Advances in the Observational Approach in Tunnelling by new Techniques of Monitoring Data Evaluation

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ABSTRACT: Even with an excellent geological investigation program and state of the art rock mass characterization, uncertainties in the ground model remain. For safe and economical construction a continuous updating of the model and adjustment of excavation and support methods to the actual conditions is required. The efficiency of this updating process to a good deal depends on the quality of the monitoring program and evaluation of the data acquired. Recently developed methods for displacement monitoring data allow extracting much more information than was the case a couple of years ago.
The monitoring of absolute displacements in underground structures has become common practice during the last decade. By evaluating ratios of different displacement components, such as the spatial orientations of the displacement vectors and their trends, it is possible to “detect” geological features outside the excavated volume, such as fault zones. The findings have been verified with a series of numerical simulations, and are successfully used since a couple of years on several sites in the Alps. This very much contributes to reduce the “surprises” during tunnelling, makes it safer, faster, and more economical.
To be able to control the excavation and support a tool has been developed to predict displacements. This software allows predicting the development of the displacements also for multiple stage excavations, even with non-steady advance. Options are provided to consider different types of support, advance rates and sequences. The actually measured displacements then can compared to the predicted ones, and deviations from the “normal behaviour” detected in time and mitigation measures designed and their efficiency tested before application.
Basic principles will be explained and the potential of the new tools demonstrated with various case histories.

1. INTRODUCTION

The observational method is widely applied in underground construction. The EUROCODE 7 [1] specifies conditions for the application of the observational method. Requirements to be met before construction are:

- acceptable limits of the behaviour shall be established;
- the range of possible behaviours shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;
- a plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
- the response time of the instruments and the procedures for analyzing the results shall be sufficiently rapid in relation to the evolution of the system;
- a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside the acceptable limits.

In underground construction the rock mass conditions in most cases cannot be defined with the required accuracy prior to construction. Subsequently the prediction of the system behaviour made during the design needs to be refined during construction to arrive an economical and safe solution. The final determination of the excavation methods, as well as support type and quantity, in most cases is possible only on site. In order to guarantee the required safety, a safety management plan needs to be established and followed during construction.

In this process up to date monitoring methods and efficient data evaluation and interpretation play an important role.

2. MONITORING

Methods for measuring displacements, as well as for evaluating the data have considerably developed during the last 15 years. The information contained in the data, especially when using spatial displacement measurements, can be evaluated in many different ways. It is basically in the interest of the owner to promote the proper use of monitored data, as this definitely has a positive influence on the construction time, costs, and safety.

There are several more or less advanced tools available on the market, which make data handling, evaluation and interpretation easier and more efficient on site. There is, however, also a demand for more basic research to be able to develop "smart" tools for the site. The following chapters shall demonstrate how monitoring data can be used for the benefit of a project.

2.1. *Spatial Displacement Monitoring*

The measurement of spatial displacements of targets fixed to the lining has widely replaced the traditional convergence measurements with the tape [2]. Due to the increase in information with this type of measurement, the use of additional methods as for example extensometers has decreased. The accuracy of absolute displacement measurements is in the range of one millimetre, which is good enough for the purpose. The observation of the transient displacements in space allows a much better evaluation of the influence of the rock mass structure, than with traditional relative measurements.

2.2. *Extensometer Measurements*

Extensometers have not much changed during the last decades. Naturally there is now the possibility to automatically record the measured values using LVDTs instead of the dial gage. Extensometers are used to determine the depth of the zone influenced by the excavation, or to detect or verify assumed failure modes. As mentioned, the use of absolute displacement monitoring with geodetical methods has limited the application of extensometers to special problems.

2.3. *Inclinometer Measurements*

When inclinometers are used in connection with tunnelling, they commonly are installed from the surface to either record slope movements or to get a better in-sight into the ground movement caused by the excavation of a tunnel.

Most recently horizontal inclinometers have been used in connection with pipe roof supports. Displacements ahead of the face can be measured efficiently, and thus the total displacement path determined [3, 4].

2.4. *Strain Measurements*

Strain measurements are occasionally taken in shotcrete linings in order to back calculate stresses, respectively the stress intensity factor. Although having been applied in several cases, not much has been published on the results.

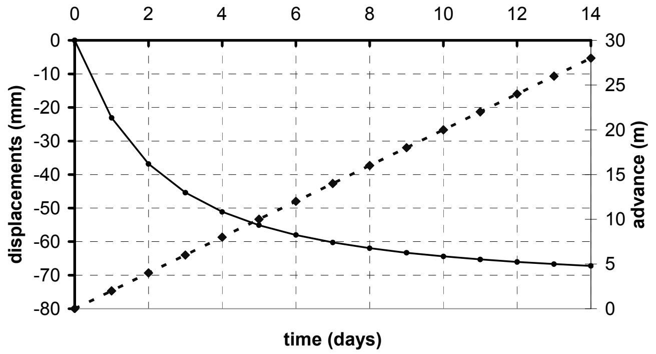

Fig. 1. Displacement history and advance for a steady excavation rate; distance between face and measuring section plotted as dashed line

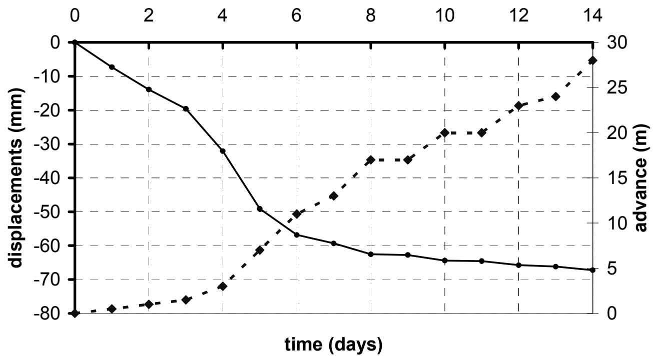

Fig. 2. Displacement history and advance for a non-steady excavation rate; distance between face and measuring section plotted as dashed line

3. EVALUATION METHODS AND DISPLAY

The following chapters focus on the most commonly absolute displacement monitoring.

3.1. *Displacement histories*

Plotting displacements versus time for one displacement component is the most common way of displaying measurement data in tunnels. The interpretation of the curve is easy for homogeneous rock mass conditions and a continuous advance rate. The condition for a satisfying stabilization process, respectively the stress redistribution is a steadily decreasing displacement rate.

The displacements can be split into a component related to the face advance and a component describing the time dependent closure. Sulem et al. [5] have formulated a relationship for the advance and time dependent closure of tunnels. Those formulations were used to produce figures 1 and 2, which show the influence of the advance rate on the development of the displacements. The example shown in figure 1 was produced with a constant advance rate. The final displacements can easily be estimated by extrapolating the measured curve.

With a non-steady advance rate it is far more difficult to judge if the development of the displacements is “normal”. Figure 2 shows such an example with an unsteady advance rate. To be able to make a well founded judgment additional tools are required, like using the equations given by Sulem.

With just a visual inspection of the plot shown in figure 2, it would be hard to judge, if the stabilization process is normal, especially in the first few days. With additional headings, heterogeneous rock mass conditions, or time dependent behaviour of the support it is even more difficult to properly interpret the results when only using the displacement histories. This difficulty to visually check the normality of a displacement development was one of the reasons to develop a tool for the prediction of displacements. Based on [5, 6], Sellner [7] extended the functions and added new features, like the possibility to consider additional support. The extended capabilities were implemented in a code, called GeoFit® [8, 9]. He uses a set of variables, describing the time dependent and advance dependent displacements, the support, and the ratio of pre-displacements to total displacements. Curve fitting techniques are used to back calculate some of the required parameters. The software has been used on a number of projects, and several improvements have been made. There is still considerable basic research required to determine the dependencies between rock mass quality, influencing factors, and support to be able to provide unique solutions. Presently still a lot of experience is required to arrive at reasonable predictions. The tool nevertheless does not want to be missed by those who already used it.

With a daily update of the monitored data it can be easily detected, when the system behaviour deviates from the “normal”.

Figures 3 to 4 show such a process to predict the displacement magnitude and the comparison of the predicted to the measured values. Two days after the zero reading the top heading excavation was stopped for the bench excavation and a temporary top heading invert installed. After approximately two months the excavation in the top heading was resumed. Figure 3 shows the predicted system behaviour with temporary invert, while in Figure 4 the measured displacements are compared to the predicted ones. It can be seen, that in this case a very good compliance between prediction and measured values was obtained (Figure 4).

Figure 5 shows a deviation from the predicted behaviour. A measuring section was installed in the

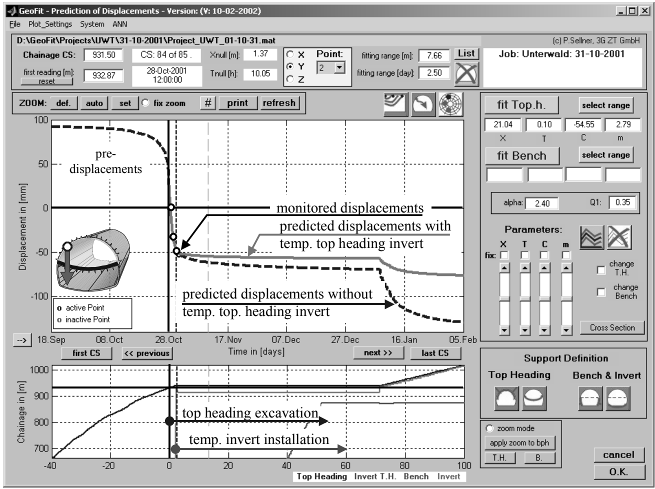

Fig. 3. Back calculation of the function parameters after 3 measurements and prediction of displacement development.

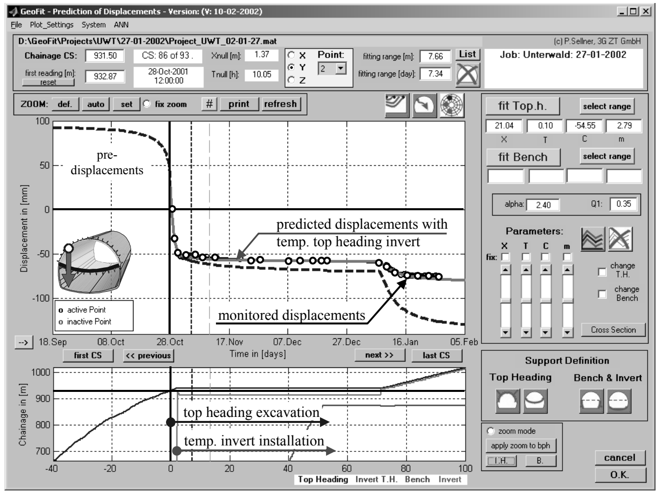

Fig. 4. Comparison of the predicted displacements to the measured ones, shown as dots.

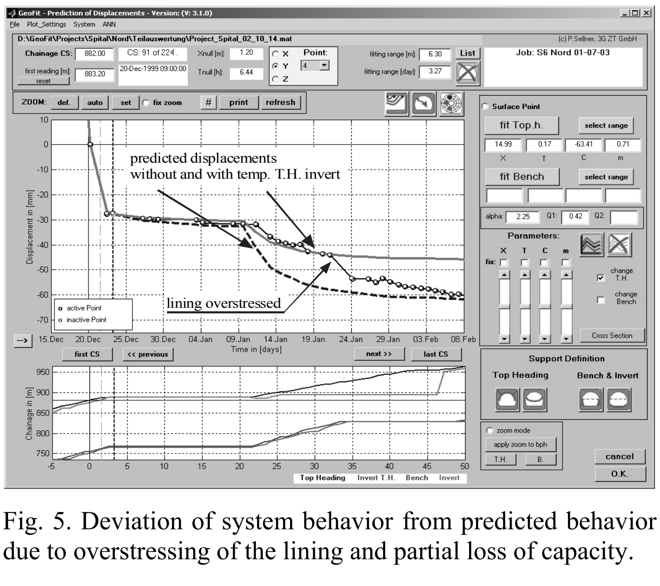

Fig. 5. Deviation of system behavior from predicted behavior due to overstressing of the lining and partial loss of capacity.

top heading immediately before the Christmas break. In addition to the primary lining and rock bolts a temporary top heading invert was used. After restart the behaviour was as expected for approximately 10 days. When the face entered poor rock mass conditions, additional loads were transferred to the sections further back, leading to an overstressing of the temporary top heading invert, which lost part of its capacity. It can be seen, that after a sudden increase of the displacements, the system stabilizes again. Although a loss of lining capacity is never desirable, this case was non critical in terms of stability.

The disadvantage of using displacement history plots is that it is difficult to obtain an overview over a longer section of the tunnel, as each section has to be inspected separately.

3.2. Deflection curves

To be able to observe a spatial overview of the displacements deflection curves are frequently used. They are produced by connecting the measured vales of one component (for example the vertical or horizontal component) at a certain time along the tunnel. By plotting these lines in regular time intervals, the influence of the progress on the sections behind the face can easily be seen. This is the reason why the deflection lines frequently are called "influence lines". Details and examples of application can be found in [10, 11, 12]. Producing trend lines from the deflection lines, a certain extrapolation beyond the face is possible. Practice however shows that the extrapolation in many cases does not reveal much about the conditions ahead of the face. To be able to show comparable data from different monitoring sections on one plot, the determination of the displacements occurring prior to the zero reading is important. Zero readings of the targets are not always done at the same distance behind the face or the same time after excavation. This implies that besides the displacement occurring ahead of the face, an additional part of the displacements is not recorded. To make displacement measurements comparable, normalization is required. Commonly the displacements ahead of the face are neglected, and the value at the face taken to zero. Various methods to determine the missing portion of the displacements between the face and the measuring section are used. The most appropriate method is to use time and distance dependent functions, as described by Sellner [7].

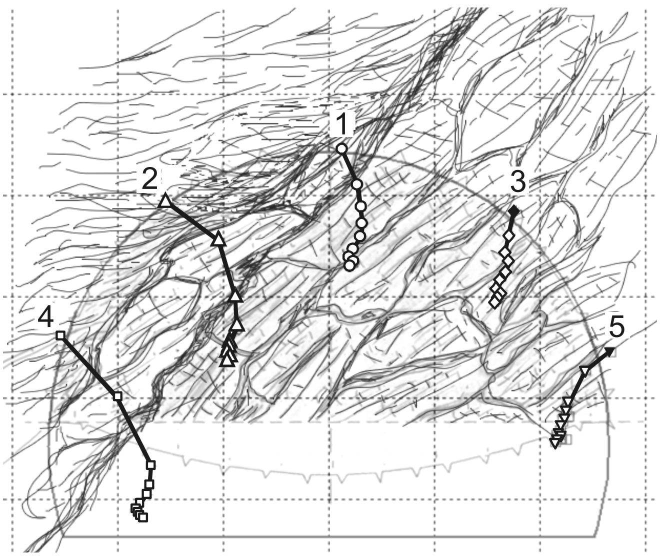

Fig. 6. Displacement vector plot showing the influence of weak material at the left sidewall on the magnitude and orientation.

It is very important to accurately record the location of the face and the time of excavation to achieve comparable pre-displacement values for different measuring sections. Neglecting this influence easily can lead to misinterpretations [13].

With appropriate data recording and evaluation the deflection curves are a useful tool to quickly obtain an overview, and to judge the influence of the excavation at the face on the sections further back.

3.3. Displacement vectors

Displacement vectors can be displayed in a cross section or the longitudinal section. In the first case, the radial displacements are displayed, in the second case, the combination of the vertical and longitudinal components are visualized.

With displacement vector plots the influence of the rock mass structure can be observed, as well as failure mechanisms detected (figure 6). Using the vector plot in a cross section, structures like faults or slickensides outside the tunnel profile can be detected before they can be seen at the face. This allows an adjustment of excavation and support in time.

3.4. Ratios of displacement components

It is very useful to produce plots of ratios of single components. It can be assumed, that the ratios of displacement components remain the same if there are no major changes in the rock mass quality in the vicinity of a tunnel. Each contrast in stiffness, or singularities, like slickensides or faults change the stress distribution around the tunnel. This reflects in a different displacement pattern. Those plots can give an early warning of changing geological conditions outside the visible excavation area. For example the ratio between the vertical displacement of the crown and the sidewall can be used to detect faults outside the tunnel. While in homogeneous conditions, there will be a constant ratio between the crown and sidewall displacement, in the case of the excavation approaching a moderately to steeply dipping fault, the displacements at the sidewall close to the fault will increase in a higher proportion than those at the crown. Routines can be incorporated into the evaluation software to automatically check on the “normality” of the respective ratios of displacement components, and to issue warnings in case certain limits are exceeded.

3.5. Longitudinal displacements

Following the idea, that the displacement pattern changes when the excavation approaches rock masses with different quality, one arrives at the evaluation of the spatial displacement vector orientation. From observations on site [14] it was concluded, that the longitudinal displacements are more sensitive to changes in the rock mass structure than the radial displacements. Using trends of the ratio between longitudinal and radial displacements, a reliable short term prediction of the conditions ahead of the face is possible [15, 16, 17, 18, 19].

Figure 7 shows the deflection curves of vertical and longitudinal displacements and the trend of the orientation of the displacement vector of the crown in a section of the Inntaltunnel.

A regional fault zone influenced the excavation on a length of more than 2.000 m. Within this fault zone on a section of approximately 100 m exceptionally poor rock was encountered. In figure 7 it can be seen, that the vector orientation considerably deviates from the “normal” orientation well before the excavation runs into the completely crushed rock mass. Once the excavation is in the fault zone, the vector orientation goes back to normal again.

Grossauer [19] found, that the stiffness contrast, as well as the extension of a zone with different stiffness influence the magnitude of the deviation of the vector orientation from “normal” up to a certain critical zone length (figure 8).

As can be seen from figure 8, the displacement vector orientation deviates from the normal in the opposite direction, when stiffer material is approached. It has been experienced, that in such situations there is an increased risk of overbreak. It is assumed that this is due to the comparatively low stresses in the area of the face, as stresses are concentrated in the stiffer material ahead. Such a situation can be seen in figure 9, where the trend of the displacement vector orientation shows a deviation from a positive (backwards) normal orientation to a negative (forward) orientation between chainage 895 and 915. Then there seems to be a chainage in the trend again towards normal. At chainage 921.5 an overbreak with a volume of about 50 m³ occurred. The analysis of other overbreaks in heterogeneous rock masses showed similar trends. It seems that the apparent “normalization” of the displacement vector orientation shortly before the overbreak is caused by the beginning of the loosening process, eventually leading to the overbreak.

To be able to detect such phenomena, the monitored data must be correct (especially in longitudinal direction), and the evaluation of the data done immediately after the acquisition.

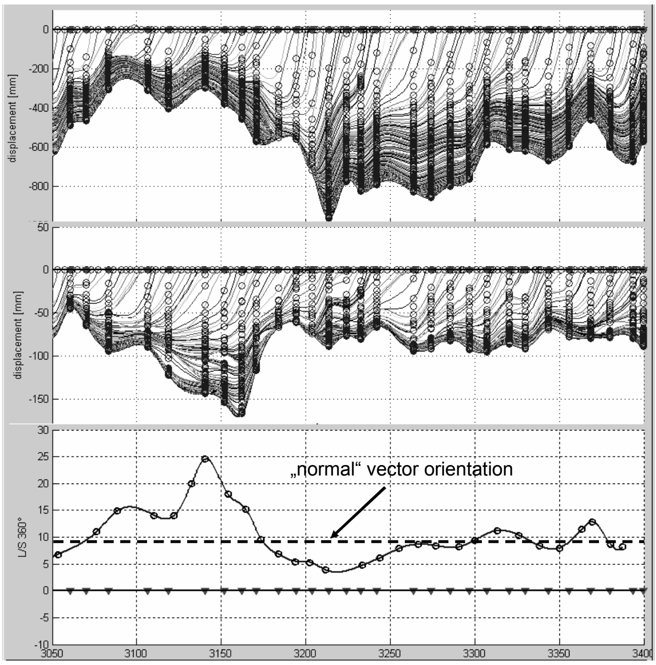

Fig. 7. Settlements of the crown (top), longitudinal displacements (middle), and ratio of longitudinal and vertical displacement (bottom) at the Inntaltunnel.

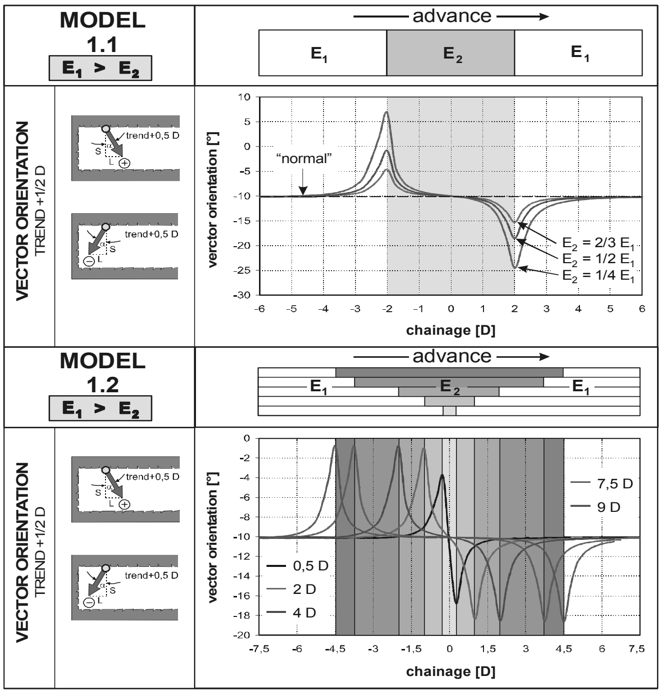

Fig. 8. Influence of the length of a weak zone on the deviation of the displacement vector orientation from “normal” for different stiffness contrasts (top), and different extensions of the weak zone (bottom) [20].

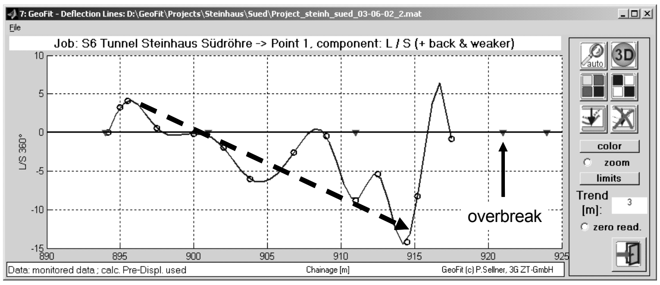

Fig. 9. Trend of displacement vector orientation of crown-point prior to an overbreak

4. CONCLUSION

For successful tunnelling in difficult geotechnical conditions or in sensitive environments, an observational approach during construction is indispensable. To be able to meet the requirements connected to the observational method, serious preparation prior to construction and an efficient monitoring program is needed, and organizational provisions made to allow for a timely reaction. Besides a state of the art design, professionally and socially competent engineers are required on site.

Monitoring and evaluation techniques have considerably developed during the last two decades. The information, which can be extracted from displacement monitoring data, is enormous. Still a lot of experience is required to correctly evaluate and interpret monitoring data, and draw the right conclusions. A sound rock- and soil mechanical education is an indispensable precondition to understand the complex transient and spatial processes during tunnel excavation.

With the improved tools for evaluation of measurement data it is possible to study and compare case histories of various sites. This can be used to further improve monitoring and interpretation techniques.

REFERENCES

1. EN 1997-1:2001. Eurocode 7: Geotechnical design – Part 1: general rules.
2. Rabensteiner, K. 1996. Advanced tunnel surveying and monitoring. *Felsbau* 14, No. 2: 98-102.
3. Volkmann, G., E.A. Button and W. Schubert. 2003. Influence of zero reading time and position on geodetical measurements. In *Proceedings of the int. Symposium on Geotechnical Measurements and Modelling, Karlsruhe, 23 – 25 September 2003,* eds. O. Natau et al, 101-104. Rotterdam: Balkema.
4. Volkmann, G. 2004. A Contribution to the Effect and Behavior of Pipe Roof Supports. In *Rock Engineering – Theory and Practice, Proceedings of the ISRM Regional Symposium and 53rd Geomechanics Colloquy, Salzburg, 7 – 9 October 2004,* ed. W. Schubert, 161-166. Essen: VGE.
5. Sulem, J., M. Panet and A. Guenot. 1987. Closure analysis in deep tunnels. *Int. Journal of Rock Mechanics and Mining Science*, Vol. 24: 145-154.
6. Barlow, J.P. 1986. Interpretation of Tunnel Convergence Measurements. *MSc Thesis,* dep. of. Civil Engineering, University of Alberta, Canada.
7. Sellner, P. 2000. Prediction of displacements in tunnelling. In *Schriftenreihe der Gruppe Geotechnik Graz,* Heft 9, eds. G. Riedmüller, W. Schubert and S. Semprich.
8. Sellner, P. and K. Grossauer. 2002. Prediction of displacements for tunnels. *Felsbau* 20, No. 2: 22-28.
9. www.geofit.3-g.at
10. Vavrovsky, G.M. and N. Ayaydin. 1988. Bedeutung der vortriebsorientierten Auswertung geotechnischer Messungen im oberflächennahen Tunnelbau. *Forschung und Praxis*, 32: 125-131.
11. Vavrovsky, G.M. 1988. Die räumliche Setzungskontrolle – ein neuer Weg in der Einschätzung der Standsicherheit oberflächennaher Tunnelvortriebe. *Mayreder Zeitschrift* 33.
12. Vavrovsky, G.M. and P. Schubert. 1995. Advanced analysis of monitored displacements opens a new field to continuously understand and control the geomechanical behaviour of tunnels. In *Proceedings of the 8th Int. Congress on Rock Mechanics (ISRM), Vol.3, Tokyo,* ed. T. Fujii, 1415-1419. Rotterdam: Balkema.
13. Schubert, W., A. Steindorfer and E.A. Button. 2002. Displacement Monitoring in Tunnels – an Overview. *Felsbau* 20, No. 2: 7-15.

14 Schubert, W. 1993. Erfahrungen bei der Durchörterung einer Großstörung im Inntaltunnel, *Felsbau 11*, No. 6: 287-290.

15. Schubert, W. and A. Budil. 1995. The Importance of Longitudinal Deformation in Tunnel Excavation. In *Proceedings of the 8th Int. Congress on Rock Mechanics (ISRM), Vol.3, Tokyo,* ed. T. Fujii, 1411-1414. Rotterdam: Balkema.
16. Schubert, W. and A. Steindorfer. 1996. Selective displacement monitoring during tunnel excavation. *Felsbau* 14, No. 2: 93-97.
17. Steindorfer, A. 1998. Short term prediction of rock mass behaviour in tunnelling by advanced analysis of displacement monitoring data. In *Schriftenreihe der Gruppe Geotechnik Graz*, Heft 1, eds. G. Riedmüller, W. Schubert and S. Semprich.
18. Golser, H. 2001. The application of Finite Element and Boundary Element Methods in Tunnelling. *PhD thesis,* Graz University of Technology, Graz, Austria.
19. Grossauer, K. 2001. Tunnelling in Heterogeneous Ground - Numerical Investigation of Stresses and Displacements. *Diploma Thesis,* Graz University of Technology, Graz, Austria.
20. Grossauer, K., W. Schubert and C.Y. Kim. 2003. Tunnelling in heterogeneous ground – Stresses an Displacements. In *Proceedings of the 10th ISRM Congress, Johannesburg, 8 – 12 September 2003,* The South African Institute of Mining and Metallurgy, 437-440. South Africa.