Evaluation and Interpretation of Displacements in Tunnels

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Abstract: The limits in the accuracy of the prediction of the geological architecture and rock mass characteristic require an observational approach for the safe and economical construction of tunnels. This especially applies for tunnels in weak ground and/or sensitive environments. It has become common practice to assign a geotechnical engineer to difficult sites to continuously evaluate the geotechnical situation and assist in the routine decision making process. Appropriate site organization and advanced methods for monitoring data evaluation and interpretation are a precondition for efficient work on site. The paper deals with the basic requirements to successfully implement an observational approach, the respective tools for monitoring, and monitoring data evaluations.

1 INTRODUCTION

The observational method is widely applied in underground construction. The EUROCODE 7 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 is 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 prediction of the system behaviour made during the design in most cases needs to be refined during construction to arrive at an economical and safe solution. To be able to adjust criteria during construction, several conditions must be fulfilled. On the one hand the geomechanical design needs to be done in a coherent way to be able to identify the parameters, which have a dominant influence on the system behaviour.

In underground engineering there are two major aspects that must be addressed during the design phase. The first and most important is developing a realistic estimate of the expected rock mass conditions and their potential behaviours as a result of the excavation. The second is to design an economic and safe excavation and support method for the determined behaviours. As the design not only depends on the behaviour of the rock mass, but also on boundary conditions, regulations, and local as well as system requirements, a systematic approach is required.

Such an approach is outlined in the Guideline for the Geomechanical Design of Underground Structures (OEGG, 2001). The process outlined in the guideline clearly distinguishes between rock, the rock mass, influencing factors, boundary conditions, rock mass behaviour, and system behaviour.

Due to the fact, that in many cases the rock mass conditions cannot be defined with the required accuracy prior to construction, during construction it is necessary to continuously update the geotechnical model and adjust the excavation and support to the actual ground conditions.

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 SITE ORGANIZATION

For a successful implementation of an observational approach an appropriate site organization is required. Direct communication between the parties involved in construction allows one to maximize the value of information and to minimize time required for decision making. To account for the responsibilities, a clear and efficient organizational structure is required. As the available reaction time in case of deviations is a crucial factor for an observational approach, the bureaucratic procedures should be minimized as much as possible.

3 MONITORING

The procedure outlined above demonstrates the importance of efficient monitoring methods, and data evaluation and interpretation on site. 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.
Reviewing literature, and the common practice on site, it is apparent, that there is still considerable potential for improvement in the data collection and interpretation techniques. This starts with the collection of geological data, where in most cases standardized parameters are recorded, which may or may not have relevance for the geological conditions. Very rarely can it be found, that a routine short-term prediction of the geological conditions ahead of the face is performed continuously, which is a precondition for the prediction of rock mass and system behaviours.
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.

3.1 Spatial Displacement Monitoring

The measurement of spatial displacements of targets fixed to the lining has widely replaced the traditional convergence measurements with the tape (Rabensteiner 1996). 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.

3.2 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.

3.3 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 insight 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 (Volkmann 2003).

3.4 *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.

4 METHODS OF EVALUATION AND DISPLAY

In the following chapters the focus is put on the absolute displacement monitoring, which is the method most commonly used.

4.1 *Displacement histories*

Plotting displacement 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, 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. (1987) 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 a varying advance rate. To be able to make a well founded judgment additional tools are required, like using the equations given by Sulem.

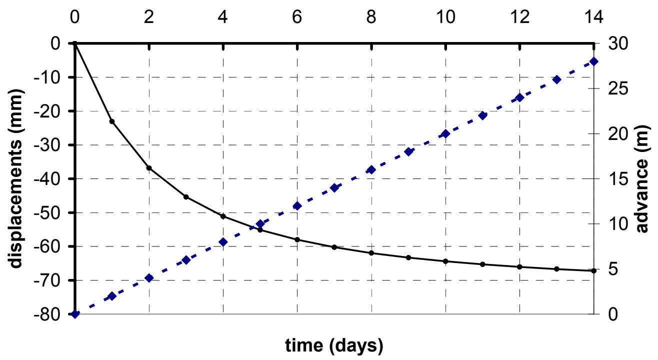

Figure 1. *Displacement history and advance for a steady excavation rate; distance between face and measuring section plotted as dashed line*

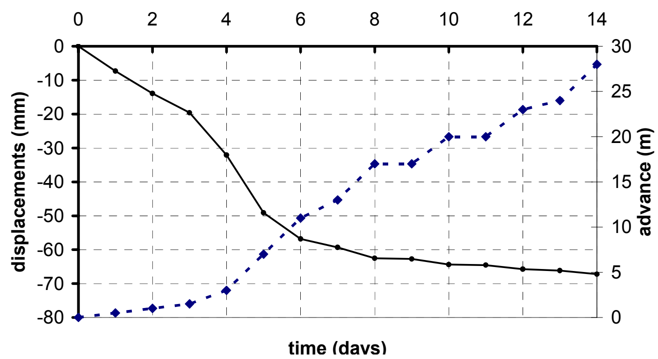

Figure 2. *Displacement history and advance for a non-steady excavation rate; distance between face and measuring section plotted as dashed line*

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. Sellner (2000) based on Sulem et al. and Barlow (1986), extended the functions and added new features, like the possibility to consider additional support. The extended capabilities were implemented in a code, called GeoFit® (Sellner & Grossauer, 2002). 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 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 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

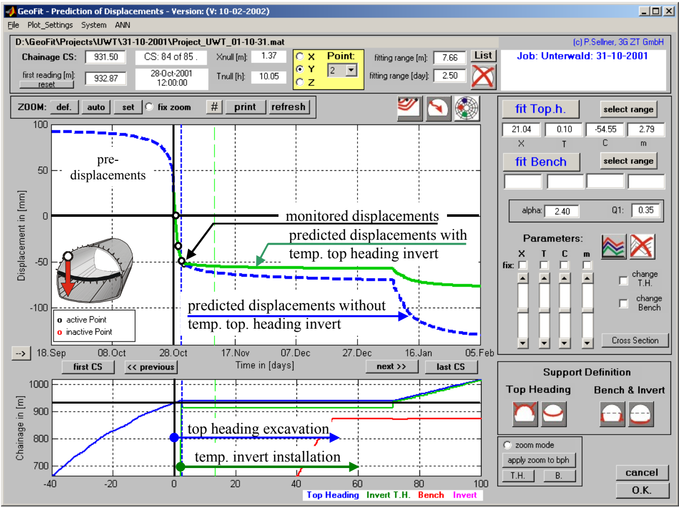

Figure 3. *Back calculation of the function parameters after 2 days of measurements, and prediction of displacement development*

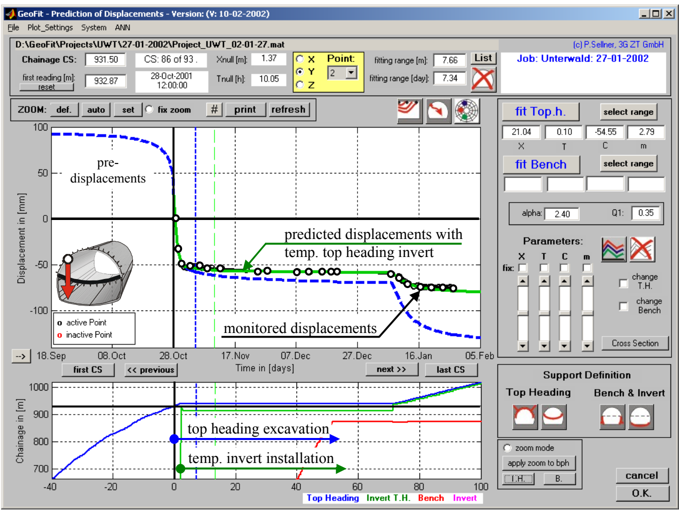

Figure 4. *Comparison of the predicted displacements to the measured ones, shown as dots*

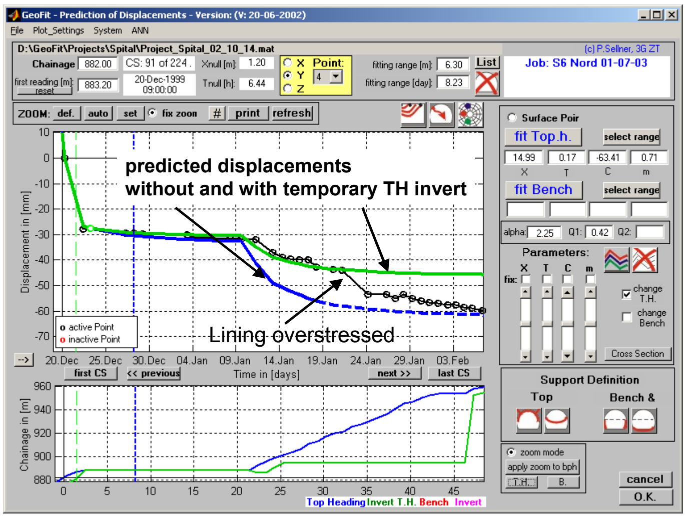

Figure 5. Deviation of system behavior from predicted behavior due to overstressing of the lining and partial loss of capacity

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 was obtained.

Figure 5 shows such a deviation from the predicted behaviour. A measuring section was installed in the 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 of the processes, as each section has to be inspected separately.

4.2 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 Vavrovsky & Ayaydin (1988), Vavrovsky (1988), Vavrovsky & Schubert (1995). 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 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 meas-

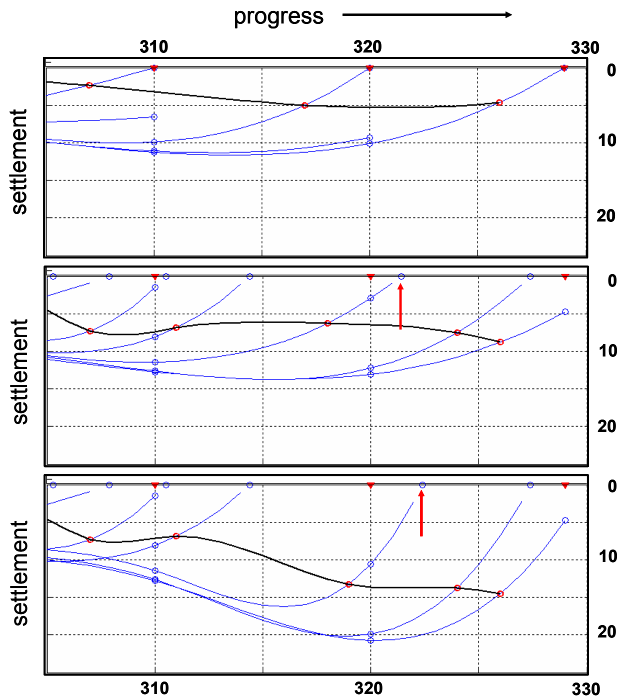

Figure 6. *Deflection lines without consideration of pre-displacements (top), with pre-displacements but wrong face position (centre) and with pre-displacements and correct face position (bottom), (Schubert et al. 2002)*

urements 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 (2000). 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. The graph in the top of figure 6 shows the deflection lines without consideration of pre-displacements. The trend 3 m behind the face is also shown. In this example the zero reading at measuring section 320 was done when the face was at station 322. In case the face station at the time of the zero reading would be erroneously recorded at station 321, the deflection curves and trend line would look like in the central plot in figure 6, while the bottom plot shows the curves with the exact recording of the face station. This rather simple example demonstrates the importance of recording the data accurately. One can arrive at wrong conclusions, when there are mistakes in the data.

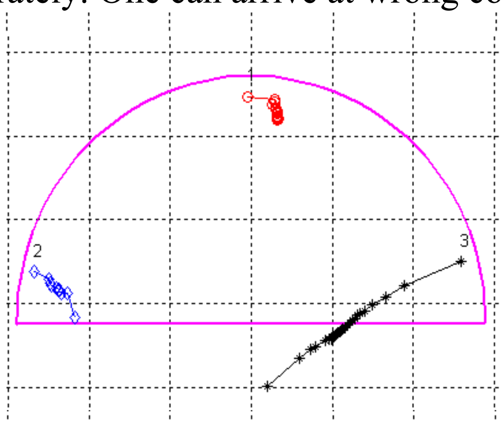

Figure 7. *Typical displacement vector plot for a top heading, where a steeply dipping fault is located close to the right sidewall*

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.

4.3 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. 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.

Figure 7 shows a situation, where the top heading approaches a steeply dipping fault, which crosses the tunnel from the right to the left side. The fault outside the right sidewall causes higher displacements.

4.4 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 and 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 case the excavation approaches 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.

4.5 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 (Schubert 1993) 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, the capability of short term prediction increases significantly (Schubert & Budil 1995, Schubert & Steindorfer 1996, Steindorfer 1998, Golser 2001, Grossauer 2001).

Figure 8 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 exceptionally poor rock on a section of approximately 100 m was encountered. In figure 8 it can be seen, that the vector orientation considerably deviates from the “normal” orientation well before the

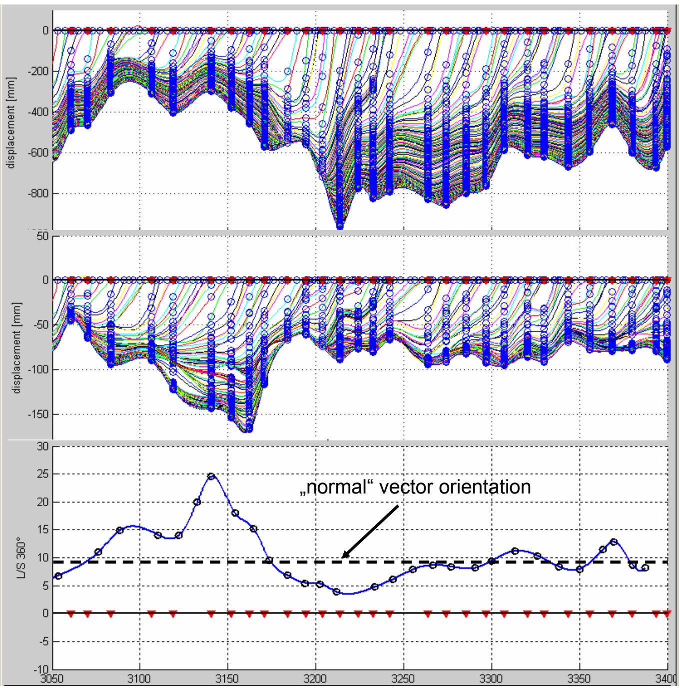

Figure 8. *Settlements of the crown (top), longitudinal displacements (middle), and ratio of longitudinal and vertical displacement (bottom) at the Inntaltunnel*

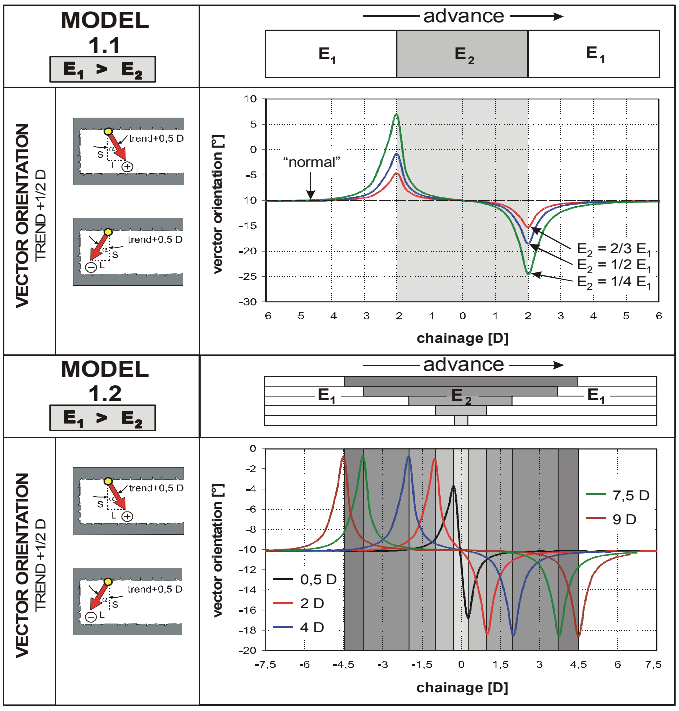

Figure 9. *Influence of the length of a weak zone on the deviation of the displacement vector orientation from normal for different stiffness contrasts (top), and different extensions of the weak zone (bottom) (Grossauer et al. 2003)*

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 (2001) 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 9).

As can be seen from figure 9, 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 10, where the trend of the displacement vector orientation shows a deviation from a positive (backwards) normal orientation to a negative (forward) orientation between station 895 and 915. Then there seems to be a change in the trend again towards normal. At station 921,5 an overbreak of about 50 m^3 occurred. The analysis of other overbreaks in heterogeneous rock masses showed similar trends. It seems that the apparent “normalization” of the displace-

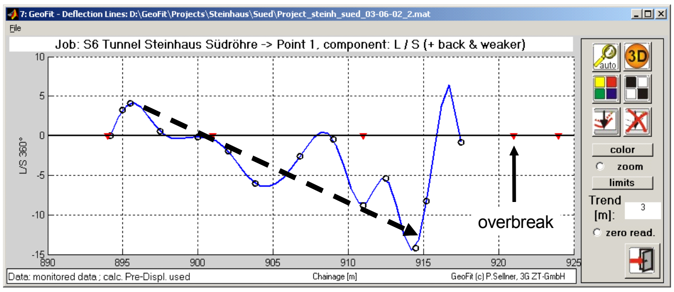

Figure 10. *Trend of displacement vector orientation of crown-point prior to an overbreak*

ment 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, and the evaluation of the data done immediately after the acquisition.

4.6 Evaluation of stresses in linings

Once data are recorded and stored, one should make the maximum use of the information contained in the data. One of the methods to increase the level of information is to analyse stresses in the lining and compare them to the strength. Rokahr and Zachow (1997) have done pioneering work in this field and the model is practically applied (Rokahr et al. 2002). Another model, simulating the complex behaviour of shotcrete is currently under development, and has been tested on one site (Hellmich et al. 1999, Macht 2002). In both routines measured displacement data are used and strains in the lining calculated. Considering the strain development and transient properties of the shotcrete, the stresses continuously are compared to the actual strength. Not only the magnitude of displacements, but also their timely development influences the stresses in the lining. When predicting displacements (for example with GeoFit) also a prediction of the stress intensity factor is possible. This shall be demonstrated with an example. An excavation proceeds with a rate of 4 m per day. Twelve hours after installation of the support the measured displacements in this section are available. The

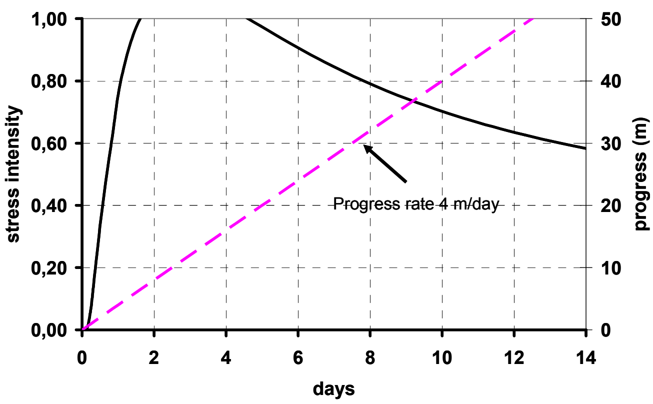

Figure 11. *Development of stress intensity factor for an advance rate of 4 m per day*

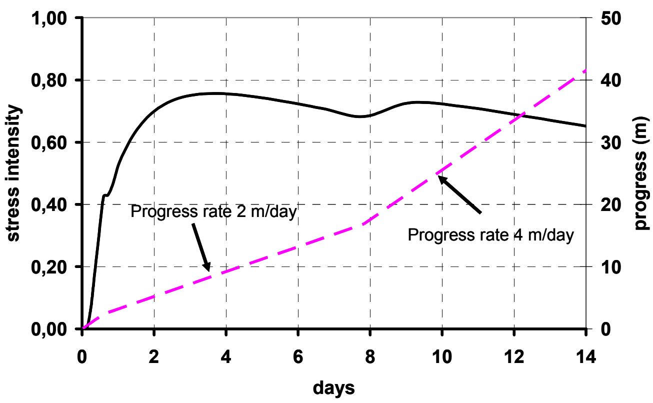

Figure 12. *Utilization of the shotcrete lining due to reduction of progress rate*

prediction of displacements based on the first reading is done. Based on this the development of the stress intensity is predicted. It shows that the stresses would exceed the strength of the shotcrete after less than two days (figure 11). By immediately reducing the advance rate to 2 m per day for about one week the stress intensity remains below 0, 8 (figure 12).
This example demonstrates that measurements have to be taken in relatively short intervals, and the data immediately processed and evaluated to be able to react in time.

5 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 and organizational program is needed. 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 to evaluate 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.

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