Observation and measurements have a long tradition in geotechnical engineering. The reasons for measurements and the evaluation and interpretation of the acquired data are multiple. Verification of design parameters, quality control and the effectiveness of construction methods, observation of the rock mass behaviour, etc. may be the motivations to implement a monitoring system.

Especially for tunnel projects in weak rock with high overburden the observation of the rock mass and system behaviour is an essential basis for the final design of the excavation and support. Due to the uncertainties in the geological model, the heterogeneity of the rock mass, and the deficiencies in modelling of the rock mass support interaction prior to construction, measurements are an important issue for optimisation of the construction while simultaneously observing the safety requirements.

For shallow tunnels the monitoring plays an important role in the stability assessment and to control surface settlement requirements.

For the last 15 years in tunnelling, the measurement of absolute spatial displacements has become very common, replacing the previously used convergence measurements. With the increased information inherent in the 3D data, additional methods of evaluation and display were developed. A vast number of projects have been successfully completed where these methods have been used.

An enormous amount of data has been collected during this period. The question now is, whether we use those data in a way that would allow for a considerable increase in understanding the rock mass behaviour, the rock-support interaction, and the degree of safety inherent in the system. A literature review shows, that there are not many institutions where site data are thoroughly analysed, and the results sufficiently explained and backed up by fundamental analyses. Considering the practice on many sites, it can be stated, that in a few places there is a high standard in evaluation of measurement data and the application of the results for the control of the construction, while on other sites not much progress in this respect can be seen. In many places displacement-time graphs are visually inspected and no further evaluation follows. How misleading this type of measurement data evaluation can be is shown in this paper and in (1).

The gap between the state of knowledge and the practice on many sites can easily lead to severe questions of responsibility and liability in case of accidents. The authors feel, that a short summary of the state of the art in evaluation and interpretation of measurement data might be beneficial.

**State of the art**

A number of reflectors (targets) are fixed to the lining. A freely positioned total station in regular intervals measures the co-ordinates of the targets, commonly once each day. The targets usually are arranged in measuring sections, which are separated by 5 to 20 m. The number of targets:

**Verschiebungsmessungen in Tunneln – Ein Überblick**

Die Verschiebungsmessung im Tunnelbau hat eine lange Tradition. Die Methoden haben sich über die Jahrzehnte verändert, was zu einer besseren Aussagekraft der Meßdaten führen kann. Der Beitrag gibt einen kurzen Überblick über die gängigen sowie neuere Methoden der Meßdatenauswertung und Darstellung. Für einfache Verhältnisse mag ein Blick auf die Zeit-Verschiebungskurven genügen, um das Verhalten des Tunnels beurteilen zu können. Bei heterogenen Baugrundverhältnissen oder nicht kontinuierlichem Vortrieb müssen hingegen weitere Analysen vor genommen werden, um die „Normalität“ der gemessenen Werte überprüfen zu können. Die Arbeit zielt darauf ab, Personen, die auf der Baustelle mit Meßdaten zu tun ha-
gets in one section depends on the size of the tunnel and to a certain extent on the number of subsequent phases (heading-bench-invert). The procedure of measuring and data processing is described in (2). The measurement accuracy is in the range of less than 1 mm, which in most cases is sufficient.

**Evaluation methods and common displays**

**Displacement history**

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 continuous advance rate. The condition for a satisfying stabilization, respectively the stress redistribution is a steadily decreasing displacement rate. Figure 1 shows the development of the displacement for the first couple of days for a steady advance rate. Sulem et al. (3) have formulated the relationships for time dependent closure of tunnels. Those formulations were used to produce Figure 1, Figure 2 and Figure 3.

When the rock mass is heterogeneous and the advance rate not constant, the interpretation of the “normality” of the measured values becomes more difficult. Figure 2 shows a displacement history for the same set of parameters as used for producing Figure 1 with an unsteady advance rate.

Without considering the progress one would not interpret the displacement development as “normal”, but rather be concerned. 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 using the displacement histories only. Figure 3 shows the total displacement histories for the two different advance rates shown above.

Recently, a tool has been developed that is able to predict displacements even for complex situations (4, 5). With this program it is possible to model face advance effects, time dependent behaviour and support effects, and thus check the measured displacements on their “normality”. The use of this tool is shown with the help of case histories in this volume (5).

**Deflection lines**

Connecting the measured values of one component (for example the vertical or horizontal component) at a certain time along the tunnel produces deflection lines. By plotting these lines in regular intervals, the influence of the progress on the sections behind the face can be easily seen. This is the reason why the deflection lines frequently are called influence lines. Details and examples of application can be found in (6, 7, 8). Deflection lines are quite useful to get an overview of the displacement development along a section of the tunnel. 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

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Fragen Sie danach.
Displacement measurements 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 are 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 in (4).

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.

Figure 4 shows the deflection lines without (top) and with consideration of the calculated pre-displacements (bottom). The blue lines represent the deflection lines, while the black line shows a trend 3 m behind the face. In this example the zero reading at measuring section 320 was done quite some time after the excavation. When this circumstance is not considered, and only the measured values taken for the plot, one would assume that the displacements are more or less uniform. Using the calculated pre-displacements, an increase in displacement between station 310 and 320 can be clearly seen. Additionally the trend lines are considerably different.

Figure 5 shows the importance of precise recording of the face location for a proper use of the plots produced. In the upper plot the red arrow marks the face location at a certain time. A mistake in the face location of only one metre (red arrow, lower plot) produces a completely different plot.

Displacement difference
Plotting differences of displacement components – for example the difference between crown and footing settlement – in certain cases can help to detect abnormal system behaviour. With this plot weak zones outside the excavated tunnel can be identified, as local failure in the rock mass will show in an increase in the difference. For this purpose the authors prefer to use displacement vector plots or ratios of the single components, as the difference may also change when the behaviour is normal, but the quality of the rock mass gradually improves or decreases.

Displacement ratios
Calculating the ratio between displacement components and plotting them as a trend can help detecting weak zones outside the tunnel. An example shall demonstrate this: under normal conditions the settlement of the sidewall will be considerably smaller than the settlement of the crown. Figure 6 shows this type of plot for a situation, where the excavation crosses a steeply dipping fault. For a timely detection of such a sit-
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BAULOS 12 UNTERWALD-KALWANG

Tunneldurchschlag auf Station 1052,6 am 21.02.2002

Bauausführung:
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Due to the measurement technique it is possible to plot the spatial displacement vectors. Some evaluation software plots the displacement vectors and their path over time in a cross section perpendicular to the tunnel axis by combining the vertical and horizontal components. This plot can be very useful to evaluate the influence of the rock mass structure on the displacement of the tunnel. Similar to the ratios of displacement components, zones of weakness outside the tunnel profile can be detected in advance, providing the measuring sections are in a reasonable distance (Figures 7 and 8). Figure 7 shows the displacement vectors in a cross section with a fairly "normal" orientation, indicating a relatively homogeneous rock mass. The tunnel was excavated in a top heading-bench-invert sequence. This is the reason why the displacement in the bench is rather minor, compared to the top heading.

The displacement vector plots are not only useful for the early detection of weak material outside the tunnel profile, but also for the layout of rock bolts.

It has been shown, that the ratio between the settlement or horizontal displacement and the longitudinal displacement can be a useful indicator for the quality of the rock mass ahead of the face (10, 11, 12). This especially applies to tunnels with relatively high overburden and weak rock mass.
ground. When the excavation approaches weaker or stiffer material, the orientation of the displacement vector significantly changes well ahead of the change in rock mass stiffness. The vector orientation can be shown in a longitudinal section, as a trend line displaying the ratio between the longitudinal displacement and settlement, or the spatial orientation in a stereo plot.

Figure 9 and Figure 10 show combined plots of the displacement vectors in the cross section and in the longitudinal section. Note the pronounced longitudinal displacement in the plot in Figure 9, indicating a fault zone ahead of the face. The radial displacements are rather small. Figure 10 shows the situation after the excavation entered the fault zone, which was met with the excavation at approximately station 2 700 m. The radial displacements dramatically increase, while the displacement vector orientation in longitudinal direction normalizes.

Figure 11 shows a trend line of the ratio between the longitudinal displacement and the vertical displacement of the crown in the area that was shown in the previous figures. The strong relative increase in longitudinal displacement around station 2 600 m indicates the fault zone, which was encountered with the excavation around station 2 700 m. The vector orientation returns to the “normal” level within the fault zone. The spatial vector orientations of the monitored points can also give a rough estimate on the primary stress condition with respect to orientation and ratio of the principal stresses (13, 14). The evaluation of the development of the displacement vector orientation is very useful for conditions, where the displacements are in the range of...
Displacement monitoring for tunnels has reached a high standard. Many sites run monitoring programs in order to control displacements and to finalize the design during construction. The extent of use of the data acquired however differs very much from site to site. Visual inspection of time-displacement histories is still standard on many sites. With a few simple examples it has been shown, that a simple visual impression of those plots in many cases is not sufficient to be able to assess the stability of the tunnel, or even the "normality" of the stress redistribution process. This especially applies with unsteady advance, multiple drifts, and variation in support. During the last years considerable research has been undertaken to improve the data evaluation methods, and to maximize the information inherent in the monitored data. Practice however shows, that those methods are adopted on site rather slowly and reluctantly out of various reasons.

Neglecting state of the art methods in data evaluation may not only cause financial losses, but also may lead to serious consequences for the persons involved on site in case of accidents. Everybody involved in the process of data acquisition and evaluation must be aware of the fact that the value of the information that can be obtained strongly depends on the quality of the data.

Much has been achieved during the last decades, but there is still ample room for improvement.

References

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