Displacement Monitoring in Tunnels – an Overview

By Wulf Schubert, Albert Steindorfer and Edward A. Button

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, observation of 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 geotechnical 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 tar-

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 vorgenommen werden, um die „Normalität“ der gemessenen Werte überprüfen zu können. Die Arbeit zielt darauf ab, Personen, die auf der Baustelle mit Meßdaten zu tun haben, zu motivieren, den erzielbaren „Mehrwert“ durch neuere Meßdatenanalysen zu nützen.

Displacement monitoring in tunnels has a long tradition. Methods have changed over the decades, allowing extracting more information from the measured data. The paper provides a brief overview of the methods to evaluate and plot the results of the measurements. For simple conditions the simple look on a displacement history plot may be sufficient to evaluate the tunnel performance. As soon as the rock mass is heterogeneous or the progress discontinuous, additional tools have to be used to check the “normality” of the measured values. With the information given in the paper it is intended to motivate persons involved in the monitoring on site to make use of the “added value” of up to date measurement evaluation.

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.

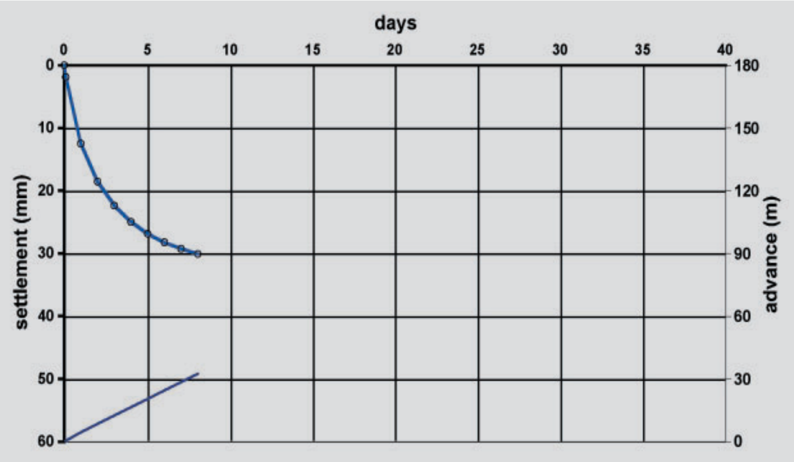

Fig. 1 Displacement history and advance for a continuous excavation rate.

Bild 1 *Zeit-Verschiebungskurve und Baufortschritt bei gleichmäßiger Vortriebsgeschwindigkeit.*

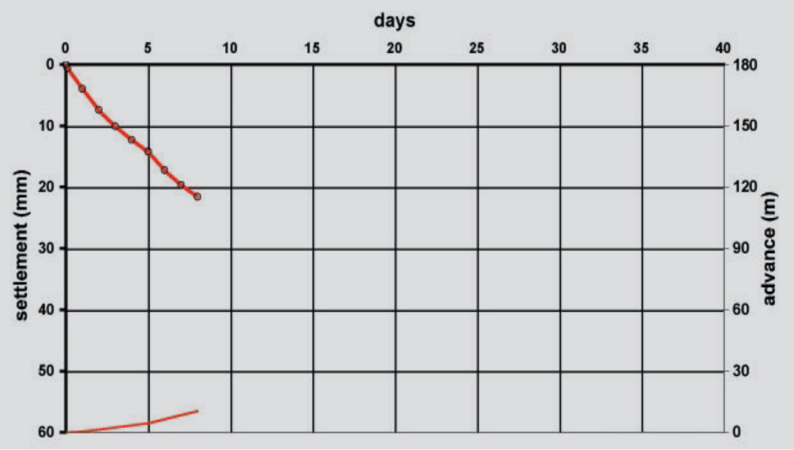

Fig. 2 Displacement history and advance for an unsteady excavation rate.

Bild 2 *Zeit-Verschiebungskurve und Baufortschritt für einen Vortrieb mit unterschiedlichen Vortriebsgeschwindigkeiten.*

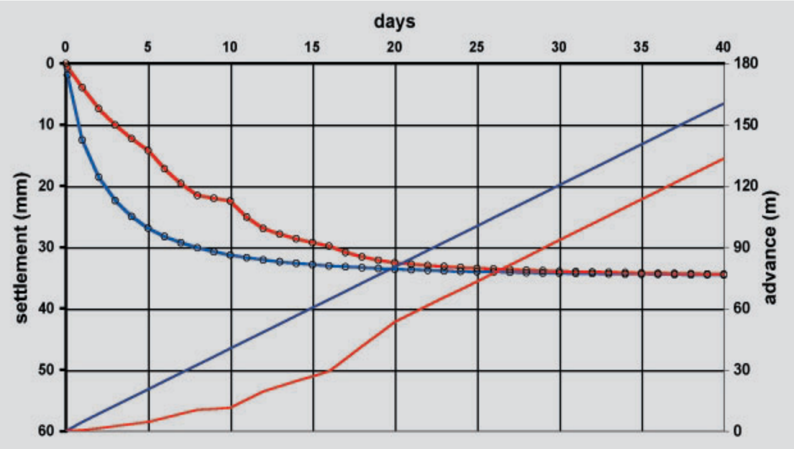

Fig. 3 Displacement histories and advance for both cases shown in Figure 1 and Figure 2.

Bild 3 *Zeit-Verschiebungskurven und Baufortschritt für beide oben gezeigten Fälle.*

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 stabilisation, 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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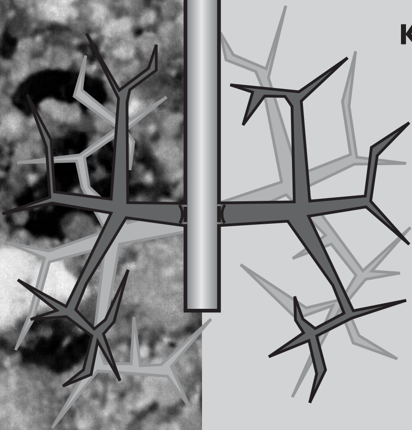

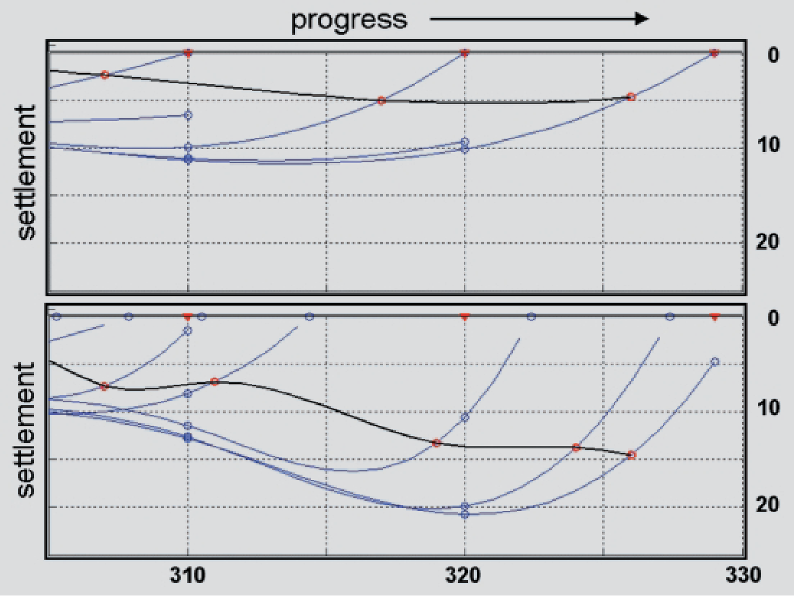

Fig. 4 Deflection lines without consideration of pre-displacements (top) and with pre-displacements (bottom) .

Bild 4 *Einflußlinien ohne (oben) und mit Berücksichtigung der Vorverschiebungen (unten).*

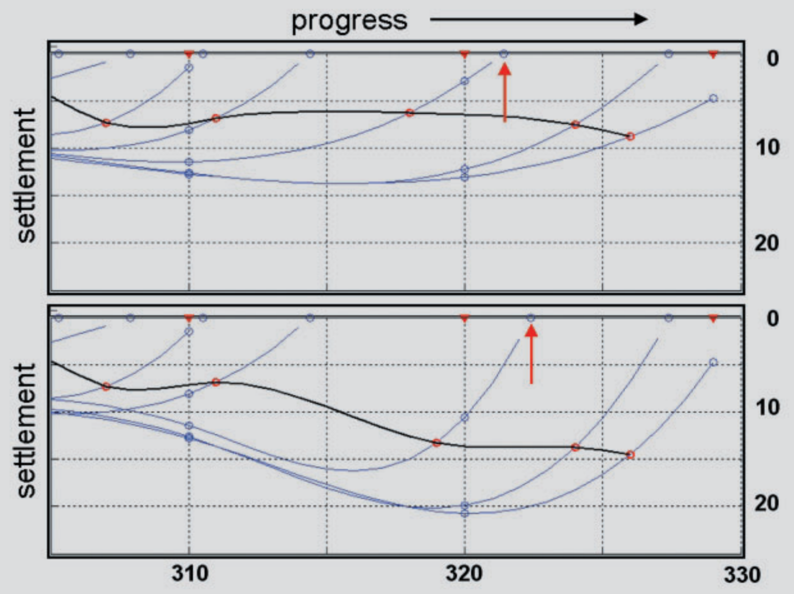

Fig. 5 Deflection lines with correct recording of the face position (top, red arrow) and with mistake in face Position (bottom, red arrow).

Bild 5 *Einflußlinien bei richtiger Aufzeichnung des Ortsbruststands (oben, roter Pfeil) und bei fehlerhaftem Ortsbruststand (roter Pfeil, unten).*

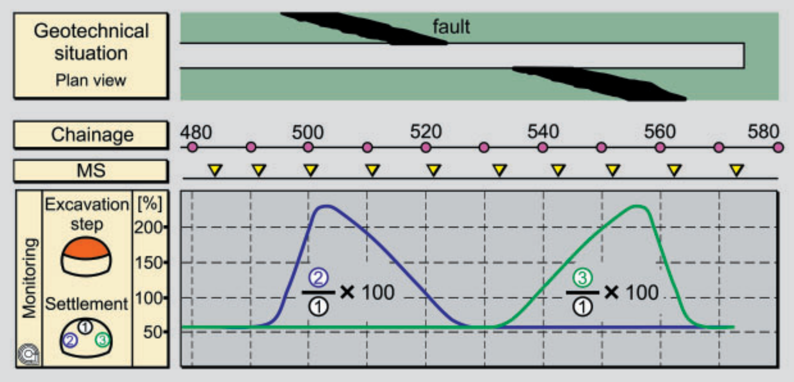

Fig. 6 Trend line of ratio of settlements of crown and sidewall points (9).

Bild 6 *Trendlinien der Verhältnisse der Setzungen zwischen den Ulmpunkten und der Firste (9).*

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 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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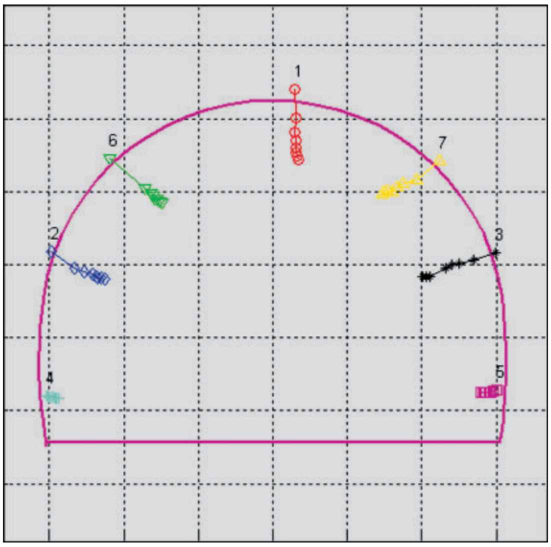


Fig. 7 Displacement vectors in a cross section with fairly "normal" orientation (first eight readings); displacements magnified by a factor of 10.

Bild 7 *Verschiebungsvektoren im Querschnitt mit annähernd „normaler" Orientierung, dargestellt sind die ersten acht Meßwerte; Verschiebungen um Faktor 10 vergrößert.*

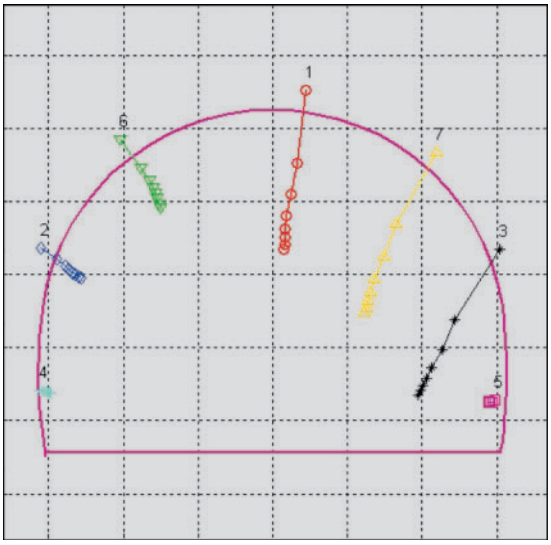


Fig. 8 Displacement vectors in a cross section, showing a strongly unsymmetrical deformation due to a fault zone outside the right sidewall (first eight readings); displacements magnified by a factor of 10.

Bild 8 *Verschiebungsvektoren im Querschnitt zeigen eine stark unsymmetrische Verformung, die durch eine Störung außerhalb des rechten Kämpfers verursacht wird; dargestellt sind die ersten acht Meßwerte in einer Vergrößerung um den Faktor 10.*

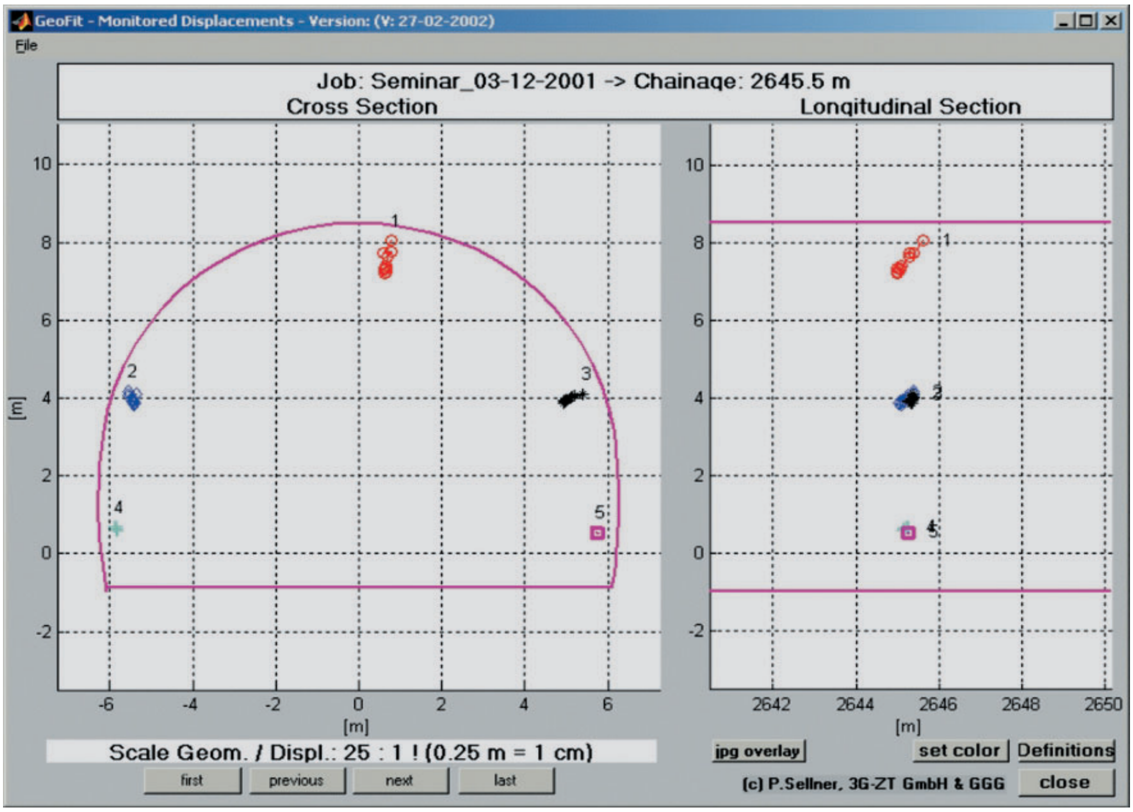
uation it is required to install measuring sections in rather small distances. As a rule of thumb the distance between the measuring sections should not exceed one tunnel diameter.

Displacement vectors

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 axisby 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



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Scale Geom. / Displ.: 25 : 1 ! (0.25 m = 1 cm)

(c) P.Sellner, 3G-ZT GmbH & GGG

Fig. 9 Combined plot of displacement vectors in a cross section and in the longitudinal section; note the relatively pronounced longitudinal displacement indicating a fault zone ahead of the excavation.

Bild 9 *Kombinierte Darstellung der Verschiebungsvektoren im Quer- und Längsschnitt. Bemerkenswert ist die relativ große Längsverschiebung, die auf eine Störungszone hinweist.*

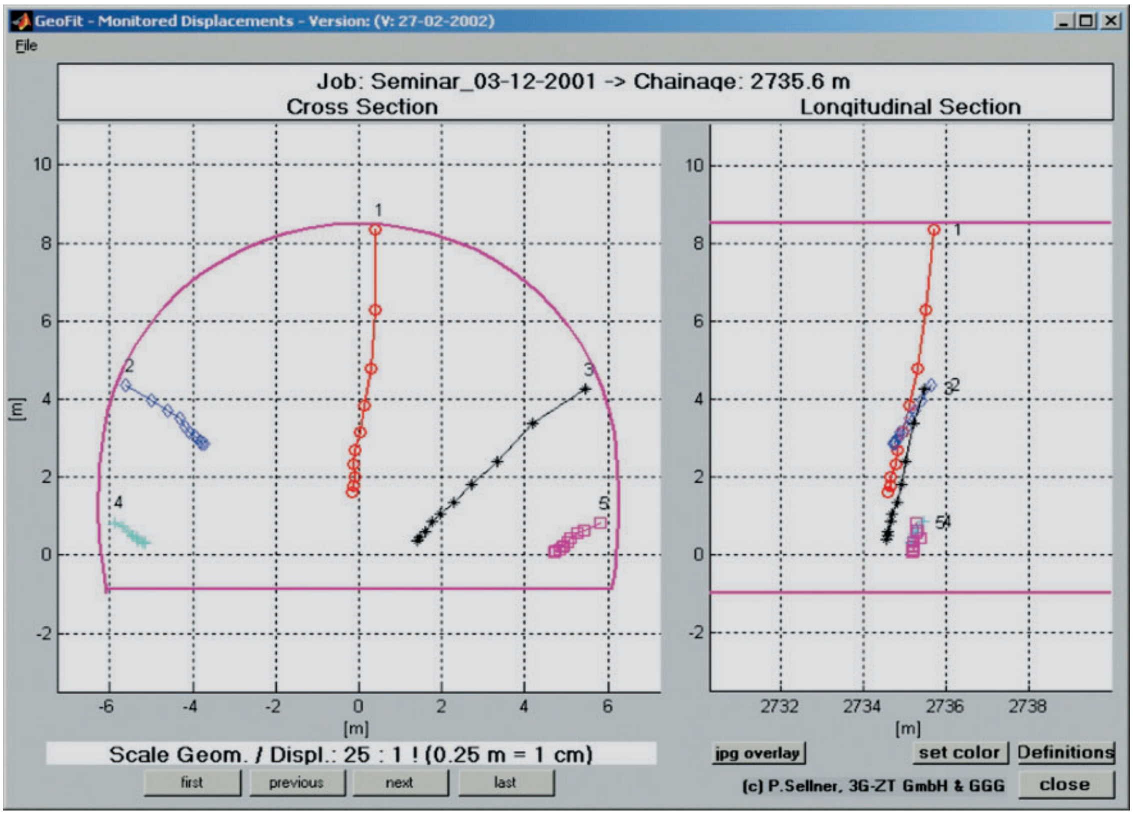

Fig. 10 Combined plot of displacement vectors in a cross section and in the longitudinal section roughly 90 m from station shown in Figure 9, after entering the fault zone.

***Bild 10** Kombinierte Darstellung der Verschiebungsvektoren im Quer- und Längsschnitt etwa 90 m nach dem in Bild 9 gezeigten Querschnitt nach Antreffen der Störungszone.*

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

Fig. 11 Trend of the displacement vector orientation showing a significant change well ahead of the fault zone met by the excavation at approximately station 2 700. The blue dashed line shows the “normal” vector orientation in homogeneous rock mass conditions.

***Bild 11** Trend der Orientierung des Verschiebungsvektors im Längsschnitt. Deutlich zu sehen ist die starke Änderung bereits weit vor der bei etwa Station 2 700 mit dem Vortrieb angefahrenen Störung. Die strichlierte blaue Linie zeigt die „normale“ Vektororientierung bei gleichmäßigen Gebirgsverhältnissen.*

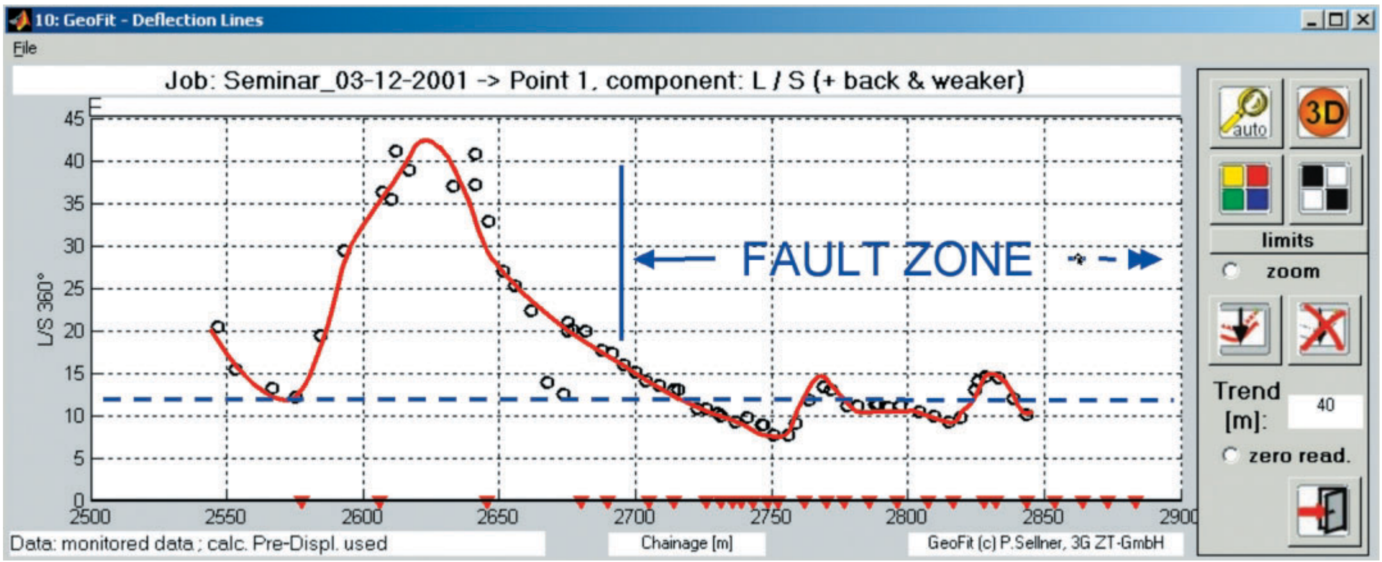

Table Overview of the value of evaluation methods for specific questions;: + = good, o = limited value, - = no value.

Tabelle *Überblick über den Wert der einzelnen Darstellungsmethoden für unterschiedliche Fragestellungen; + = gute Aussage, o = beschränkte Aussagekraft, - keine Aussage möglich.*

	Evaluation of stabilization process	Prediction final displacements	Stress redistribution longitudinal	Detection weak zones outside profile, kinematics	Prediction ahead	Estimate of stress intensity in lining
Displacement history	+	+	-	o	-	+
Deflection lines, trends	o	-	+	o	o	-
Trends of relative displacement values	-	-	-	+	-	-
Vectors in cross section	-	-	-	+	-	+
Vectors in longitudinal section	-	-	-	o	+	-
Spatial vector orientation	-	-	+	+	+	-

several centimetres. In shallow tunnels due to the small stress level and the usually relatively stiff lining, the vector orientation is not a reliable indicator for changing rock mass conditions.

As has been discussed in the previous sections, an efficient use of the information provided by the evaluation of the measurement data is possible only, when the quality of the data is good. Poor quality in surveying or data processing severely reduces the potential for further evaluations and may lead to misinterpretation.

Additional evaluations

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 (1, 15) has done pioneering work in this field and the model is practically applied. Another model, simulating the complex behaviour of shotcrete is currently under development (16), but has not proved its practical applicability yet. Especially for tunnels with low overburden, where the shotcrete lining is the predominant support and the rock mass plays a minor role in the stress redistribution, the knowledge of the development in the stress intensity index is an important decision aid. With higher overburden the integrity of the shotcrete lining usually looses importance, because in most cases the natural "rock arch" can compensate the loss in lining capacity, under the condition that is has still reserves or is properly reinforced by rock bolts.

Value of the different evaluation methods

It has been shown, that methods of data evaluation have to be chosen according to the problem on hand. The Table shows a brief and preliminary overview of the applicability of the single evaluation and display methods for specific targets.

It is pointed out, that usually a combination of evaluation methods is required to obtain a clear understanding of the geotechnical situation and the rock mass and tunnel behaviour. In addition the continuous updating of the geological model and its prediction into the volume of interest is of essential importance for the reliability of the measurement data interpretation.

Conclusion

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.

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