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Smart monitoring analysis system for tunnels in heterogeneous rock mass

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Abstract: Tunnelling in poor and heterogeneous ground is a difficult task. Even with a good geological investigation, uncertainties with respect to the local rock mass structure will remain. Especially for such conditions, a reliable short-term prediction of the conditions ahead and outside the tunnel profile are of paramount importance for the choice of appropriate excavation and support methods. The information contained in the absolute displacement monitoring data allows a comprehensive evaluation of the displacements and the determination of the behaviour and influence of an anisotropic rock mass. Case histories and with numerical simulations show, that changes in the displacement vector orientation can indicate changing rock mass conditions ahead of the tunnel face (Schubert & Budil 1995, Steindorfer & Schubert 1997). Further research has been conducted to quantify the influence of weak zones on stresses and displacements (Grossauer 2001). Sellner (2000) developed software, which allows predicting displacements (GeoFit®). The function parameters describe the time and advance dependent deformation of a tunnel. Routinely applying this method at each measuring section allows determining trends of those parameters. It shows, that the trends of parameter sets indicate changes in the stiffness of the rock mass outside the tunnel in a similar way, as the displacement vector orientation does. Three-dimensional Finite Element simulations of different weakness zone properties, thicknesses, and orientations relative to the tunnel axis were carried out and the function parameters evaluated from the results. The results are compared to monitoring results from alpine tunnels in heterogeneous rock. The good qualitative correlation between trends observed on site and numerical results gives hope that by a routine determination of the function parameters during excavation the prediction of rock mass conditions ahead of the tunnel face can be improved. Implementing the rules developed from experience and simulations into the monitoring data evaluation program allows to automatically issuing information on the expected rock mass quality ahead of the tunnel.

1. Introduction

During tunnel excavation a systematic monitoring is important for the determination of support type and quantity as well as for controlling the tunnel stability. Geodetic methods of absolute displacement monitoring allow determining the spatial displacement vector of each measured point (Rabensteiner 1996). These methods to a large extent have replaced relative displacement measurements in many countries. The increase in information has led to additional possibilities in data evaluation. The plotting of displacement histories, deflection curves, trend lines or displacement vectors in a plane perpendicular to the tunnel axis have become common practice (Vavrovsky & Ayayadin 1998, Vavrovsky 1998, Schubert & Vavrovsky 1994, Heim & Rabensteiner 1995, Vavrovsky & Schubert 1995, Schubert et al 2002).

The evaluation of data gained from the excavation of tunnels constructed in Austria showed, that the ratio between radial and longitudinal displacement varied in a wide range. Matching the observed phenomena with the geological documentation, it was found that deviations of the ratio appeared when zones of different deformability were approached with the excavation (Schubert 1993). To verify the hypothesis, numerical 3-D simulations have been performed. The results showed that changing rock mass conditions ahead of the tunnel face clearly influence the displacement vector orientation (Schubert & Budil 1995, Steindorfer & Schubert 1997, Steindorfer 1998). To quantify the influence of weak zones on stresses and displacements, further research has been conducted (Grossauer 2001).

For safe and economical tunnelling through heterogeneous rock mass conditions a continuous adaptation of the support and excavation concept is required. Simple, quick and efficient tools are needed to predict the rock mass behaviour and displacements.

2. Influence of fault zones

A fault zone has a significant influence on the stresses and displacements of tunnels. When the excavation approaches a fault zone, stresses increase in the stiffer material. On the other hand, due to an arching effect in the fault zone, stresses close to the stiffer boundaries decrease within the fault zone. This influences the displacements as well. Figure 1 shows the stress and displacement changes in the vicinity of a fault zone for different stiffness contrasts. Variations of the embedded fault zone widths lead to similar results (Grossauer 2001).

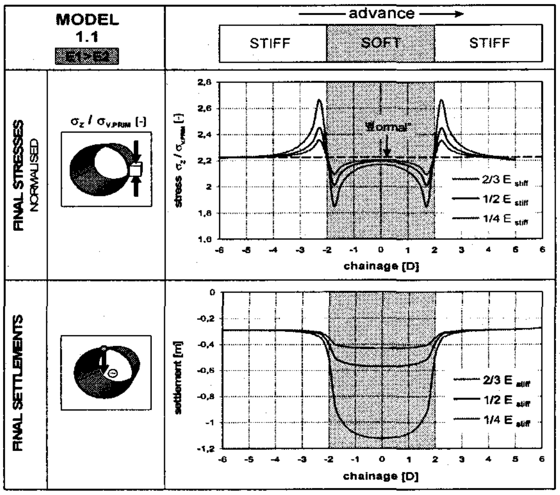

Fig. 1. Stress distributions and final displacements when tunnelling through a fault zone (different stiffness contrasts). Stresses are normalized to the primary stresses.

3. Influence on displacements

When excavating in uniform rock mass and primary stress conditions, it can be assumed that the single displacement vector components have a certain relationship. With different deformability of the ground, the absolute displacement values change but the ratios between the single components do not vary substantially. Evaluations of data from tunnels constructed in poor rock show that the average angle between longitudinal displacements and settlements have a certain value against the direction of excavation. This vector orientation can be considered as 'normal'. Different boundary conditions, like changes in the rock mass structure or in the primary stress situation, influence the stress distribution around the cross section of the tunnel as well as ahead of the face, which leads to deviations of the vector orientation from 'normal'. When the excavation approaches a 'stiffer' rock mass the vector orientation shows an increasing tendency to point in direction of excavation. On the other hand when excavation approaches 'weaker' rock mass the vector orientation shows an increasing tendency to point against the direction of excavation.

Displacement Vector Orientation

The changed spatial stress situation around a tunnel in the vicinity of a fault zone strongly influences the deformations of the rock mass. It could be shown, that the displacement vector orientation shows significant changes much earlier than radial displacements.

Fig. 2 shows settlements and the trend of the displacement vector orientation for a tunnel in a tectonic melange. Pronounced changes in the displacement vector orientation can be observed well before the excavation actually reaches the stronger or weaker rock masses.

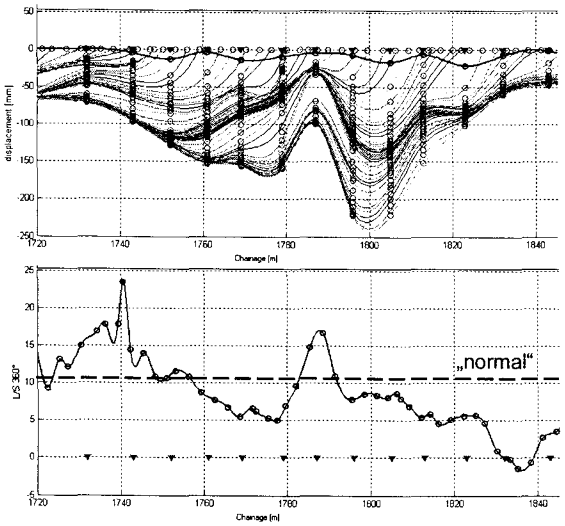

Fig. 2. Settlements and displacement vector orientation trend for a side wall point at the tunnel Spital, Austria.

Results from numerical simulations

The phenomenon described can be easily shown with numerical simulations. The left part of Figure 3 shows the deviation of the displacement vector orientation from the 'normal', obtained from a numerical 3D model for different stiffness contrasts between fault zone and intact rock mass (Grossauer 2001).

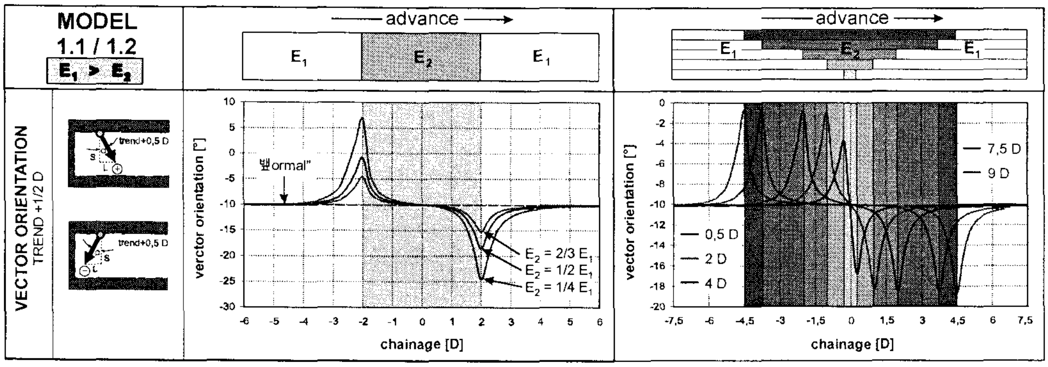

Fig. 3. Deviation of the displacement vector orientation from 'normal' for different stiffness contrasts and fault zone widths (width normalized to tunnel diameter).

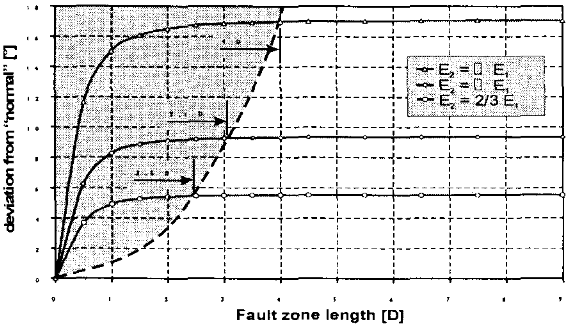

Fig. 4. Deviation of the displacement vector orientation from 'normal' at the transition from intact rock mass to the fault zone, depending on the stiffness contrast and the width of the fault zone.

The amount of the deviation not only depends on the stiffness contrast between the rock masses, but also on the width of the fault zone. The deviation increases with increasing fault zone length up to a certain critical length, above which no further increase of the vector orientation can be observed (right part of Fig. 3). This critical zone length is in between 2,5 and 4 tunnel diameters (Fig. 4).

4. Prediction of displacements

Several ways of plotting the monitored displacements have been developed.

The displacement history plot is the simplest and most common method of plotting the displacement data. For an individual measuring section one displacement component is plotted versus time.

Guenot & al. (1985) and Sulem & al. (1987) proposed analytical functions that describe displacements in a plane perpendicular to the tunnel axis as a function of time and the advancing face. Barlow (1986) and Sellner (2000) modified this approach. The displacement behaviour of the rock mass and support basically is represented by four function parameters. Two parameters (T, m) describe the time dependency and two parameters (X, C) describe the face advance effect. These parameters can be back calculated from case histories using curve-fitting techniques. Figure 5 shows the measured displacements and the fitted curve from a section in the Inntaltunnel.

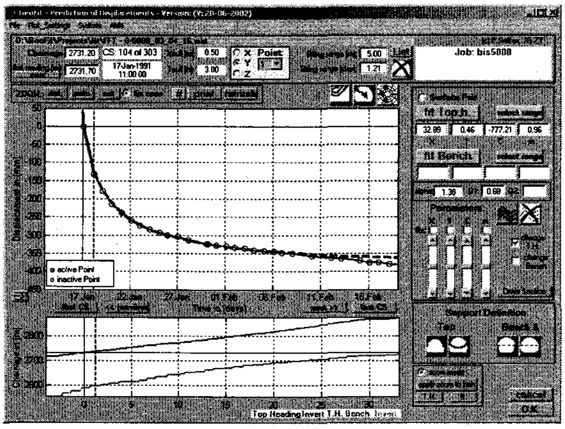

Fig. 5. History Plot of the monitored settlements (circles) and the fitted curve (dashed line).

The use of function parameters for prediction

Numerical Simulation

Following the ideas on the influence of the changing stress field in a heterogeneous rock mass on the displacements, it is obvious that the trends of the function parameters X, T, C, and m should reflect the geotechnical situation, and thus could be used for prediction. The results of numerical models with elastic rock mass behaviour were imported into GeoFit® and the function parameters obtained by curve fitting (Kim 2003).

Figure 6 shows the back calculated function parameters X and C for a fault zone width of one tunnel diameter and a stiffness contrast of 2,0 between the two rock masses. It can be seen, that the parameter X significantly increases already 15 m ahead of the transition between stiff rock and weak rock, which is located at station 45 m.

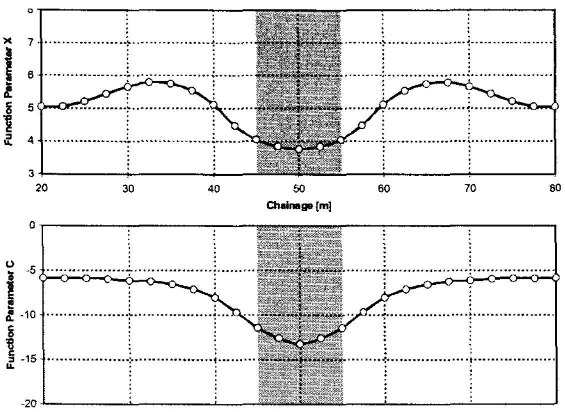

Fig. 6. Back calculated function parameters X and C for a fault zone width of one tunnel diameter and a stiffness contrast of 2,0 between the two rock masses.

Figure 7 shows the distribution of the function parameters X and C for lengths of the weak zone of 0,5, 1,0 and 2,0 tunnel diameters. Besides the increase of the parameter X well ahead of the weak zone, the results clearly show the influence of the fault zone length on the final displacements within the weak zone, which are reflected through the parameter C. With some experience in this kind of monitoring data evaluation, the combination of displacement vector orientation trends and distributions of function parameter trends can be used to predict quality and extension of weak zones ahead of the tunnel face.

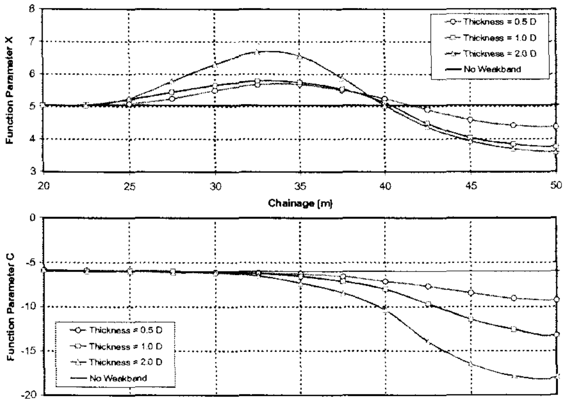

Fig. 7. Distribution of the function parameters X and C for different fault zone widths.

Case history

On several projects the program GeoFit® was used to predict displacements. Figure 8 shows the vertical displacements of the tunnel crown and the parameter sets for a tunnel in phyllites at the transition to a major fault zone As in the numerical simulations a significant increase of the parameter X can be observed well before the excavation reaches the fault zone.

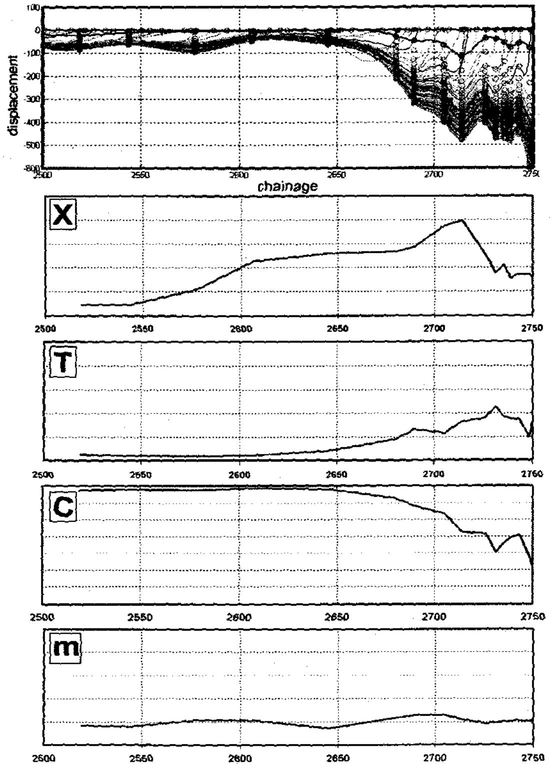

Fig. 8. Vertical displacements of the crown point and the appropriate distribution of the function parameters X, T, C and m.

4. Conclusion

Modern monitoring methods in combination with newly developed methods of data evaluation have improved the possibilities for short term prediction in tunnelling. Especially in heterogeneous rock masses, the short term prediction plays a major role with respect to safety and economical success of a tunnel project. Software for the evaluation of displacement monitoring data is continuously improved and functions added. With the evaluation of a number of projects in different geological environments under various boundary conditions a knowledge base will be developed, eventually leading to a 'smart' data evaluation tool.

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