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Influence of Foliation Orientation on Tunnel Behavior

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Abstract

The relative orientation of foliation or closely spaced bedding has an important influence on the behavior of underground structures. Not only the potential failure mode is controlled by the relative orientation between underground opening and foliation strike, but also the longitudinal development of the displacements. Case histories and numerical simulations have shown that the magnitude of the displacements can differ almost by an order of magnitude for cases where the strike is parallel and perpendicular to the tunnel axis respectively. The reason is the usually low shear strength parallel to the foliation, which can lead to shearing or buckling failure modes. The knowledge of the influence of the relative foliation orientation on the mechanical behavior of the ground is extremely important for excavation and support design. The paper will show the results of numerical simulations, as well as monitoring data from tunnels in foliated rocks. Recommendations for excavation and support strategies are given.

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1. Introduction

Frequently homogeneous models are used for the design of tunnels, applying empirical relations to account for the jointing influence on strength and deformability. Those methods may result in more or less realistic results in generally fractured rock masses, but will not be able to provide realistic results in strongly anisotropic rock masses.

The structure of the rock mass plays an important role for the behavior of tunnels. The generally reduced shear strength, as well as missing tensile strength perpendicular to the foliation can lead to shearing along

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the discontinuities, as well as their opening. Depending on the relative orientation between tunnel axis and foliation orientation the modes change between opening of discontinuities, shearing, shearing and opening, as well as buckling. The discontinuities also influence the development of the displacements in longitudinal direction, as well as the orientation and magnitude in the cross section. Results from numerical simulations and examples of measured displacements shall demonstrate this [1, 2].

2. Excavation parallel and perpendicular to foliation strike

To start out, we deal with relatively simple cases, namely when the foliation strikes perpendicular, respectively parallel to the tunnel axis.

2.1. Foliation strike parallel to the tunnel axis

In case the foliation strikes parallel to the tunnel axis, shearing along discontinuities with low shear strength, as well as opening of discontinuities are the dominating phenomena. Figure 1 demonstrates very clearly the change in displacement magnitude and orientation when the dip angle of the foliation is varied.

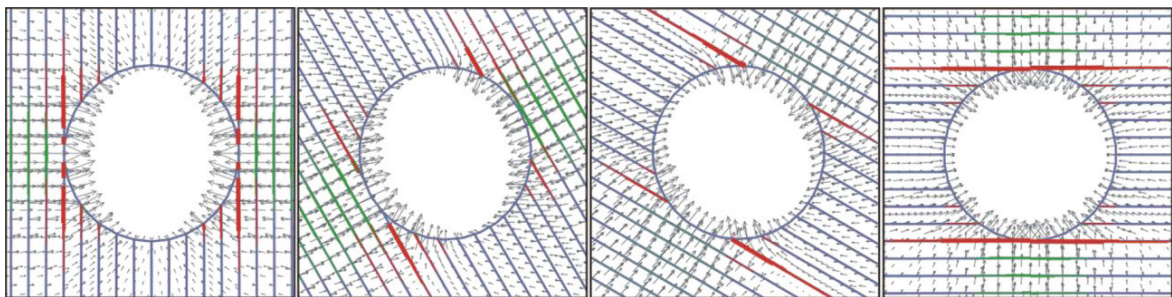


Fig.1. UDEC simulation of various joint dip angles, showing shearing and opening of discontinuities; foliation strike parallel to tunnel axis [1].

Generally, the largest displacement can be observed perpendicular to the foliation due to opening of the joints, and bending of the layers. Shearing predominately is observed at the discontinuities tangent to the tunnel perimeter. Stress redistribution perpendicular to the foliation is possible only to a limited extent, causing high stresses in the layers tangent to the tunnel, and a relative extended influence length ahead and behind the face. In addition, the magnitude of the displacements is considerably larger compared to cases with homogeneous material or in case of strike perpendicular to the tunnel axis [1, 2].

The localized shearing along the foliation during construction can lead to shearing of the lining (Figure 2 left). In many cases the shear displacement is rather limited until new equilibrium is reached. In order to prevent damage of the lining, bolts can be installed, preferably in an acute angle to the potential shear plane. However, when grouted bolts are used, it is questionable, if the grout has set to an extent allowing the transfer of larger stresses. As the overall stability usually is not jeopardized by the shearing, a pragmatic way of preventing damage to the lining is leaving an open slot in the critical regions (Figure 2 right), which is filled with shotcrete after displacements have come to a halt.



Fig. 2. Shearing of lining due to localized shearing along foliation (left), and open slot in the lining to allow for localized displacements without damage to the lining.

2.2. Foliation strike perpendicular to the tunnel axis

In case the foliation strikes perpendicular to the tunnel axis and the dip is approximately vertical, stress redistribution is easy in lateral direction, but limited across the foliation planes in longitudinal direction. As a consequence, the majority of the stress redistribution occurs close to the area of excavation, with a relatively small amount of displacements ahead of the face, and a relatively short influence length behind the face. Figure 3 shows the normalized displacement development for the cases of strike parallel and perpendicular to the tunnel axis for a 10 m diameter tunnel. Displacements are normalized to the final displacements of each case.

In case of shotcrete linings, the relatively rapid development of the displacements behind the face may lead to an overstressing of the still fresh shotcrete. This is of special importance in cases where the excavation has been stopped for some time, allowing the shotcrete to increase in stiffness.

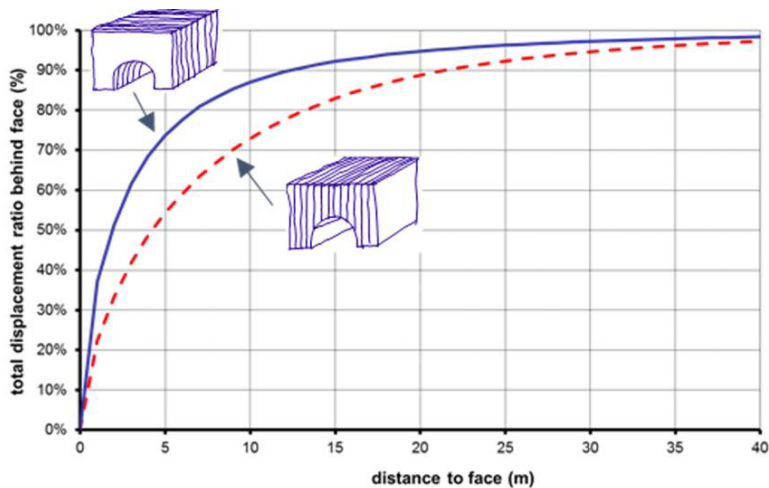


Fig. 3. Normalized displacement development behind tunnel face; solid line: strike perpendicular to tunnel axis, dashed line: strike parallel to tunnel axis for a tunnel with 10m diameter [1].

3. Numerical simulations

In order to systematically evaluate the influence of foliation on the ground and system behavior, numerical simulations as well as monitoring results have been used. Numerical simulations were performed with the code FLAC3D, using the ubiquitous joint model [2].

Considering symmetrical behavior, the following trend evaluations make use of the eastern area of the stereogram ($000 < DD < 180$). Direction of tunnel excavation in all cases was taken to direction 0 (North).

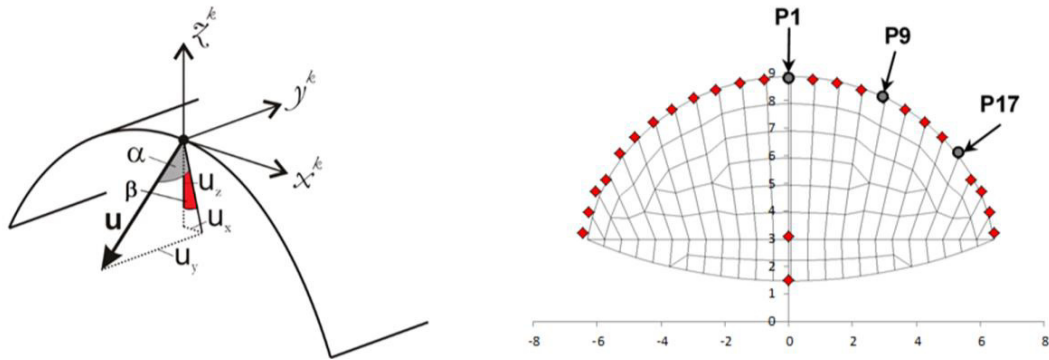


Fig. 4. Convention summary and monitored points; (radial displacement ‘Uz’, tangential displacement ‘Ux’ and longitudinal displacement ‘Uy’. Deviation of displacement vector orientation in longitudinal direction ‘α’ and deviation of displacement vector from radial direction ‘β’.

Trends are evaluated in terms of magnitude, expressed by radial and tangential displacements and displacement vector angle orientation, summarized by Beta (2D) and Alpha (3D) rotation. The used conventions and monitoring points are shown in Figure 4.

Making use of a calibrated numerical model (calibration based on on-site displacement monitoring data from the Galgenbergtunnel), it was feasible to simulate the ground behavior of foliated rock masses varying the relative orientation of the foliation with respect to the tunnel axis.

The results presented in are normalized by the maximum displacement. Figure 5 shows the variation of the displacements with varying dip angles for dip direction 45° for the three monitoring points P1 (crown), P9 (shoulder) and P17 (sidewall). A general trend can be detected:

- While the magnitude of displacements does not change too much at the crown (P1), the sidewall shows a considerable increase in displacement magnitude, once the dip angle exceeds 30° , with a maximum at a dip angle of 45° , showing an increase over the homogeneous reference model by approximately 45%. This is linked to the shearing along the foliation, where the foliation is quasi-tangent intersects to the excavation perimeter.

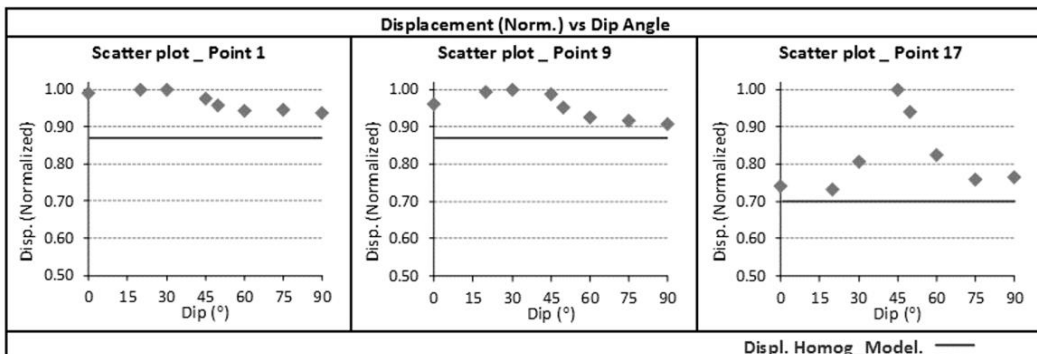


Fig. 5. Scatter plots, displacements vs. dip angles for dip direction 45° (DD045); as a reference the displacements of the homogeneous model are shown as solid lines.

Figure 6 shows the influence of varying dip directions on the magnitude of displacements. Dip angle has been fixed at 45°. Again the most significant influence on the displacements can be observed at the sidewall (P17), as the strike of the foliation approaches a parallel orientation to the tunnel axis.

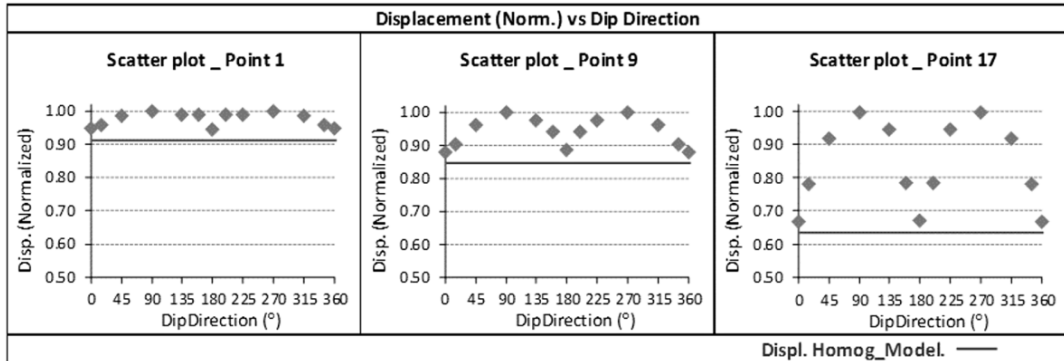


Fig. 6. Scatter plots, normalized displacements vs. dip directions; dip angle fixed at 45°.

Figure 7 shows the deviations in the displacement vector orientation with varying dip angle for the case with dip direction 45°. Again, it can be observed that the largest deviations occur at the sidewalls, with a deviation of the displacement vector orientation as well in longitudinal direction (ΔAlpha), as in the cross section (ΔBeta) of up to nearly 20° compared to the homogeneous model.

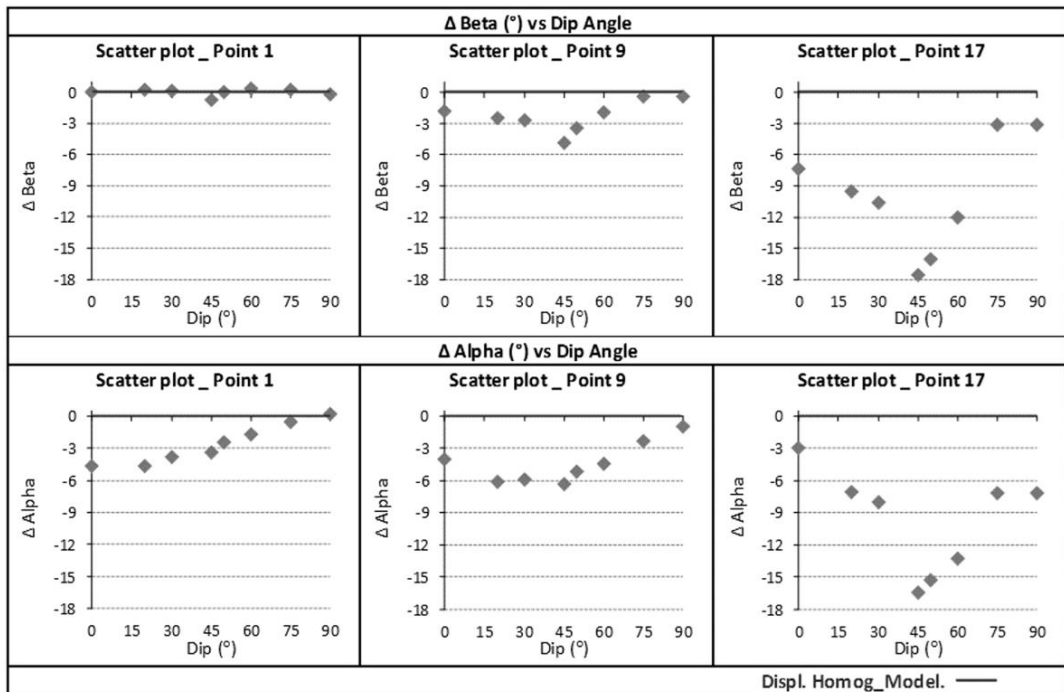


Fig. 7. Scatter plots, deviation of displacement vector orientations vs. dip angle for dip direction 45°.

This deviation of the displacement vector orientations has frequently been observed also on site. Figure 8 shows the result of displacement monitoring of a tunnel constructed in phyllites, where the foliation's strike was subparallel to the tunnel axis, with a dip angle of approximately 55° . It can be seen that the right sidewall point (3) is pointing in direction of advance, while the displacement vector at the left sidewall points in the opposite direction. As the relative orientation between foliation strike and tunnel axis changes, also the displacement vector orientations change in a characteristic manner.

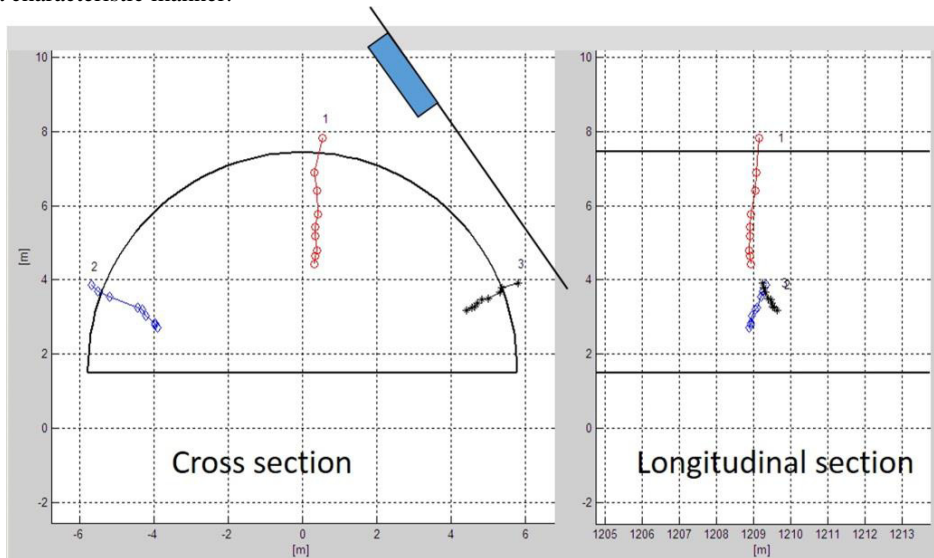


Fig. 8. Displacement vector plot from a tunnel in foliated rock mass, Dip direction approximately 120° , dip angle approximately 55° ; cross section (left) and longitudinal section (right); direction of advance from the left to the right.

4. Conclusion

For safe and economical tunneling it is essential to continuously adjust construction to the ground conditions. Several aspects have to be considered to allow for optimum construction. Among those aspects are the prediction of the tunnel deformation to be able to provide for sufficient over-excavation in order not to violate the clearance profile. This is of particular importance in foliated rock masses, where the mechanism and the magnitude of the displacements can change dramatically, as the relative orientation between tunnel axis and foliation strike changes. The knowledge about the particular mechanisms is of great importance when deciding on appropriate support. In case major shearing is expected, dense bolting usually is recommended to reduce shear localized shearing. With higher ground stress, the use of a non-continuous lining or a ductile lining with integrated yielding elements allows for limiting damage to the lining, without impairing the overall stability. Simplified procedures and models will not provide reliable information on this subject.

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