Short Term Prediction of System Behaviour of Shallow Tunnels in Heterogeneous Ground

By Bernd Moritz, Karl Grossauer and Wulf Schubert

Several complications have to be expected when tunnelling in heterogeneous ground, such as in bimrocks (block-in-matrix rocks) or fault zones:

- The necessity of using different excavation methods, such as drill-and-blast and an excavator, sometimes during the same round.
- The frequently changing stresses and deformations of the rock mass and the support.
- The potential for several different failure mechanisms, such as excessive overbreak, collapse of the face and crown, brittle failure of hard blocks, and long term creep of matrix, to name only a few.
- The heterogeneous distribution of ground water with the potential for heavy water inflows especially in fault zones.

Kurzzeitprognose des Systemverhaltens von seicht liegenden Tunneln in heterogenem Gebirge

Der Artikel behandelt die Auswertung und Interpretation von Verschiebungsdaten sowie die Prognose der Verschiebungen für seicht liegende Tunnel in heterogenem Gebirge. In den letzten Jahren wurden die Auswertemethoden erheblich verbessert und ausgeweitet. Für tief liegende Tunnel wurden im Speziellen die Trendänderungen der Verschiebungsvektororientierung erfolgreich zur Kurzzeitprognose der Gebirgsqualität in den der Ortsbrust voraus liegenden Gebirgsbereichen herangezogen. Unklar war allerdings, ob solche Auswerte- und Prognosemethoden auch für Bereiche mit geringem Spannungsniveau angewendet werden können. Die Auswertung von Verschiebungsmessdaten von seicht liegenden, in einer tektonischen Melange in den Ostalpen Österreichs aufgefahrenen Tunneln hat gezeigt, dass die oben beschriebenen verbesserten Auswertemethoden ebenfalls zur Kurzzeitprognose bei seicht liegenden Tunneln herangezogen werden können, vorausgesetzt die aufbereiteten Messdaten liegen in entsprechend guter Qualität und Genauigkeit vor.

The paper deals with the evaluation, interpretation and prediction of monitored displacements for a shallow tunnel in heterogeneous ground. Over the last few years evaluation methods in tunnelling have been considerably improved and extended. In particular the changes in the displacement vector orientation have been successfully used in deep tunnels for the short term prediction of the rock mass quality ahead of the face. Up to recently it has not been clear if such methods can be used also in low stress environments as well. However, using data from shallow tunnels excavated in a tectonic melange in the Eastern Alps of Austria, it is apparent that the described improved methods of measurement data evaluation can also be used in shallow tunnels for short term prediction, providing the measurement data are of good quality.

Establishing a reliable ground model in heterogeneous ground during the design phase is close to impossible. Even with an exceptional effort in mapping, drilling, and geophysical investigation there still remain considerable uncertainties with respect to location, size and quality specific and individual weak and competent components. This lack of certainty about ground conditions requires continuing ground investigations and updating of the ground model during construction, to be able to adjust excavation and support methods to the ground conditions, and allow a safe construction process. Possible methods for the refinement of the ground model during construction are: probing ahead, geophysical methods, and evaluation of displacement monitoring data, or a combination thereof. But both probing ahead with drillings and geophysical investigations demand a temporary stop to the excavation, and thus are rather costly. In addition, probe drillings give only pinpoint information, while the interpretation of results of geophysical investigations is difficult and the state of the art needs further development.

For the purposes of short term prediction of the rock mass condition ahead of the face and around the tunnel, the evaluation of 3D displacement monitoring data has been shown to be very efficient. In-situ observations, (1, 2, 3), as well as theoretical studies (4, 5, 6, 7) have shown the potential for an advanced analysis of displacement monitoring data to reliably predict the rock mass conditions. The trends of both vector orientation and the spatial orientation of the displacement vectors allow a good short term prediction of the rock mass structure and quality ahead and outside the excavation area.

Initially it was thought that these methods yielded reliable results only at relatively high overburden and poor ground but recent experience has shown that these new methods can also be successfully used in heterogeneous ground and low overburden conditions. Tools have been developed to predict the system behaviour of the combined rock mass support system (8). The observed system behaviour can easily be compared to the predicted one, and the development of critical conditions detected in timely fashion.

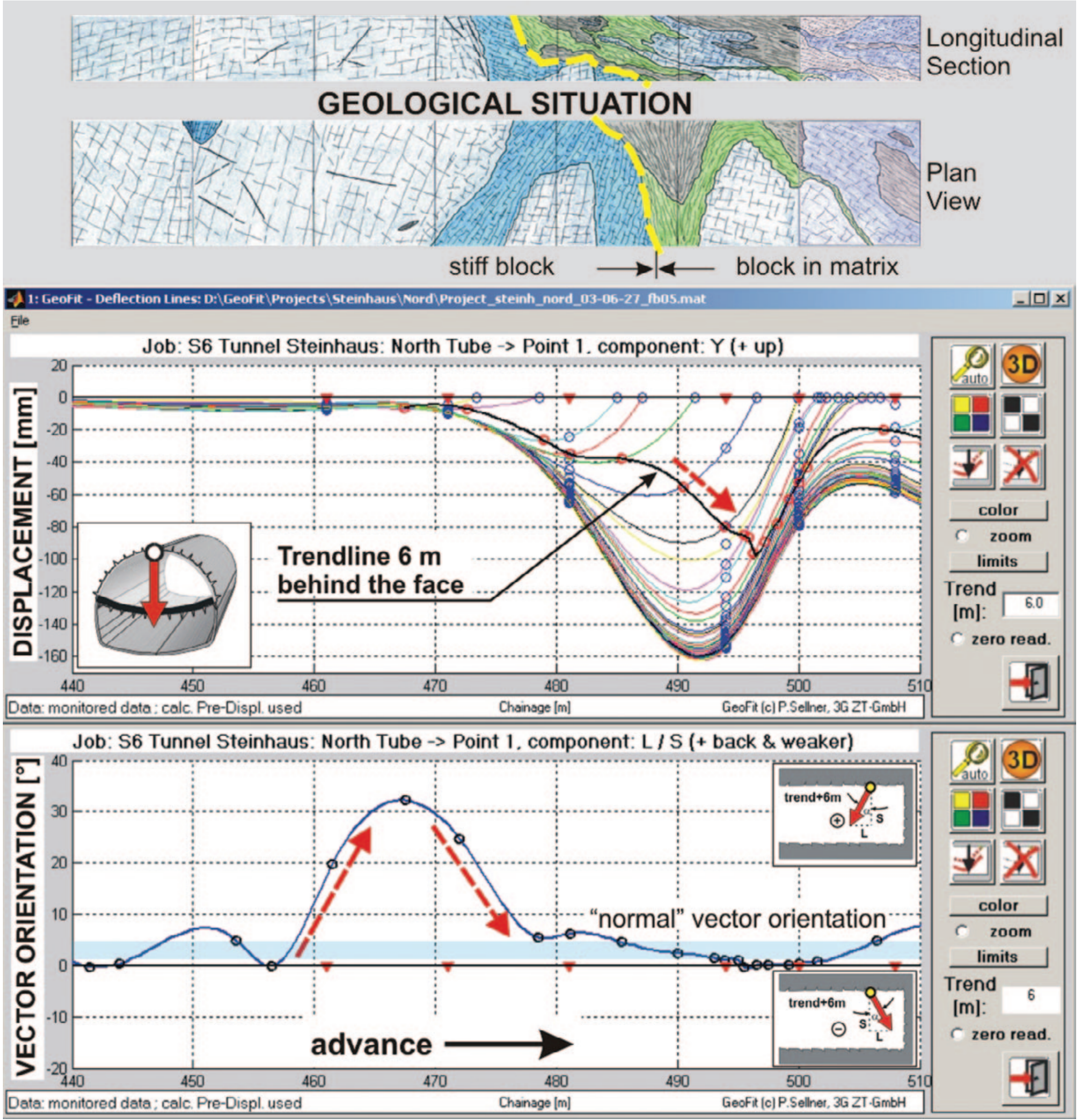

Fig. 1 Top: Geological situation (12) with lime marble (light blue coloured), lime schist (dark blue coloured) and cataclastic phyllites (grey and green coloured). Middle: Development of crown settlements. Bottom: Trend of displacement vector orientation (L/S) of the crown between tunnel metre 440 and 510. All diagrams shown were produced with GeoFit (13).

***Bild 1** Oben: Geologische Verhältnisse (12) mit Kalkmarmor (hellblau gefärbt), Kalkschiefer (dunkelblau gefärbt) und Phyllitkataklasite (grau und grün gefärbt). Mitte: Räumliche Entwicklung der Firstsetzungen. Unten: Trend der Verschiebungsvektororientierung (L/S) der Firste zwischen Station 440 und 510 m. Alle gezeigten Diagramme wurden mit GeoFit (13) erzeugt.*

This paper describes the observed system behaviours of shallow tunnels excavated in a tectonic melange in the Eastern Alps of Austria. Also illustrated is how advanced methods of displacement monitoring data evaluation can assist in in-situ short term predictions on site and in decision making about the selection of excavation and support methods.

Case studies

Geological conditions

The case histories described in this paper are from a tunnel located within a unit of the "Semmering-Unterostalpine" geologic sequence. The geological situation is characterized by a tectonic block-in-matrix rock (bimrock) mixture com-

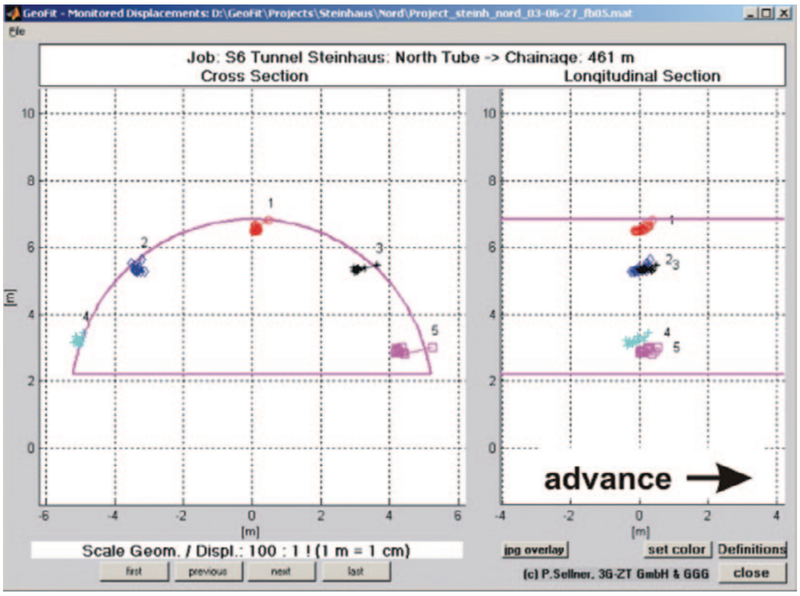

Fig. 2 Monitoring section MS461: Displacement vector orientation in a cross section and a longitudinal section (13).

Bild 2 *Messquerschnitt MS461: Verschiebungsvektororientierung im Querschnitt und Längsschnitt (13).*

posed of predominantly quartzitic, carbonatic, chloritic phyllites and gouge matrix material with embedded blocks of marble and quartzite. This chaotic tectonic mixture was generated from the surrounding host rocks during thrusting associated with the alpine orogeny and was further disaggregated during subsequent strike slip faulting. This bimrock is geologically defined as a polygenetic melange after Raymond (9, 10).

The melange is dominated by a north to north east shallowly to moderately dipping foliation formed during thrusting. However, local folding around the blocks results in continuous variations in the local dip and dip direction. The blocks are typically lenticular in shape and orientated with their long axes sub-parallel to parallel to the foliation. The original structures formed during thrust tectonics are overprinted by brittle strike slip faulting along steeply dipping east-northeast trending strike slip faults associated with the Mur-Murztal fault zone. This combination of tectonic events has created an extremely heterogeneous rock mass exhibiting varying degrees of rock mass strength and spatially complex distribution.

Case study 1: Underpass in a residential area; tunnelling from stiff to soft rock mass

The first case illustrates the behaviour of the rock mass-support system (in the following referred to as system behaviour) in the vicinity of a fault zone intersecting a larger block. For this case study, a section between tunnel metre 440 and 510 is evaluated (Figure 1). Up to tunnel metre 475 the tunnel was excavated in a lime marble block (Figure 1, Top: indicated by light blue colour) of considerable size and high strength and stiffness (11, 12). The fault zone consists of a matrix of chloritic and cataclastic phyllites (indicated by green and grey colour), with some smaller embedded blocks (Figure 1, Top: "block-in-matrix").

Unfortunately the distance between the measuring sections was rather large, as the block was originally expected to be continuous for some distance. A closer spacing of the measuring sections would have allowed more reliable observation the trend described below. A careful analysis of the data after encountering the fault zone with the excavation showed that even with the few data available, and the low amount of displacements observed, the fault zone could have been predicted.

Data were evaluated using the GeoFit software (13) to provide a reliable and accurate procedure for prediction of displacements. The program GeoFit is based on analytical functions which simulate the time-dependent behaviour of the rock mass and support as well as the face advance effect. Several of the Figures shown below were generated by the program GeoFit (13).

As can be seen from Figure 1 (Middle) the vertical displacements of the crown in the section of the stiff block were in the millimetre range. But after the face reached the weak rock, a considerable increase in the displacements was observed, reaching a maximum of about 150 mm at tunnel metre 490. The evaluation of the ratio between longitudinal and vertical displacements (L/S) (Figure 1, Bottom) shows a strong deviation from the "normal" value starting at around tunnel metre 460. The longitudinal displacement increases sig-

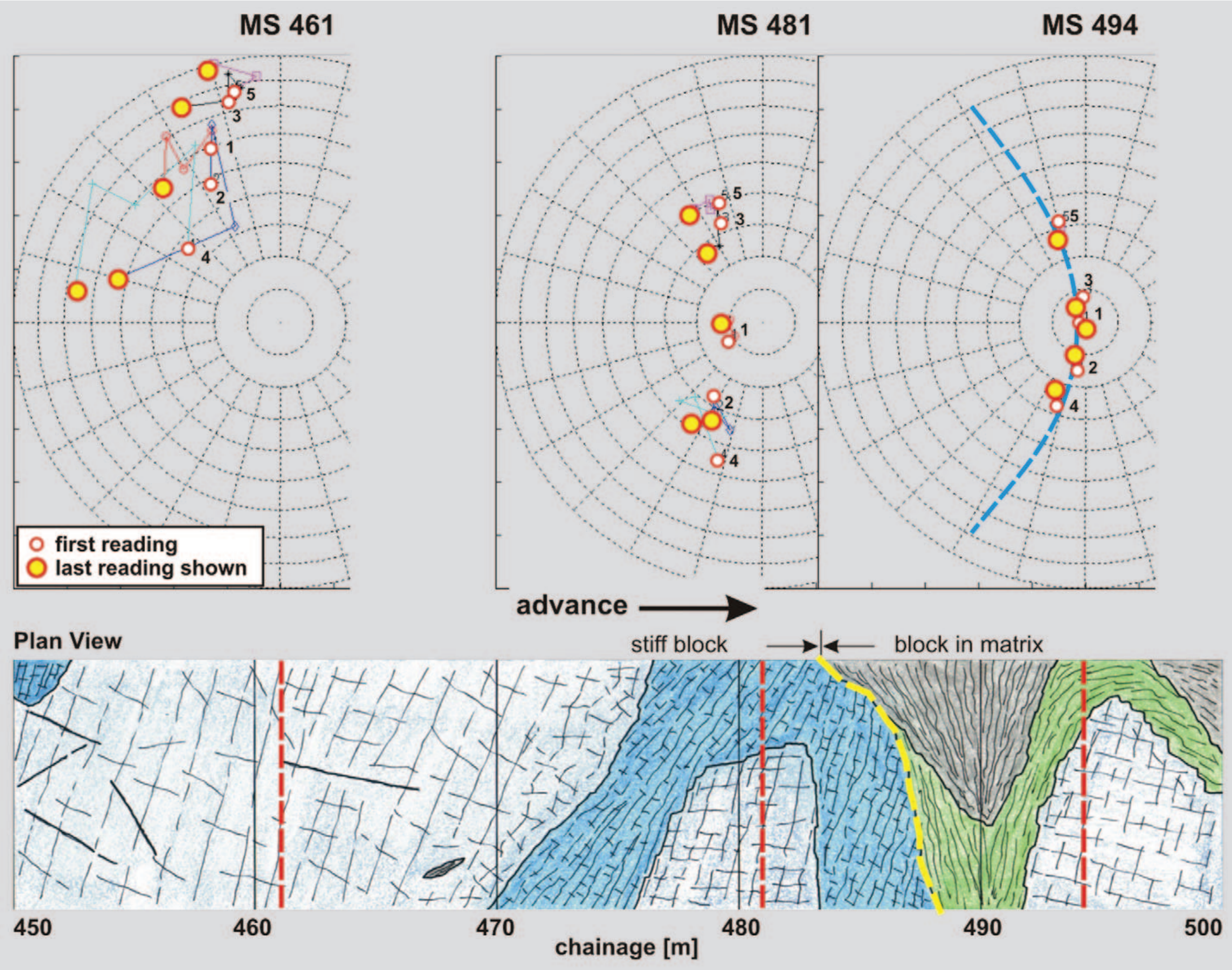

Fig. 3 Top: Stereographic projection (lower hemisphere): Spatial orientation of displacement vectors in monitoring sections MS461, MS481 and MS494 (13). Bottom: Geological situation (12) with lime marble (light blue coloured), lime schist (dark blue coloured) and cataclastic phyllites (grey and green coloured).

***Bild 3** Oben: Langenkugelanalyse (untere Hemisphäre): Räumliche Orientierung der Verschiebungsvektoren in den Messquerschnitten MS461, MS481 und MS494 (13). Unten: Geologische Verhältnisse (12) mit Kalkmarmor (hellblau gefärbt), Kalkschiefer (dunkelblau gefärbt) und Phyllitkataklasite (grau und grün gefärbt).*

nificantly, while the settlements remain more or less constant. The displacement vector in this case strongly points away from the direction of excavation. Based on previous experience and research results (6, 14), this trend clearly indicates that a weaker rock mass is ahead of the face. After entering the shear zone at approximately tunnel metre 485, the displacement vector orientation returns to "normal" again.

The orientation of the transition can be determined by analysing the displacement vector orientations shown in the cross section and longitudinal section of Figure 2, or by evaluating the spatial vector orientation, plotted in the stereonet shown in Figure 3 (Top). From both plots it can be seen that the displacements are strongly

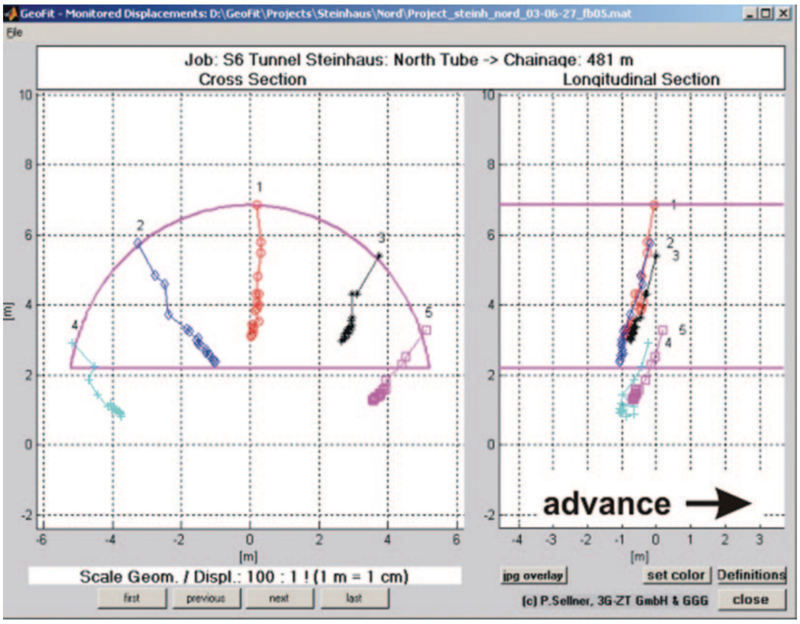

Fig. 4 Monitoring section MS481: Displacement vector orientation in a cross section and a longitudinal section (13).

***Bild 4** Messquerschnitt MS481: Verschiebungsvektororientierung im Querschnitt und Längsschnitt (13).*

asymmetrical, with the higher magnitudes at the right side, which indicates that the weak material will be encountered first on this side.

The stereographic projection (lower hemisphere) of Figure 3 (Top) shows the spatial orientation for all points in the top heading. With some practice the orientation of significant geological features outside the tunnel can be estimated. At tunnel metre 461 – this is about 20 m ahead of the transition – all vectors point to the left and backwards, indicating the increased stress at the right sidewall in the stiffer zone caused by the weak material ahead.

At measuring section MS481 the vector orientations are nearly in the "normal" position again, while the vectors in measuring section MS494 plot very steeply, showing a generally uniform settlement of the whole top heading.

Clearly, such abrupt changes in the deformation magnitude over a few metres will impose

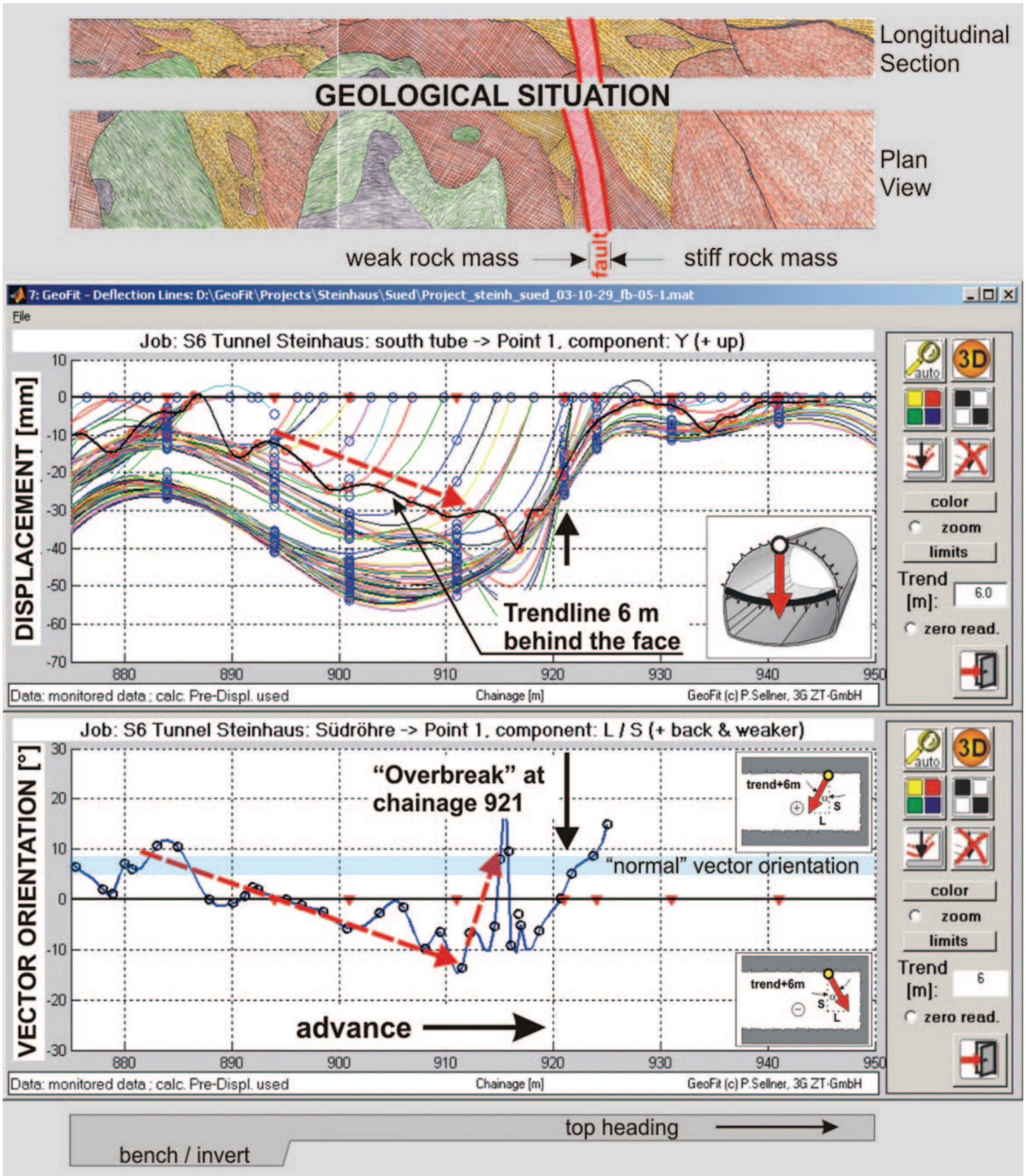

Fig. 5 Top: Geological situation (12) with quarzitic-cataclastic rock (yellow and orange coloured), fault (red coloured), cataclastic phyllites (green and grey coloured) and stiffer rock mass (orange coloured). Middle: Development of crown settlements. Bottom: Trend of displacement vector orientation (L/S) of the crown between tunnel metre 875 and 950 (13).

***Bild 5** Oben: Geologische Verhältnisse (12) mit quarzitisch-kataklastischem Gebirge (gelb und orange gefärbt), Störung (rot gefärbt), kataklastische Phyllite (grün und grau gefärbt) und steiferem Gebirge (orange gefärbt). Mitte: Räumliche Entwicklung der Firstsetzungen. Unten: Trend der Verschiebungsvektororientierung (L/S) der Firste im Abschnitt zwischen Station 875 und 950 m (13).*

high strains and stresses on the tunnel lining. Thus, the advantage of an early detection of changes in the rock mass stiffness is that the excavation and support methods (e.g. for this case increase of support measures) can be adjusted in time, with the aim of reducing the differences in strain in the rock mass-support system.

Figure 4 shows the displacement path in a cross section and longitudinal section for monitoring section MS 481, which is situated in the vicinity of the transition (see Figure 3, Bottom). The displacements in the cross sections are much more uniform than those observed at MS 461. The ratio of longitudinal to vertical displacement (L/S) is almost "normal", indicating a continuation of weak material for some distance ahead.

Case study 2: Tunnelling from soft to stiffer rock mass

Case study 2 illustrates a situation where the tunnel advance is from softer rock toward a stiffer rock mass. The section discussed is between tunnel metres 875 and 950 of the parallel tube discussed in case study 1 and as shown in Figure 1. The overburden in the analysed section is about 25 m thick. The geological condition (Figure 5, Top) is characterized by a quarzitic-cataclastic rock (indicated in Figure 5 by yellow and orange colours) with intercalated cataclastic phyllites (green and grey coloured). At tunnel

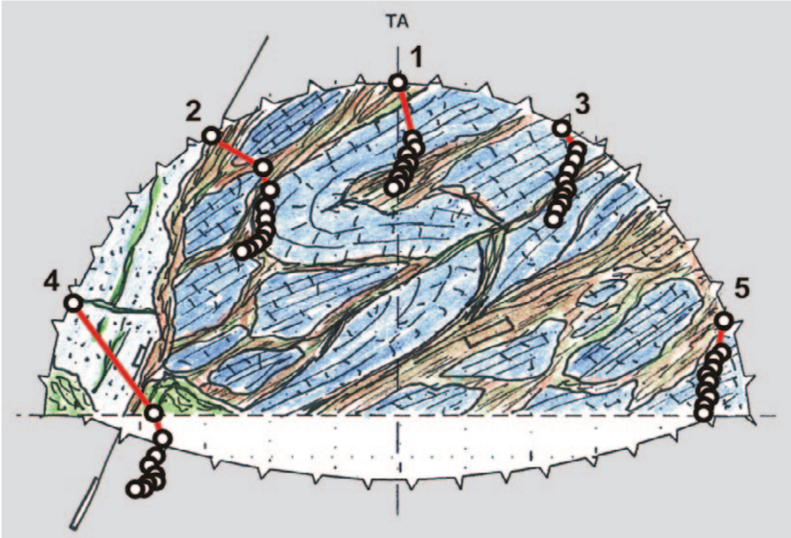

Fig. 6 Face map at tunnel metre 1097.5 (12): Blocks of dolomite marble (light and dark blue coloured) embedded in a soft, weathered matrix consisting of cataclastic phyllites (green and brown coloured) and displacement vector plot at monitoring section MS1101 (13).

Bild 6 *Brustbild bei Station 1097,5 m (12): Dolomitmarmorschollen (hell und dunkelblau gefärbt) in einer weichen, verwitterten Matrix aus kataklastischen Phylliten (grün und braun gefärbt) in der Zusammenschau mit der Verschiebungsvektororientierung im Messquerschnitt MS 1101 (13).*

metre 921 a fault (red colour) was encountered, crossing the tunnel axis nearly perpendicularly, followed by a comparatively stiffer block (orange coloured). Associated with the increasing proportion of fault gouge, the displacements also in-

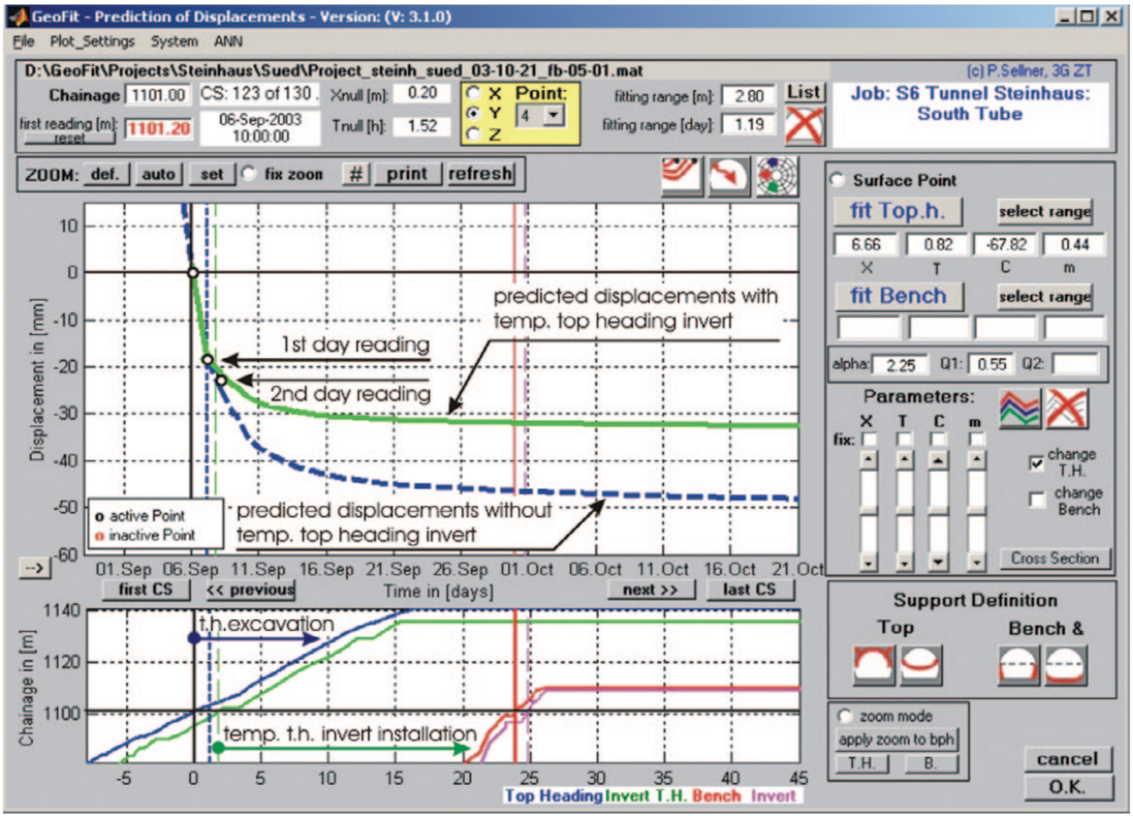

Fig. 7 Time-displacement characteristic of point No. 4 located in the left sidewall in monitoring section MS1101: Prediction of displacements with (green solid line) and without (blue dashed line) temporary invert from a few readings of the measured displacements (black circles) during top heading excavation (13).

Bild 7 *Zeit-Verschiebungscharakteristik des linken Kalottenfußpunkts Nr. 4 im Messquerschnitt MS1101: Prognose der Verschiebungen mit (grün durchgezogene Linie) und ohne (blaue strichlierte Linie) temporärem Kalottensohlgewölbe nach zwei Folgemessungen (schwarze Kreise) während des Kalottenvortriebs (13).*

crease between tunnel metre 890 and 910 (Figure 5, Middle).

Between tunnel metre 875 and 915 (Figure 5, Bottom) the trend of the orientation of the displacement vector shows a deviation from a positive "normal" vector orientation (backwards) to a negative (forward). Basically such tendencies indicate a "stiffer" rock mass ahead of the face (14, 6) and therefore lower displacements could be expected compared to those observed in the already excavated sections. This tendency abruptly changes close to the fault at about tunnel metre 912, indicating another change in mechanism, the nature of which could not be explained at the time of excavation. At tunnel metre 921, just at the location of the fault, an overbreak occurred, with a volume of about 40 m³.

Later investigations from overbreaks at different tunnel sites showed a similar behaviour. The mechanism is not yet investigated in full detail, but the current interpretation is that the change in tendency of the displacement vector orientation is associated with the beginning of a failure process at the face. Due to the stress concentration in the stiffer section close to the transition, the stress level in the weak material is comparatively low, increasing the risk of an overbreak. This diagnostic indicator has since been successfully used at other sites to warn of imminent overbreaks. The appropriate measures to reduce the risk in such situations are to increase the face support (e.g. by a certain number of face bolts, or a thicker sealing) and by carefully excavating in several sections with subsequent support of the excavated areas.

Case study 3: Tunnelling in bimrock conditions

Case study 3 illustrates an example of the prediction of displacements in a section of the tunnel

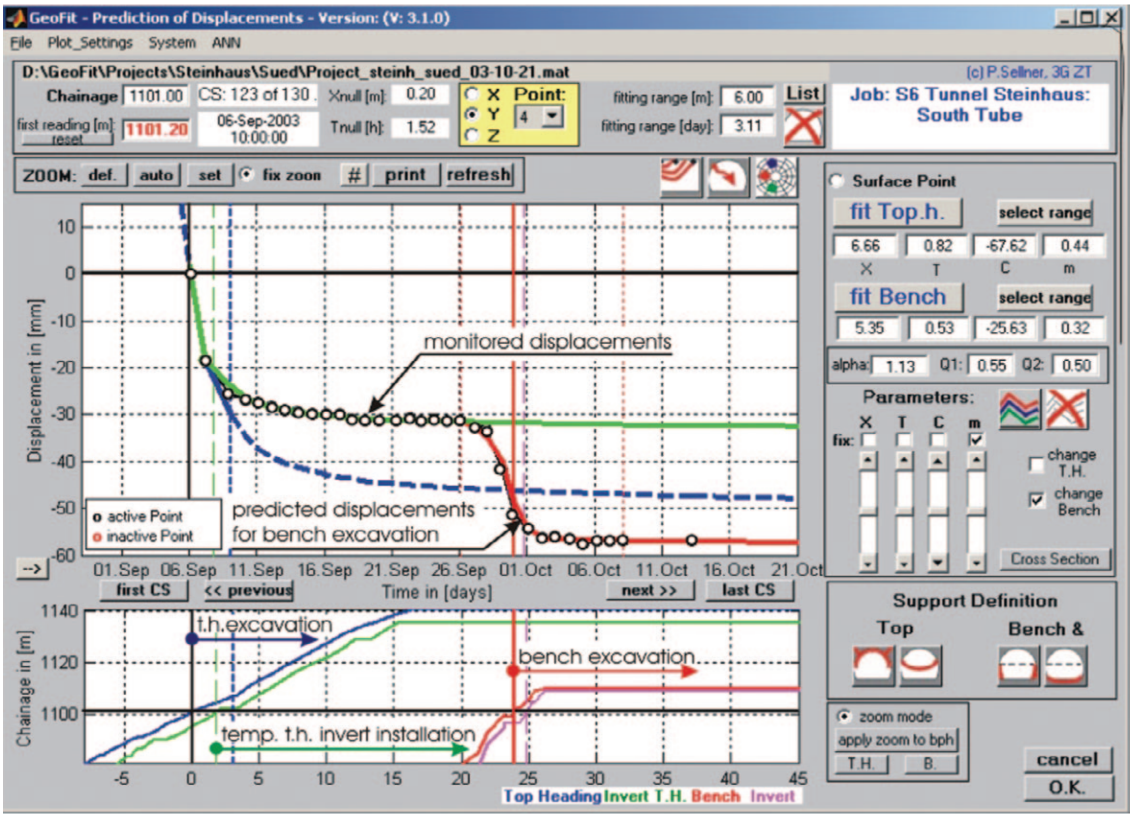

Fig. 8 Time-displacement characteristic of point No. 4 located in the left sidewall in monitoring section MS1101: Predicted displacements with (green solid line) and without (blue dashed line) temporary invert during top heading and bench/invert excavation (red line) (13) in comparison with the measured displacements (black circles).

***Bild 8** Zeit-Verschiebungscharakteristik des linken Kalottenfußpunkts Nr. 4 im Messquerschnitt MS1101: Prognostizierte Verschiebungen mit (grün durchgezogene Linie) und ohne (blaue strichlierte Linie) temporärem Kalottensohlgewölbe während des Kalotten- und Strosse/Sohlevortriebs (rote Linie) (13) im Vergleich zu den gemessenen Verschiebungen (schwarze Kreise).*

excavated in bimrocks. The monitoring section discussed is at tunnel metre 1101 of the same tunnel as described for case study 2. The overburden in this section above the crown is about 15 m. The geological condition (Figure 6) is characterized by smaller blocks (dolomite marble indicated by light blue and dark blue colour) embedded in a soft, weathered matrix consisting of cataclastic phyllites (green and brown coloured).

Besides a prediction of the geological conditions ahead of the face, a reliable prediction of the system behaviour is required. With the knowledge of the "normal" behaviour of the system the measured displacements can be compared to the predicted values in order to detect deviations in the behaviour in a timely fashion.

Figure 7 shows the development of the settlements over two days, for measuring point 4 located in the left sidewall in monitoring section MS 1101 (see Figure 6, black circles). The dashed blue line in Figure 7 shows the predicted displacements of the top heading and the solid green line shows the predicted system behaviour with an additional top heading invert installed close to the face.

The plot of Figure 7 shows the whole predicted displacement path including the pre-displacements developing ahead of the face, and after the excavation until the zero-reading is taken. For this example, final settlements of about 33 mm during top heading excavation are predicted. It can be seen that the temporary invert very effectively reduces displacements, leading to a quick stabilization of the top heading.

Figure 6 shows the displacement paths for several days at a cross-section for monitoring station MS 1101 and at the location of the face map illustrated. The asymmetrical deformation pattern of the system rock mass-support can be clearly seen. The displacements on the left sidewall are greater than those on the right side. This is attributed on the one hand to the influence of the slope, dipping to the right; and on the other hand, to the lesser block/matrix ratio at the left side.

Figure 8 shows the predicted and observed displacements. It can be seen that the observed displacements were almost exactly the same as those predicted during top heading and bench/ invert excavation. The bench excavation causes additional settlements of around 25 mm (red line, predicted displacements). Any significant deviation of the monitored displacements from the predicted behaviour would have been interpreted as an abnormal behaviour, requiring detailed analysis such as described elsewhere as an example of overstressing and failure of the temporary top heading invert (15, 16).

Conclusions

Tunnelling in heterogeneous rock mass is one of the most difficult tasks in subsurface engineering. The difficulty of establishing a reliable ground model during the design necessitates continuous updating of observed ground conditions during construction. A lot of time and money can be saved by using advanced displacement monitoring data evaluation methods for short term prediction of the rock mass structure and quality instead of the conventional approach of probing ahead. Recent experience has shown that the use of advanced displacement monitoring and data evaluation can be used to predict the rock mass quality and thus assist in the timely adaptation of excavation and support methods in shallow tunnels in heterogeneous rocks. Furthermore, a new tool, developed to predict the development of displacements, has proved to be very valuable for checking the "normality" of the system behaviour, allowing the timely detection of unfavourable developments.

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Authors

Dipl.-Ing. Dr.techn. Bernd Moritz, Geoconsult ZT GmbH, Sterneckstrasse 52, A-5020 Salzburg, Austria, E-Mail bernd.moritz@geoconsult.at; Dipl.-Ing. Karl Grossauer, o. Univ.-Professor Dipl.-Ing. Dr.techn. Wulf Schubert, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechauerstrasse 12, A-8010 Graz, Austria, E-Mail grossauer@tugraz.at; schubert@tugraz.at