INTERPRETATION OF DISPLACEMENT MONITORING DATA FOR TUNNELS IN HETEROGENEOUS ROCK MASS

W. Schubert[1], K. Grossauer[2], E.A. Button[1]
[1]) Institute for Rock Mechanics and Tunnelling, Graz University of Technology
schubert@tugraz.at, button@tugraz.at
[2]) 3G Gruppe Geotechnik Graz ZT GmbH
grossauer@3-g

Abstract: The introduction of geodetic methods to measure absolute displacements in tunnels has improved the value of the data significantly. Structurally controlled behaviour and influences of anisotropy can be determined and the excavation and support adjusted accordingly.
In heterogeneous rock masses, a reliable prediction of the conditions ahead of and outside the tunnel profile is of paramount importance for the choice of appropriate excavation and support methods. The increased information contained in the acquired data allows a more comprehensive evaluation of the displacements. The use of advanced methods such as the evaluation of displacement vector orientations on tunnel sites in Austria showed that changing rock mass conditions ahead of the tunnel face can be indicated.
The combination of such methods with new developed software for the prediction of displacements in a plane perpendicular to the tunnel axis (GeoFit®) allows the detection of deviations from 'normal' system behaviour in time.

Keywords: System behaviour, displacement monitoring data, prediction, numerical simulation, fault zones.

1. INTRODUCTION

During a tunnel excavation a systematic monitoring program is important for the determination of support type and quantity, as well as for controlling the tunnel stability. Geodetic methods to measure absolute displacements allow the spatial displacement vector of each measured point to be determined, 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 and Ayayadin (1998), Vavrovsky (1998), Schubert and Vavrovsky (1994), Heim and Rabensteiner (1995), Vavrovsky and 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 and Budil (1995), Steindorfer and Schubert (1997), Steindorfer (1998). To quantify the influence of weak zones on stresses and displacements, further research with numerical simulations has been conducted by Grossauer (2001).

Sellner (2002) developed software which allows the prediction of displacements in a plane perpendicular to the tunnel axis (GeoFit®). This process is based on analytical functions introduced by Guenot et al. (1985), and Barlow (1986). The main parameters of this function are X, T, C and m, which describe the time and advance dependent deformation of a tunnel.

Routinely applying this method at each measuring section allows trends in the parameters to be determined. It shows that the parameter trends also 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 weakness zones with different properties, thicknesses and orientations relative to the tunnel axis were carried out and the function parameters evaluated from the results. For elastic calculations the parameters X and C show a clear correlation between the distance of the face from the weakness zone, and the stiffness ratio between stiff and weak ground. Typical results of these simulations are shown and 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 the 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 the expected rock mass quality ahead of the tunnel to be automatically determined.

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. CHARACTERISTICS OF FAULT ZONES

Faults are elongated, complex zones of deformation, ranging from decimetres to kilometres in magnitude. From the geotechnical point of view it is the fault zone generated in the upper 5 to 10 kilometres of the Earth's crust, the so called brittle fault that deserves our particular attention. A regular pattern of shear and tensile fractures has developed in brittle faults, reflecting the geometry of the strain field and, consequently, the orientation of the principal stresses, Mandl (1988, 1999).

The brittle rock deformation, such as particle size reduction by crushing of grains and reorientation of grains by shearing, generates the characteristic fine grained gouge, Scholz (1990), Twiss and Moore (1992). Low temperature solution transfer contributes substantially to the alteration of fault rocks, in particular of gouge, through transformation and neoformation of clay minerals, Riedmüller (1978), Wu (1978), Klima et al. (1988).

In geotechnical engineering brittle faults are significant because of their substantial heterogeneity in strength properties. Brittle fault zones consist of randomly occurring units of more or less undeformed, unaltered rock, called ‘knockers’ or ‘horses’, Goodman (1993). These mainly lenticular units exhibit a fractal distribution of dimensions, ranging from the micro scale to hundreds of meters in length and are typically surrounded by highly sheared fine grained gouge and fractured, brecciated rock mass which appears to be flowing around the horses in an anastomosing pattern. The ratio of weak clayey gouge matrix to rock blocks of different sizes, shapes and strengths is extremely variable. Medley (1994, 1998) has used the term ‘bimrocks’ to characterize tectonic block-in-matrix-rocks.

2.1 Characteristic engineering problems

Several characteristic engineering problems occur when tunnelling through heterogeneos rock masses, including:

- rapid changes in both deformation characteristics and magnitudes, anisotropic behavior
- large competency contrasts between blocks and matrix results in stress concentrations and potential for rapid brittle failure and severe overbreaks
- large blocks can be local aquifers, resulting in water inflows, high pressure gradients, and undrained loading
- time dependent behaviour
- systematic overbreak
- mixed face conditions

The following sections should help to understand the influence of fault zones on stresses and displacements of tunnels and how to identify such zones ahead of the tunnel face.

3. 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.

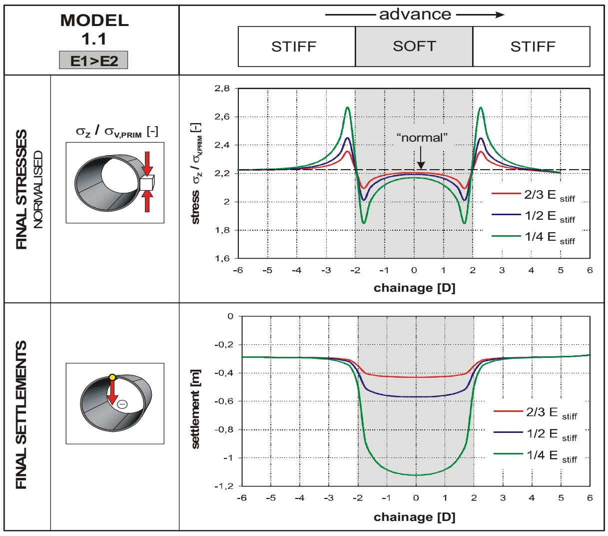

Figure 1. Stress distributions and final displacements when tunnelling through a fault zone (different stiffness contrasts). Stresses are normalized to the primary stresses.

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).

4. INFLUENCE ON DISPLACEMENTS

When excavating in a uniform rock mass and primary stress condition, 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.

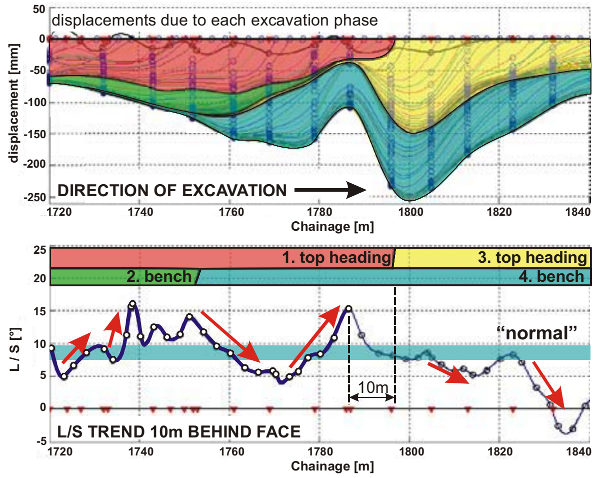

Figure 2. Settlements and displacement vector orientation trend for a side wall point at the tunnel Spital, Austria.

4.1 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.

Figure 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.

4.2 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 numerical 3D simulations, for different stiffness contrasts between the fault zone and surrounding rock mass, Grossauer (2001).

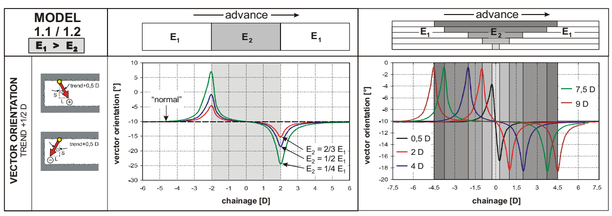

Figure 3. Deviation of the displacement vector orientation from 'normal' for different stiffness contrasts and fault zone widths (width normalized to tunnel diameter).

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 Figure 3). This critical zone length is in between 2.5 and 4 tunnel diameters.

5. SYSTEM BEHAVIOUR

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 et al. (1985) and Sulem et al. (1987) proposed analytical functions to 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 is basically 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.

Sellner (2000) implemented the system of these analytical functions in a program package called GeoFit®. It provides easy-to-use tools for back calculating displacement-monitoring data (curve fitting technique), for prediction of displacements and for handling the expert system. The application acts interactively.

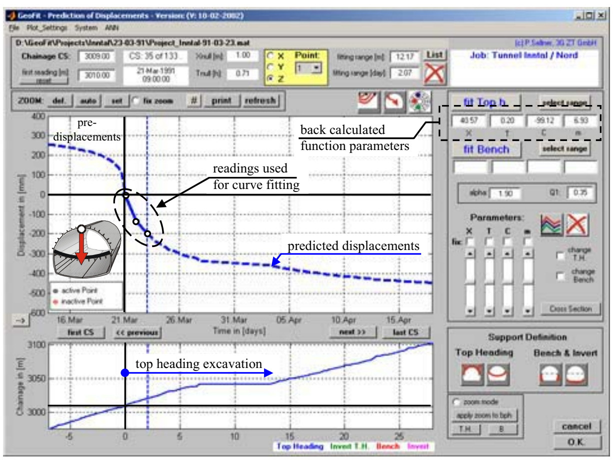

Figure 4. Back calculation of the function parameters and prediction of the displacements.

Each change in the calculation assumptions is displayed on the screen immediately. Both monitored and predicted results are displayed.

This procedure allows one to predict displacements for any time and point of the tunnel wall as well as of the ground surface considering different construction stages and supports. Trend lines, deflection lines, displacement plots and spatial displacement vector orientations can be evaluated and displayed on the basis of monitored, calculated and predicted data, allowing a continuous comparison of the measured and predicted values.

5.1 Case history

The following case history from a tunnel constructed in Austria shows the crown settlements at a certain cross section. On December, 20th, excavation reached station 882 and two days later the ring closure was done by installing the temporary top heading invert. Due to Christmas break, the construction was stopped for about two weeks. Measurements taken during the break showed only insignificant creep. The excavation was restarted on January 10th and due to the further advance the settlements increased to a value of some 40 mm and showed normal displacement behaviour.

On January 21st the settlements showed a deviation from the predicted value and suddenly increased to about 45 mm. This significant displacement increment of more than 5 mm within one day was a clear indicator of abnormal system behaviour. Reasons for this behaviour had to be found and the tunnel stability to be judged.

The shotcrete had matured during the stop and lost its creeping capacity, thus behaving relatively brittle also close to the face. As no visual damage of the lining of the crown could be identified, the reason for the increase of displacements could either be a failure of the temporary invert or a failure in the rock mass. To be able to judge the stability of the system, two scenarios were developed.

In the first case (failure of temporary invert) it could be expected, that the displacement development would follow the predicted one for the case with no temporary invert installed (blue dashed line in figure 5). In the latter case (failure in the rock mass), the displacements would exceed those of the system without temporary invert. As can be seen from figure 5, the measured displacements soon followed the predicted path for the case without temporary invert.

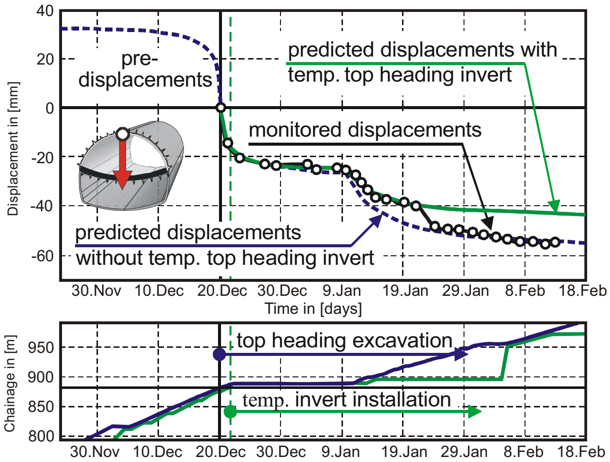

Figure 5. Comparison of predicted and finally observed displacements.

The lining had lost part of its capacity, but the overall stabilisation process was back to normal again. In this case study the prediction of the displacements provided a valuable aid for the decision making process to predict the system behaviour, to identify an abnormal behaviour and its reasons and to judge the 'new' system behaviour.

5.2 The use of function parameters for prediction

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 along each measuring section 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. The parameter C also begins to increase, but at a distance of approximately 10 m from the transition.

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.

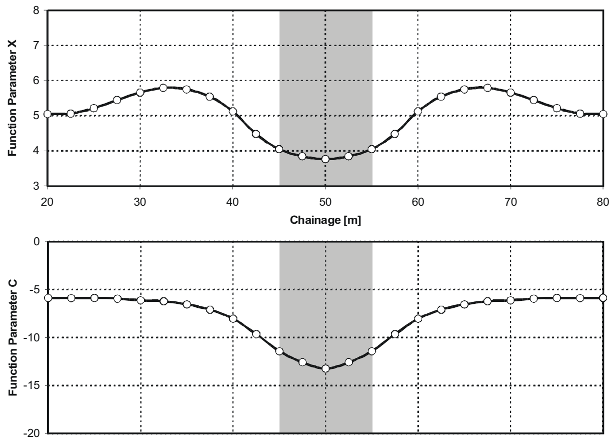

Figure 6. Back calculated function parameters X and C for a fault zone width of one tunnel diameter and a stiffness contrast of 2.0 between the two rock masses.

6. CONCLUSION

Modern monitoring methods in combination with newly developed methods of data evaluation have improved the possibilities for interpretation and 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 increasing number of projects evaluated with these methods in different geological environments and boundary conditions a knowledge base is being developed leading to a 'smart' data evaluation tool.

7. REFERENCES

Barlow, J.P. 1986. Interpretation of Tunnel Convergence Measurements. MSc Thesis, Dep. of Civil Engineering, University of Alberta, Canada.

GeoFit®. http://www.geofit.3-g.at

Goodman, R.E. 1993. *Engineering Geology.* John Wiley & Sons, Inc.: 412 pp.

Grossauer, K. 2001. *Tunnelling in Heterogeneous Ground – Numerical Investigation of Stresses and Displacements.* Master thesis at the Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Austria.

Guenot, A., Panet, M., Sulem, J. 1985. A New Aspect in Tunnel Closure Interpretation. In Proc. 26th US Symposium on Rock Mechanics, Rapid City: pp. 445-460.

Heim, N. and Rabensteiner, K. 1995. Zusammenspiel Geologie / Messtechnik am Beispiel des Sonnbergtunnels, *Felsbau 13, Vol. 3:* pp. 139 – 145.

Kim, C.Y. 2003. Investigation of fault zones on displacements. Project report at the Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Austria. Unpublished.

Klima, K., Riedmüller, G. & Stattegger, K. 1988. Statistical analysis of clay mineral assemblages in fault gouges. *Clay and Clay Minerls.* Vol. 36. pp. 277 – 283.

Mandl, G. 1988. Mechanics of tectonic faulting. In H.J. Zwart (ed.). *Developments in structural geology.* 407 pp. Elsevier.

Medly, E. 1994. *The engineering characterization of melanges and similar block-in-matrix-rocks (bimrocks).* Dept. of Civil Engineering, University of California at Berkeley, California: Ph.D. thesis: 175 pp.

Medly, E. 1998. Order in chaos: The geotechnical characterization of melange bimrocks. In Robertson & Mayne (eds.). *Proc. of the 1st Conf. on Site Characterization,* Atlanta, 19-22 April. pp. 201 – 206. Rotterdam: Balkema.

Rabensteiner, K. 1996. Advanced Tunnel Surveying and Monitoring. *Felsbau 14, Vol. 2:* pp. 98 – 102.

Riedmüller, G. 1978. Neoformation and transformation of clay minerals in tectonic shear zones. *Tschermaks Min.Petr.Mitt.* 25: pp. 219 - 242.

Scholz, Ch.H. 1990. *The mechanics of earthquakes and faulting.* Cambridge University Press: 439 pp.

Schubert, P. & Vavrovsky, G.M. 1994. Interpretation of monitoring results. *World Tunnelling, November:* pp. 351 – 356.

Schubert, W. 1993. Erfahrungen bei der Durchörterung einer Großstörung beim Inntaltunnel. *Felsbau 11, Vol. 6:* pp. 443 – 447.

Schubert, W. & Budil, A. 1995. Importance of longitudinal deformations in tunnel excavation. In T. Fuji (ed.), *Int. Congress on Rock Mechanics*, Proc. intern. Symp., Tokyo: pp. 1411 - 1414. Rotterdam: Balkema

Schubert, W., Steindorfer, A., Button, E.A. 2002. Displacement Monitoring in Tunnels – an Overview. *Felsbau 20,* Vol. 2: pp. 7 - 15

Sellner, P.J. 2000. Prediction of Displacements in Tunnelling. Ph.D. thesis, Graz University of Technology, Austria. In G. Riedmüller, W. Schubert, S. Semprich (eds.). *Schriftenreihe der Gruppe Geotechnik Graz,* Heft 9. Graz

Steindorfer, A. & Schubert, W. 1997. Application of new methods of monitoring data analysis for short term prediction in tunnelling. In Golser, Hinkel, Schubert (eds.). *Tunnels for People.* Vol. I: pp. 65 – 69. Rotterdam: Balkema.

Steindorfer, A.F. 1998. Short term Prediction of Rock Mass Behaviour in Tunnelling by advanced Analysis of Displacement Monitoring Data. PhD thesis, Graz University of Technology, Austria. In G. Riedmüller, W. Schubert, S. Semprich (eds.). *Schriftenreihe der Gruppe Geotechnik Graz,* Heft 1. Graz.

Sulem, J., Panet, M., Guenot, A. 1987. Closure analysis in deep tunnels. In *Int. Journal of Rock Mechanics and Mining Science.* Vol. 24: pp. 145-154.

Twiss, R.J. & Moore, E.M. 1992. *Structural geology.* 532 pp. Freeman.

Vavrovsky, G.M. & Schubert, P. 1995. Advanced analysis of monitored displacements opens a new field to continuously understand and control the geotechnical behaviour of tunnels. Proc. 8th Int. Congress on Rock Mechanics, Tokyo, Vol. III. Rotterdam: Balkema.

Vavrovsky, G.M. & Ayayadin, N. 1998. Bedeutung der vortriebsorientierten Auswertung geotechnischer Messungen im oberflächen-nahen Tunnelbau. *Forschung + Praxis*, Vol. 32, pp. 125 – 131. Düsseldorf: Alba Fachverlag.

Vavroysky, G.M. 1998. Die räumliche Setzungskontrolle - ein neuer Weg in der Ein-schätzung der Standsicherheit oberflächennaher Tunnelvortriebe. *Mayreder Zeitschrift*, 33. Jg. Austria.

Wu, F.T. 1978. Mineralogy and physical nature of clay gouge. *Pure Appl. Geophys. 116:* pp. 655 - 689.