2 into Equation 1.

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



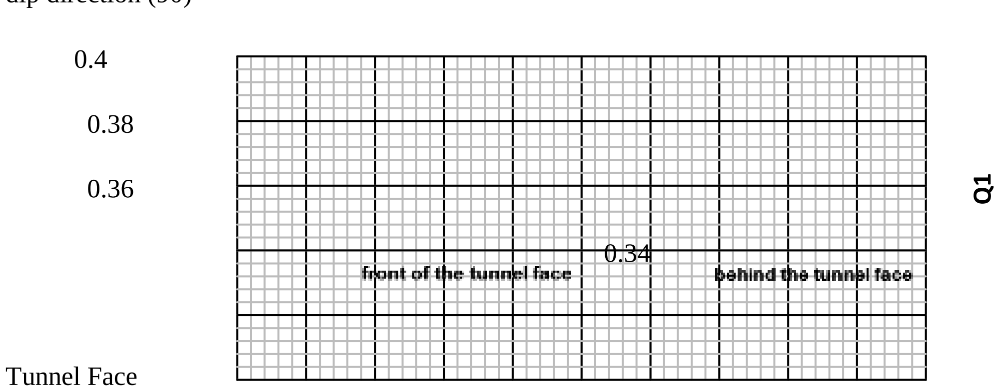


Figure 8. Values of Q1 for dip direction of 90° and different dip angles

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When the foliation angle is 0 degrees, the values of Q1 are the same for different dip angles, but have opposite signs for excavation along and against the dip, as shown by a comparison of the findings. In other words, most deformations happen before the section of excavation face if the tunnel is excavated down the dip and the foliation orientation is perpendicular to the tunnel axis. When excavation begins in the direction of dip, however, most displacements occur before the excavation tunnel's back wall) in front of you. Given geographical conditions (such as low or high depth of excavation, proximity to highly inhabited regions and structures vulnerable to settlement, etc.), this is a very practical issue that impacts the choice of excavation direction in pragmatic difficulties. This behavior occurs along the zero-degree foliation dip because, when excavating downslope, rock mass deformations occur toward the excavation site and the subsidence is affected by the speed of lining, but when tunneling upslope, rock mass deformations occur toward the excavation face, creating entirely different conditions. The Q1 is not influenced by the dip angle of layer, and the slope produces the same results whether the dip is 90 degrees along or against the excavation dip.

6. CONCLUSION

This research measures how tunnel excavations in metamorphic rocks change in position as a result of foliation orientation. The preferred orientation of rock minerals causes foliation, the most notable structural feature of metamorphic rocks. As lateral pressures increase, the effect of foliated surfaces decreases, and the rock behavior becomes more uniform in different directions, as shown by the investigations; 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. Examining the influence of foliation and looking at the vertical movement of the crown section for the first tunnel panel.

slope and tilt of tunnel movements In this research, two foliation directions (0 and 90 degrees) are examined at various dip angles (+30 degrees), (45 degrees), (60 degrees), (-45 degrees), and (-30 degrees). The following are the findings from this study:

More than 60% of all deformations take place between 4 and 6 meters from the crucial face, where the vertical displacement of the tunnel crown occurs in all samples. Six to fifteen meters out from the excavation face portion is where 20% of all observed deformations occur. When excavating in a 90° foliation direction, the tunnel excavation reaction is independent of excavation direction.

Second, a decrease in strength properties and stiffness of these rocks is indicated by the fact that the tunnel crown displacement in foliated rocks is greater than the tunnel crown displacement of the tunnel crown in non-foliated rocks with the same general properties.

Third, most deformations take place behind the tunnel face if the foliation direction is perpendicular to the tunnel axis and the tunneling is performed along the dip direction. Most displacements happen in front of the tunnel face if excavation is begun against the direction of dip.

The Q1 value is sensitive to variations in the layer parameters, and this is especially true for samples with a 0° dip direction. No noticeable change in Q1 values is seen, however, in samples with a dip direction of 90 degrees.

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