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Evaluation of the influence of the rock mass structure on the deformation behavior of tunnels

T. Solak
General Directorate of Turkish Highways, Turkey

W. Schubert
Graz University of Technology, Austria

ABSTRACT: During the construction of tunnels, the system behaviors derived from the design are verified and updated by absolute displacement monitoring. Advanced evaluation methods of the monitoring data enable detecting the influence of geological features on the rock mass behavior around the tunnel. Displacement data from Alpine tunnels were analyzed in correlation with the geological structure. The influences of the geological features (orientation of the joint sets and their strength properties) and fault zones on the deformation behavior of the tunnel were investigated. The monitoring data were compared to the results of the numerical simulations of the tunnel excavation in rock masses with two joint sets with UDEC.

1 INTRODUCTION

The Austrian Society of Geomechanics (ÖGG 2001) recommended a procedure for the geomechanical design both at design and construction stage. At the design stage for the evaluation of the potential rock mass behavior, rock mass types and local influencing factors including the relative orientation of relevant discontinuities to the excavation are considered. Relative orientation of the underground structure and discontinuities are used as a basis for kinematical analyses and the influence of the rock mass structure on the stress redistribution are evaluated.

Failure mechanisms are determined by numerical analyses which allow the modeling of discrete failure planes. At the construction stage observations during excavation such as signs of excessive stress, deformation pattern and observed failure mechanisms and results from probing ahead are used to continuously update the geological model. The reaction of the ground to the excavation has to be observed, using appropriate geotechnical monitoring methods.

With the displacement vector plots the influence of the rock mass structure can easily be observed as well as failure mechanisms detected. Using vector plot in a cross section, structures like faults outside the tunnel profile can be detected before they can be seen at the face and influence of dilatation and shearing on displacement vector orientations can be seen (Schubert 2002).

Considering the value of evaluation methods for specific questions, vectors in the cross section give good results for detection of weak zones outside profiles (Schubert et al. 2002).

Sellner developed software (GeoFit) for the prediction of displacements. This software has been applied on several Austrian tunnel projects to predict normal behavior and detect deviations from the normal behavior (Sellner et al. 2002, 3G).

Case histories from the tunnels in phyllites, where 3 D absolute displacement monitoring was carried out, have been used to identify the influence of the rock mass structures. For phyllites basic key parameters are stated as anisotropic strength and deformability associated with the foliation. The main influencing parameters are relative orientation of foliation to the excavation, fault orientations and spatial characteristics. For the identification of failure modes for the tunnels in phyllites the documented geological conditions and monitored displacements were evaluated (Button 2004 & Button et al. 2004).

2 EVALUATION OF MONITORING DATA

The absolute displacement measurements from the Strenger tunnel are analyzed to evaluate the influence of the rock mass structure on the deformation behavior of the tunnel. The Strenger Tunnel on the S16 four lane express way between Landeck and Bludenz has two tubes with a diameter of approximately 10 m. Maximum overburden reaches more than 600 m. The rock mass primarily is quartz phyllite consisting mainly of quartz phyllonites and phyllonitic mica schists. The uniaxial compressive strength of the phyllites is between 15–25 MPa. The foliation strikes nearly parallel to the tunnel axis, and its dip angle is between 50° to 80° to the South. Additional joint sets striking nearly parallel to the tunnel axis show dip angles between 40°–70°.

Due to this condition monitored displacements in the cross section can be compared to the results of 2 dimensional numerical simulations carried out considering the characteristics of the Strenger tunnel (Solak & Schubert 2004). The comparison is done based on the general behavior considering the influence of block size, shape and joint residual strength. For the sake of simplicity sequential excavation and supports are not considered in the numerical analyses.

In Figure 1 the displacement vector orientations from a section of the tunnel with lower overburden are shown. In this case the foliations dip is to the left. The displacements are more or less uniform and directed radially. It is interesting to note that the biggest displacements in general are at the shoulder/sidewall located under the foliation, with an orientation approximately perpendicular to the foliation (points 2 and 6 in Figure 1).

With increasing overburden stresses and displacements increase. In Figure 2 the measured displacements at the station 1935 m are compared to the calculated values shown with arrows. The measured displacement orientations agree well with those calculated with the numerical model (block size = 2.9 m, apex angle = 20°, joint residual friction angle = 20°) at the early stages of measurements.

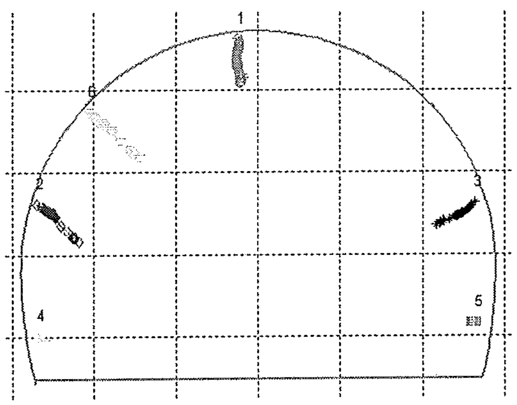

Figure 1. The displacement vector orientation in cross section.

As shear failures occur along joints the displacement vectors change their directions at the side walls and displacements increase. This process was not captured in the numerical model. A variation of parameters or an addition of additional singularities would definitely yield a better agreement. Another cause for this increase can be the heaving at the left invert measured as 20–50 cm.

The deformation history graph shows the significant increase at the side wall due to the change in mechanism. The deformation curve deviates from the normal behavior which is predicted by GeoFit considering the first measurements (Figure 3).

In Figure 4 the measured displacements at station 2188 m are compared to the calculated values from

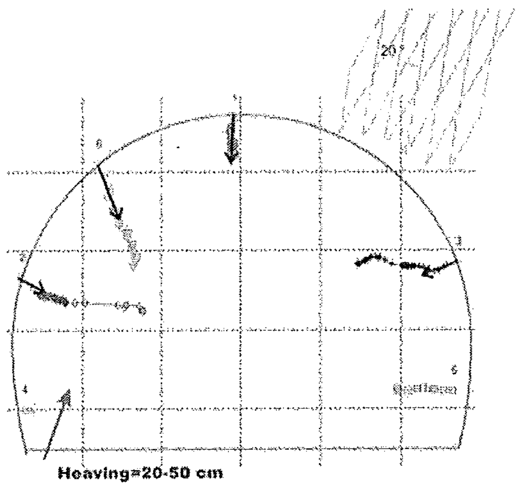

Figure 2. Measured and calculated displacement vectors at the cross section (1935 m).

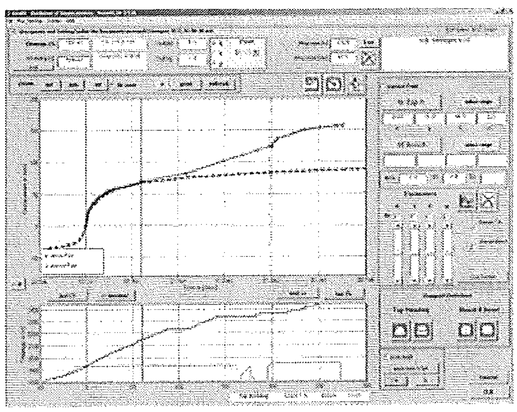

Figure 3. Development of horizontal displacement of the left sidewall and deviation from the predicted one.

the numerical simulation. The measured displacement amounts and orientations at the crown right shoulder and sidewall agree well with those calculated (block size = 1.4 m, apex angle = 20°, joint residual friction angle = 16°, no additional features). The difference in orientation and magnitude between the measured and calculated displacements at the left side of the tunnel cross is caused by a fault zone located outside the profile (Figure 5).

Similar to the last example the deformation curve deviates from the predicted normal behavior (Figure 6).

In the numerical analysis a subvertical fault zone located in a distance of 5 m from the left side wall, with a thickness of 10 m was introduced. It shows that the orientations of the computed displacement vectors now are very similar to those observed, while the magnitude of displacements at the crown and right shoulder are a bit overestimated.

In Figure 8 the measured displacements at the station 2230 m are compared to the calculated values. The measured displacement amounts are similar to those from the numerical model (block size = 1 m, apex angle = 20°, joint residual friction angle = 18°, no additional features).

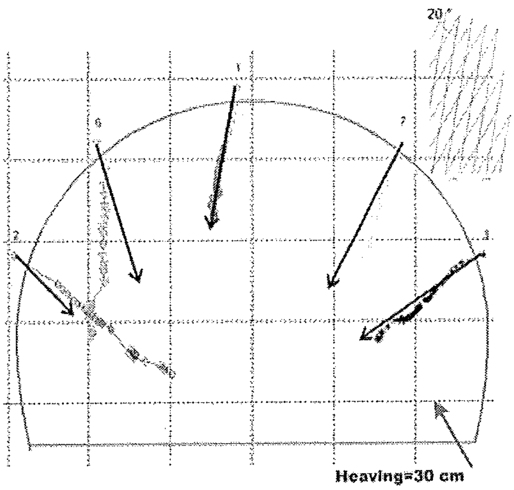

Figure 4. Measured and calculated displacements and their vectors at the cross section (2188 m).

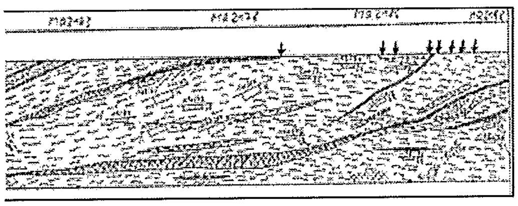

Figure 5. Geological plan view.

The difference between measured and calculated displacement orientations are attributed to a fault zone located at the left side of the cross section and the heaving at the right invert (Figure 9). A numerical analysis including a steeply dipping fault zone with a width of 5 m yields a better agreement between measured and calculated displacement vector orientations, as well as an increase in magnitude.

In Figure 11 the measured displacements at station 2306 m are compared to the calculated values. The measured displacement orientations are similar to those calculated from the numerical model (block size = 1.6 m, apex angle = 40°, joint residual friction angle = 16°). The calculated displacement at the right shoulder significantly exceeds the measured one. The reason is that in the simulation no support was used,

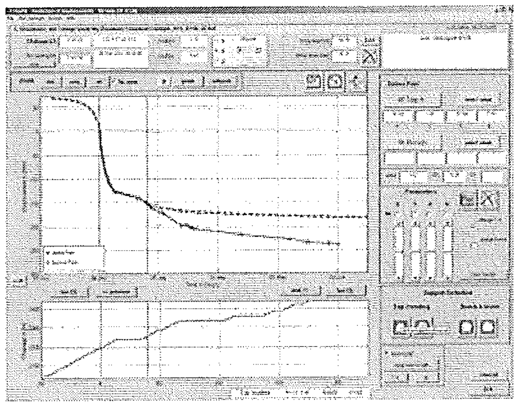

Figure 6. Y displacement curve of Point 6 and deviation from the predicted one (2188 m).

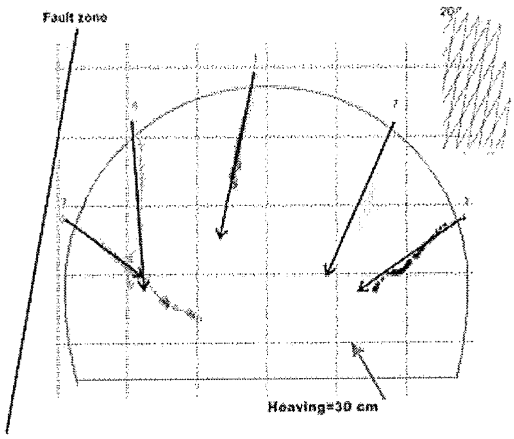

Figure 7. Measured and calculated displacements and their vectors at the cross section (2188 m) considering a fault zone outside the tunnel cross section.

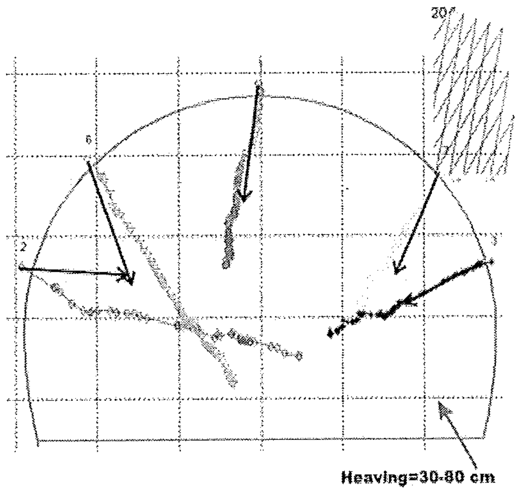

Figure 8. Measured and calculated displacements and their vectors at the cross section (2230 m).

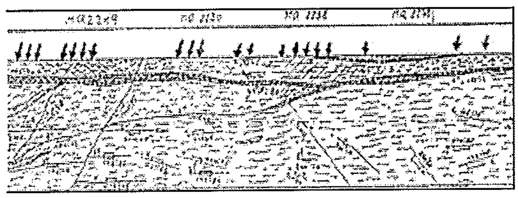

Figure 9. Geological plan view.

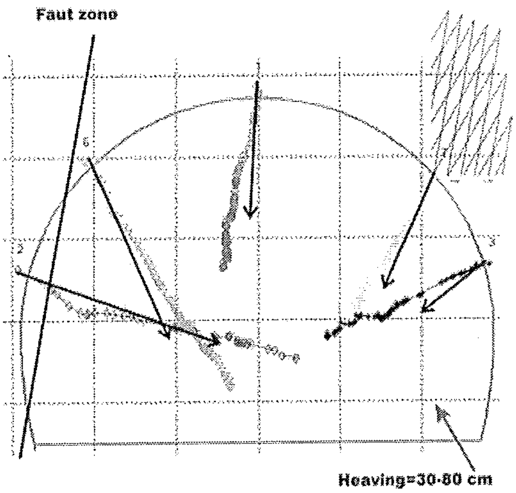

Figure 10. Measured and calculated displacements at cross section 2230 m, considering a fault zone at the left side of the tunnel cross section.

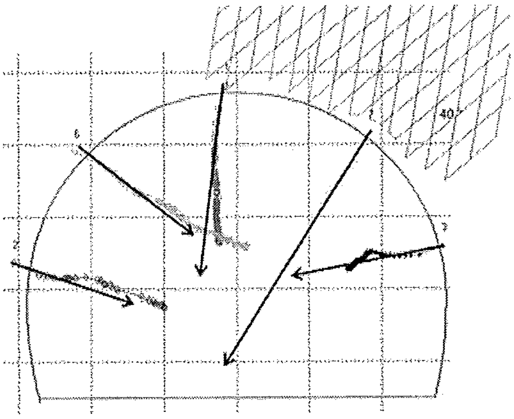

Figure 11. Measured and calculated displacements and their vectors at the cross section (2306 m).

allowing a wedge to slide into the excavation, which on site was held back by the dense bolting.

3 CONCLUSION

Absolute displacement monitoring enables to evaluate the influence of the rock mass structure and fault zones located outside the tunnel profile. In blocky rock mass the relative orientation of the joints, joint spacing and strength properties determine the failure modes, displacement amounts and directions. Discrete numerical analyses are valuable tools to evaluate failure modes and deformation behavior of tunnels in jointed rock masses. The study shall contribute to a better understanding of rock mechanical processes during tunneling. It is hoped that the results will contribute to safer and more economical tunneling.

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