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Analysis of Tunnel Displacements for the Geotechnical Short Term Prediction

Measurement of displacements in tunnels is primarily used for the assessment of the stabilization process and the verification of the system behaviour. In addition the displacement data can be used for the prediction of changing ground conditions ahead of the face. For this purpose, the evaluation of displacement vector orientation turned out to be the most appropriate method. Several authors showed the influence of the excavation on the stress and displacement field when tunnelling through zones of different stiffness. One of the main findings was that the displacement vector orientation significantly changes when the excavation approaches ground with different deformability. Hence, it was concluded that the development of the spatial orientation of the displacement vector can be used for the prediction of the ground conditions ahead of the face. The main results of the investigations performed are summarized in this paper. The evaluation of data from three different case histories is shown in order to encourage the use of advanced displacement data evaluation.

Die Analyse der Tunnelverschiebungen als Instrument für die geotechnische Prognose

Verschiebungsmessdaten im Tunnelbau werden hauptsächlich für die Beurteilung des Stabilisierungsprozesses und zur Überprüfung des Systemverhaltens verwendet. Zusätzlich können diese Daten auch für die Prognose von Änderungen in den Gebirgsverhältnissen vor der Ortsbrust benutzt werden. Die Auswertung der Orientierung der Verschiebungsvektoren hat sich dabei als die am besten geeignete Methode herausgestellt. Für einen Vortrieb in einem Gebirge mit Bereichen unterschiedlicher Steifigkeit hat eine Reihe von Autoren den Einfluss auf das Spannungs- und Verschiebungsfeld untersucht. Als eine der wichtigsten Feststellungen dabei hat sich erwiesen, dass sich die Orientierung des Verschiebungsvektors mit der Annäherung an einen Gebirgsbereich mit unterschiedlicher Verformbarkeit deutlich ändert. Man kam zum Schluss, dass der Verlauf der räumlichen Orientierung der Verschiebungsvektoren für die Prognose der Gebirgsverhältnisse vor der Ortsbrust herangezogen werden kann. Die wichtigsten Ergebnisse dieser Untersuchungen werden in diesem Beitrag zusammengefasst. Die Anwendung der modernen und weitergehenden Messdatenauswertung wird mit Beispielen der Verschiebungsdaten von drei Fallstudien demonstriert.

1 Introduction

Since nearly twenty years absolute displacement monitoring is an essential part of modern tunnelling. Especially in complex and difficult ground conditions, absolute displacement data provide valuable information on the response of the ground to the excavation process.

With the increased use of these data, different displacement data evaluation methods have evolved. Initially rather simple methods such as time-displacement plots were utilized for the evaluation of the tunnel stabilization process [1] [2] [3]. The development of more advanced methods allowed extracting more information from the available data. Schubert and Vavrovsky [4] already described the geotechnical information which can be extracted from these data and listed the geotechnical relevance for each displacement evaluation method. Schubert et al. [5] summarized the value of information for the different methods available up to now.

Following the table presented in [5], the evaluation of the spatial vector orientation is one of the most appropriate methods in order to predict the ground conditions ahead of the face or to detect weak zones outside the tunnel profile. The representation of the spatial displacement vector in two specific vertical planes (cross section and longitudinal section), as well as in horizontal plane (plan view) yields three displacement vectors, H/S, L/S, and L/H as the ratio between the different displacement components H (horizontal displacements), L (longitudinal displacements), and S (settlements). These so called vector orientations can be evaluated as trend lines at certain distances behind the face and allow the identification of changes in the displacement behaviour already close behind the excavation face.

The phenomenon of changing displacement vector orientation with regard to changing ground conditions was first described in [6]. The evaluation of displacement data from different sites and series of numerical simulations validated that changes in the displacement vector orientation are indicators for changing ground conditions [7] [8] [9].

The most common ways for evaluating the vector orientation are trend lines of L/S. Hence this paper focuses on this method and demonstrates the usefulness with the help of examples.

2 Evaluation and analysis procedure

In order to utilize tunnel wall displacement data for the prediction of the ground conditions, a clear and consequent evaluation procedure is mandatory. General steps which should be followed for each displacement data evaluation are:

- Determination of the expected displacement behaviour considering the actual ground conditions as well as the influencing factors; the resulting behaviour is referred to as the normal displacement behaviour;
- Continuous comparison of the actual displacement development with the normal behaviour in order to identify any deviations;
- Detailed analysis of the kind and magnitude of deviation in case of displacements deviating from normal;
- Comparison of the identified deviation with displacement scenarios already established for typical geological situations, such situations, for instance comprise the transition from strong to weak ground;
- Determination of the situation which corresponds to the actual displacement conditions best;
- Check the plausibility of the situation determined and comparison with regard to geological compatibility;
- Prediction of the geological/geotechnical conditions ahead of and outside the tunnel for areas of up to three tunnel diameters.

As already stated by several authors [8] [10], the establishment and determination of the expected displacement behaviour, also called the "normal" behaviour, is a crucial part within the evaluation procedure. Only the knowledge of how the displacements should develop spatially and transiently allows the detection of a deviation from the expected performance.

It is a well established fact that in particular the geological structure strongly influences the displacement characteristic of a tunnel. In [8] [11] [12] the influence of the spatial orientation of the rock mass structure on the displacement vector orientation is shown utilizing data from case histories as well as numerical simulations. Further investigations on this topic summarize the spatial development of a set of monitoring points at different positions in the tunnel cross section with regard to the relative discontinuity orientation to the tunnel axis.

For the case histories shown in this paper, the normal ranges for the particular displacement trend lines are determined by evaluating tunnel sections with nearly constant ground conditions and keeping in mind that the influencing factors (stress state, excavation geometry, relative orientation between tunnel and rock mass structure) as well as support measures do not substantially change. Within this framework the final displacement magnitudes observed for top heading excavation are used to identify zones with similar ground quality. Nearly constant crown settlements, for instance, are an indication for nearly constant ground conditions within the evaluated section. Hence, the corresponding displacement vector orientations represent "normal" orientations and typically vary only in a certain small range.

3 Predicting changing ground conditions

The evaluation of a considerable amount of displacement monitoring data acquired during tunnel excavation has proven the ability to use these data in combination with the appropriate evaluation method to predict changing ground conditions.

In general tunnel excavation in a deformable medium under certain stress conditions changes the stress and deformation field. The stress redistribution causes displacements, which are a function of mechanical material parameters and geometrical parameters. If excavating in a ground with constant properties, certain characteristic displacements will develop. Changing conditions within the ground volume affected by the tunnel excavation will change the stress redistribution leading to a displacement characteristic different from the previous situation. Hence, changes in the displacement behaviour attribute to changes in the influencing factors (ground properties, stress state). The manner of the change in the displacement characteristic results from the differences in these factors, for instance, the stiffness difference of adjacent rock masses.

3.1 Displacement vector orientation

As already mentioned above, the displacement vector orientation is the most appropriate method to identify changes in the ground conditions. In [8] [13] the main characteristics of the vector orientation development when approaching rock mass with different stiffness were demonstrated using the orientation of the displacement vector L/S. A rotation of this displacement vector against the direction of excavation indicates relatively soft ground ahead of the face. In contrast, a rotation in direction of the excavation reflects relatively stiff conditions ahead.

The influence of the stiffness contrast and of rock mass with frequently changing stiffness on the behaviour of the spatial displacement vector is demonstrated in [14]. Figure 1 shows the basic development of the vector orientation trend L/S when tunnelling through a zone of relatively soft ground. The diagram summarizes the results of a set of calculations within comprehensive numerical FE analyses [15].

The left part of Figure 1 shows the trend lines L/S for the crown point and three different stiffness contrasts between stiff and embedded soft ground, with a ratio of $E_{stiff}/E_{soft} = 1.5$, 2 and 4, respectively. The displacement trends are taken at a distance of $^1/_2$ tunnel diameter behind the face (abbreviated in the figure with trend +0.5 D, with D = tunnel diameter). The displacement vector L/S deviates from a normal orientation against the direction of excavation when approaching the zone of soft ground. The magnitude of deviation is different for the three scenarios shown. The larger the contrast between the stiff and soft zone, the more the displacement vector L/S deviates from the normal orientation. After entering the soft zone, the vector tends to return to the normal orientation. Approaching the stiff ground, an inverse tendency can be observed. The displacement vector deviates in direction of excavation and reaches a maximum at the transition. After entering the stiff zone, the vector returns to normal.

The right part of Figure 1 illustrates the development of the displacement vector L/S for an embedded soft zone with different lengths and with a constant stiffness contrast of $E_{stiff} = 4\ E_{soft}$. The development of L/S when approaching the soft zone and the stiff zone, respectively, is

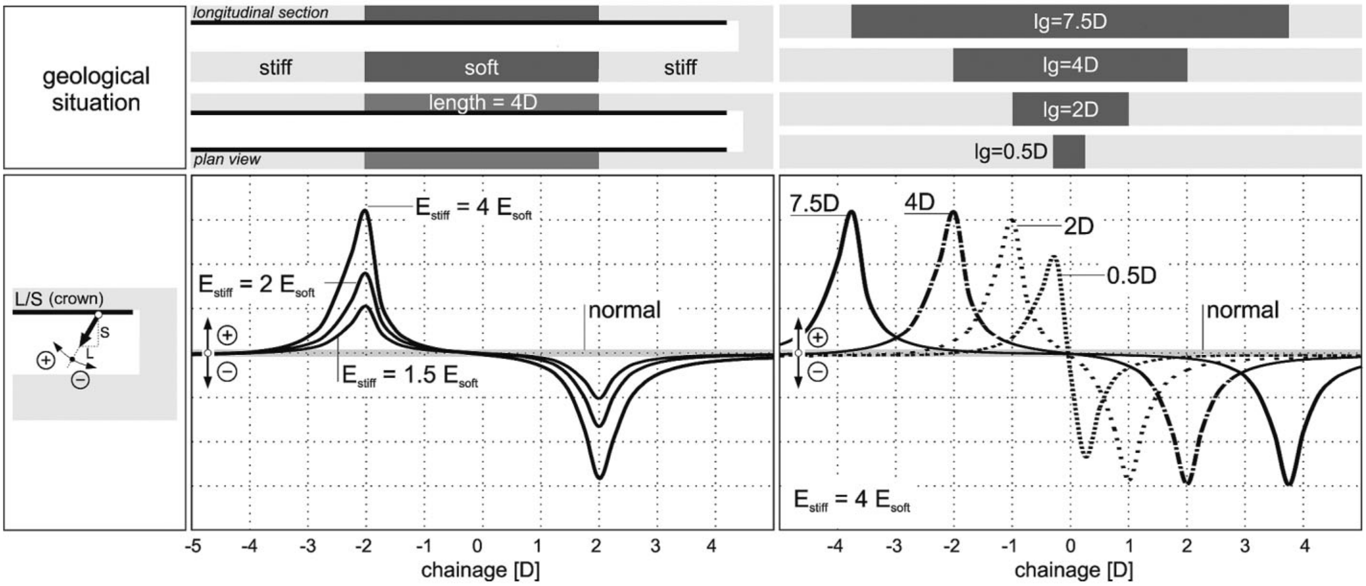

Fig. 1. Development of L/S when tunneling through ground with different stiffness; trend +0.5D (D = tunnel diameter) shown for different stiffness contrasts (left) and different zone lengths (right)
Bild 1. Verlauf von L/S für einen Vortrieb durch ein weiche Zone; Trendverlauf +0,5D (D = Tunnel Durchmesser) für unterschiedliche Steifigkeitskontraste (links) und unterschiedliche Zonenlängen (rechts)

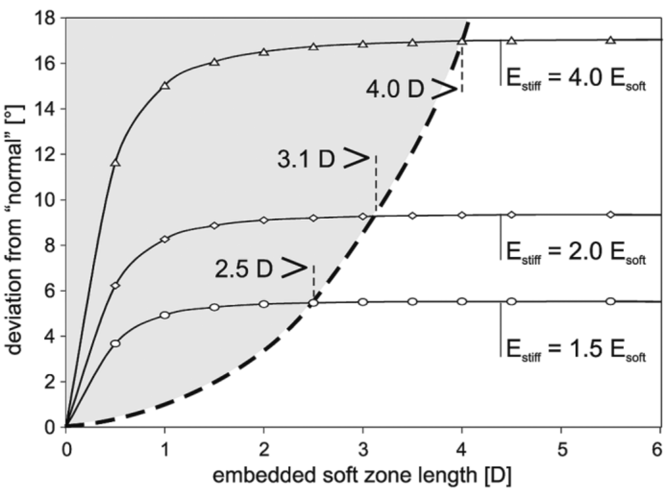

Fig. 2. Deviation of the vector orientation L/S from "normal" as a function of the embedded soft zone length and the stiffness contrast (shown for the crown point)
Bild 2. Abweichung der Vektororientierung L/S von „normal" als Funktion der eingebetteten Zonenlänge und dem Steifigkeitsunterschied (dargestellt für den Firstpunkt)

generally the same as shown in the left part of the figure. With decreasing embedded zone length, though, the return of the displacement vector to a normal orientation within the embedded zone is superimposed by the effect of the stiff zone ahead of the excavation. This stiff zone induces a rotation of the L/S trend in direction of excavation. The result for short embedded zones is a more linear trend between the two maxima of trend deviations from normal, the one when entering the soft zone and a reversed situation when encountering the stiff zone. In contrast, the development of L/S is more or less S-shaped for larger soft zone lengths. Also the magnitude of the vector deviation decreases with reduced embedded zone width. Shorter zones have less effect on the deviation of L/S.

The influences of the length of a soft zone embedded between stiff ground, as well as the stiffness differences are outlined in [15] and [16]. The results originate from the evaluation of numerical 3D simulations. Figure 2 shows the magnitude of the displacement vector deviation from normal as a function of embedded soft zone length and stiffness contrast. The magnitude of deviation increases with increasing soft zone length, as well as with increasing

Table 1. Summary of relevant data for the case histories
Tabelle 1. Übersicht zu den Fallbeispielen

	Type of tunnel	Overburden at evaluation section	Rock description
Strenger Tunnel	2-lane motorway tunnel	320–330 m	quartz phyllites, phyllonites
Galgenbergtunnel	2-track railway tunnel	160–170 m	graphitic phyllites, greenschist
Gräberntunnel	2-lane motorway tunnel	30–70 m	mica schist to gneiss, faulted rock

stiffness difference. The dashed line in the figure limits the length of influence of the embedded soft zone on the vector orientation deviation. Within the grey shaded area, the length of the soft zone influences the magnitude of deviation of the displacement vector orientation. In contrast, zone lengths and stiffness contrasts, which plot outside this area, do not result in larger L/S deviations as already reached with an embedded soft zone length marked by the dotted line.

3.2 Case histories

The capabilities utilizing the development of the displacement vector orientation as a prediction method for the identification of changing ground conditions ahead of the face are demonstrated using three different case histories in Austria. Table 1 summarizes the relevant information for the selected tunnel sites.

Compared to the theoretical examples shown above, the assessment of the ground quality in terms of stiffness and strength is not as simple for actual conditions. For this reason, the displacements monitored at a certain distance behind the face where the top heading advance has no influence on the displacements are used as a measure for interpreting the ground quality. This allows a proper distinction between tunnel sections with different ground characteristics. The distance behind the face at which the displacements were taken are 30m and 50m, respectively and quoted for the particular examples as S+30 and S+50.

Generally, the displacement trend line definitions are abbreviated. For instance, S denotes vertical displacements (settlements) and +30 a trend distance of 30 m behind the face. The labelling of the displacement vector orientation trend L/S and the remaining trend lines used is done in the same way.

3.3 Approaching a fault zone

The first example originates from the Strenger Tunnel and features encountering of a massive fault zone. Figure 3 shows the displacement situation at the south tube, top heading excavation west, and evaluated for the crown point between chainage 1,080 and 1,190 m. The upper part shows the settlement trend line (S+10), while the lower part displays the trend lines for the displacement vector orientation (L/S+10 and L/S+15). Generally, the trend lines are evaluated at a distance of 10 m behind the face (denominated in Figure 3 as L/S+10). In order to compare the effect of an increased trend distance to the face, the trend for L/S is also displayed for a distance of 15 m behind the face (L/S+15). Both vector orientation

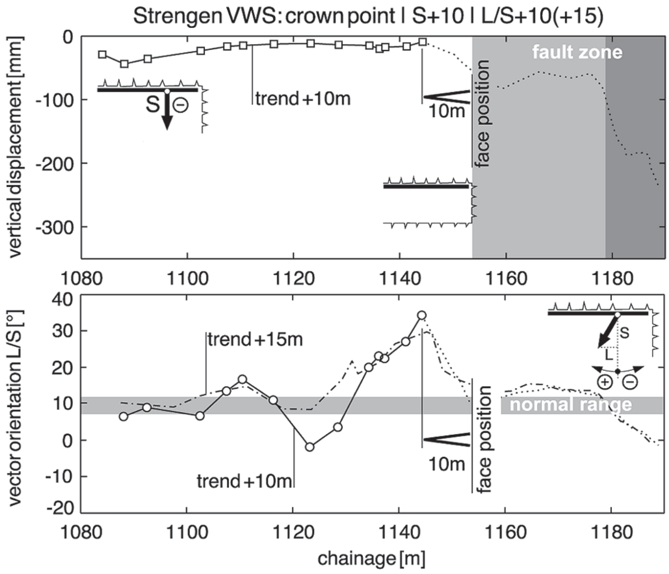

Fig. 3. Strenger tunnel, crown point – development of settlement trend line S+10 and vector orientation trend line L/S+10 and L/S+15 when approaching a major fault zone
Bild 3. Strenger Tunnel, Firstpunkt – Verlauf der Setzungstrendline S+10 und der Trendlinie zur Verschiebungsvektororientierung L/S+10 und L/S+15 bei Annäherung an eine Störungszone

trend lines show a similar characteristic, except at around chainage 1,125 m. Due to relatively small vertical and longitudinal displacements, the ratio of these displacement components is very sensitive to slight changes, especially in the longitudinal direction. With increased distances to the face, the displacement increments become smaller and hence, the vector orientation trend line smoother.

The settlement trend line up to chainage approximately 1,145 m shows a rather linear characteristic. The vector orientation L/S, though, clearly deviates from its normal orientation (marked with the grey shaded area in the lower part of the Figure 3) against the excavation direction and therefore, indicates relatively soft ground conditions ahead. The maximum deviation of the vector orientation occurs well ahead of the fault zone with a distance of about 10 m. The vector orientation returns to normal with the advancing face.

The theoretical examples shown above, in contrast, yield the peak in the L/S trend at the transition to changing ground conditions. The evaluation of actual data, however, shows the occurrence of the peaks in the L/S trend deviations at a certain distance ahead of the zone with different quality.

The upper diagram of Figure 4 shows the effect of the fault zone encountered on the displacement behaviour.

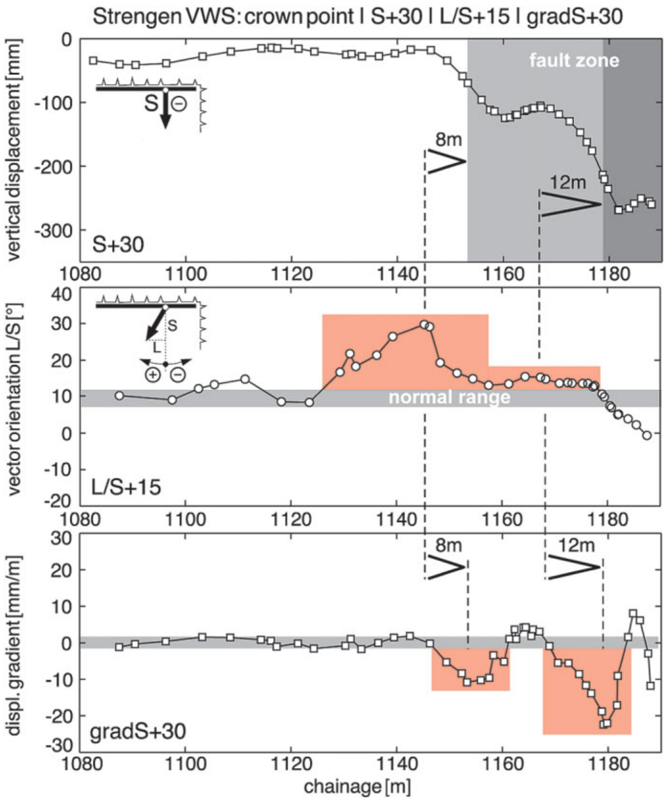

Fig. 4. *Strenger tunnel, crown point – development of trend lines for the settlements S+30, vector orientation L/S+15 and displacement gradient grad S+30*
Bild 4. *Strenger Tunnel, Firstpunkt – Verlauf der Trendlinien für die Setzungen S+30, die Vektororientierung L/S+15 und die Verschiebungsinkremente grad S+30*

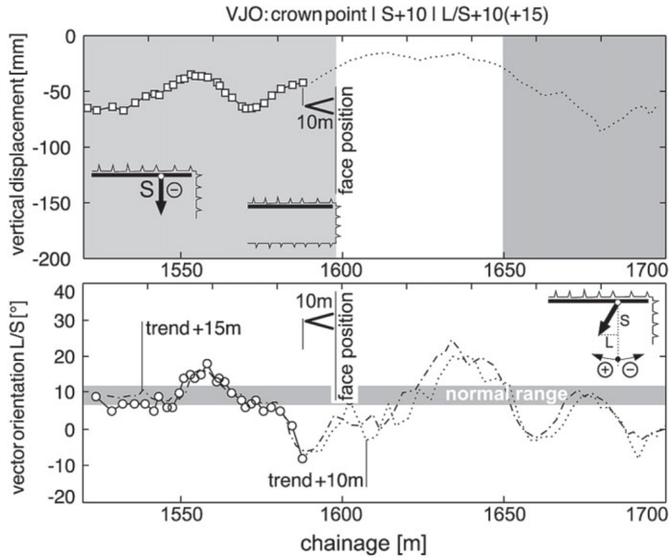

Fig. 5. *Galgenbergtunnel, crown point – development of settlement trend line S+10 and vector orientation trend lines L/S+15 and L/S+15 when approaching a stiffer zone*
Bild 5. *Galgenbergtunnel, Firstpunkt – Verlauf der Setzungstrendlinie S+10 und der Trendlinien zur Verschiebungsvektororientierung L/S+10 und L/S +15 bei der Annäherung an eine steifere Zone*

The crown point settlements 30 m behind the face (S+30) increase from a few centimetres up to 13 cm within the first part of the fault zone and reach a maximum of approximately 29 cm at around chainage 1,180 m. The change in the settlements along the tunnel is calculated as the gradient of the settlement trend line (quoted as grad S+30) and displayed in the lower part of Figure 4. This is a convenient method in order to evaluate and easily identify changes in the tunnel displacement behaviour.

A detailed analysis of the displacement vector orientation trend L/S+15 (middle diagram in Figure 4) in combination with the displacement gradient grad S+30 (lower diagram) reveals a certain correlation of both trend lines. The maximum deviation in the vector orientation from normal occurs several metres ahead of the fault zone. The displacement gradient trend gradS+30 shows also a clear change with a maximum deflection around 8 m after the peak in L/S+15, which more or less corresponds well with the transition to the fault zone. The second deviation of L/S from normal, which is not as pronounced as the first observed, develops approximately 12 m ahead of the very pronounced change in the trend line of grad S+30 reflecting a considerable decrease in the rock mass quality.

However, a clear deviation of the displacement vector orientation for the crown point with a magnitude at approximately 20° clearly indicates changing ground conditions ahead of the face.

3.4 Embedded "stiffer" rock mass

The next example illustrates the development of the vector orientation L/S with regard to an embedded stiffer rock mass. It is taken from the Galgenbergtunnel, heading Jassing east between chainage 1,520 and 1,700 m.

Figure 5 shows the development of both, the settlement trend line S+10 and the vector orientation trend line L/S+10 and L/S+15 for the crown point, respectively. The two L/S trends lines with different distances from the face (+10 and +15 m) are plotted in order to underline their similar characteristic. For the face position at chainage 1,585 m, as indicated in the figure, the crown settlement trend S+10 shows around 5 cm. The displacement vector orientation L/S+10, though, rotates in direction of excavation with a maximum deviation from the normal orientation of approximately 20° and hence, indicates stiffer ground conditions ahead. The vector orientation returns to normal with ongoing excavation. At around chainage 1,620 m the displacement vector again starts to deviate from the normal orientation with a rotation against the excavation direction indicating softer ground conditions ahead. The peak in the deviation is reached at approximately chainage 1,635 m.

The displacement trend lines for the settlements S+50, the vector orientation L/S+15 and the settlement gradient gradS+50 are summarized for the crown point in Figure 6. The vector orientation trend line (middle diagram) within the evaluated section deviates from the normal range several times. Red shaded areas highlight deviations against the direction of excavation and thus, indicate softer rock mass ahead. In contrast, green shaded areas mark deviations in the direction of excavation and consequently signify relatively stiffer ground ahead. It has to be

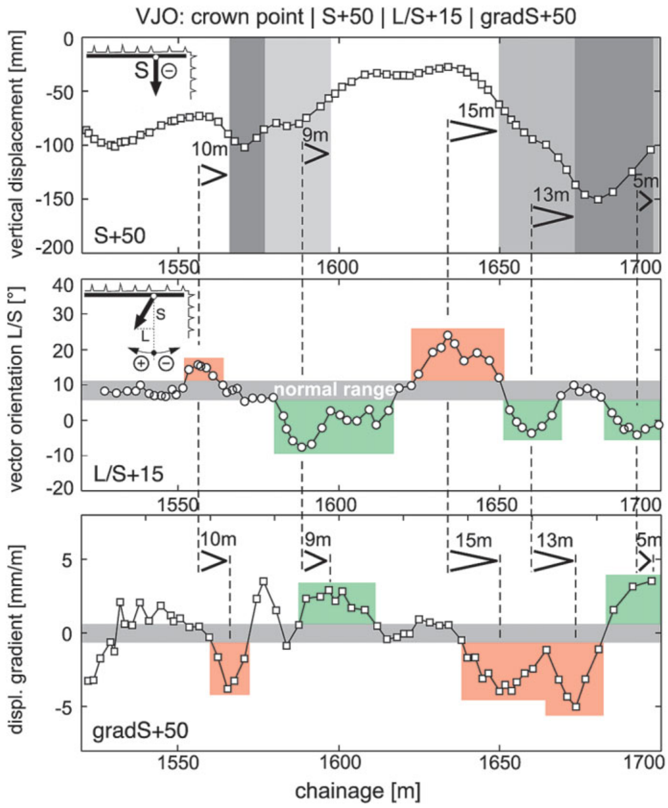

Fig. 6. Galgenbergtunnel, crown point – development of trend lines for the settlements S+50, vector orientation L/S+15 and displacement gradient grad S+50
Bild 6. Galgenbergtunnel, Firstpunkt – Verlauf der Trendlinien für die Setzungen S+50, die Vektororientierung L/S+15 und die Verschiebungsinkremente grad S+50

emphasised that each deviation of L/S from the normal range is accompanied by a significant change in the settlements monitored 50 m behind the face (upper diagram). The displacement changes are calculated as the displacement gradient of S+50 and plotted in the lower diagram (gradS+50). Relative maxima in this trend line occur with a certain off-set to the relative maxima in the displacement vector orientation. The magnitude of these off-sets ranges from approximately 5 up to 15 m. As already mentioned in the beginning of this chapter, the trend lines of the settlements S as well as the displacement gradient gradS are take at a distance of +50 m behind the face in order to evaluate the influence of ground quality on the final displacements due to the top heading excavation.

The most pronounced deviation of L/S can be observed at around chainage 1,590 and 1,635 m, respectively. Both changes in the trend line indicate clear changes in the ground quality. While the first deviation reveals stiffer rock mass, the next deviation signifies a contrary situation.

The vector orientation trend line shows a certain abnormality at chainage 1,660 m. Although the displacement vector tends to deviate from normal into the excavation direction, which would indicate stiffer ground ahead, the inverse situation occurs. This probably originates from a stiffer block ahead, which was overloaded during the excavation and thus, has no significant influence with regard to the finally observed settlements.

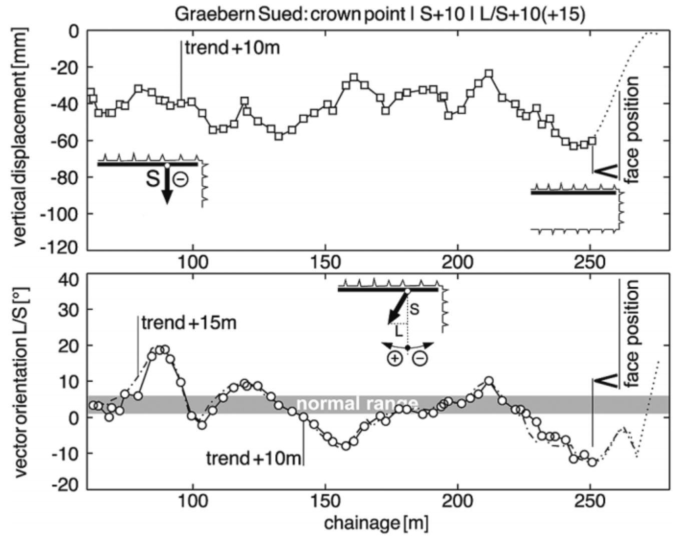

Fig. 7. Graebern Tunnel, crown point – development of settlement trend line S+10 and vector orientation trend line L/S+10 and L/S+15 when tunnelling through frequently changing rock mass
Bild 7. Gräberntunnel – Verlauf der Setzungstrendlinie S+10 und der Trendlinie zur Verschiebungsvektororientierung L/S+10 und L/S+15 für den Vortrieb durch heterogene Gebirgsverhältnisse

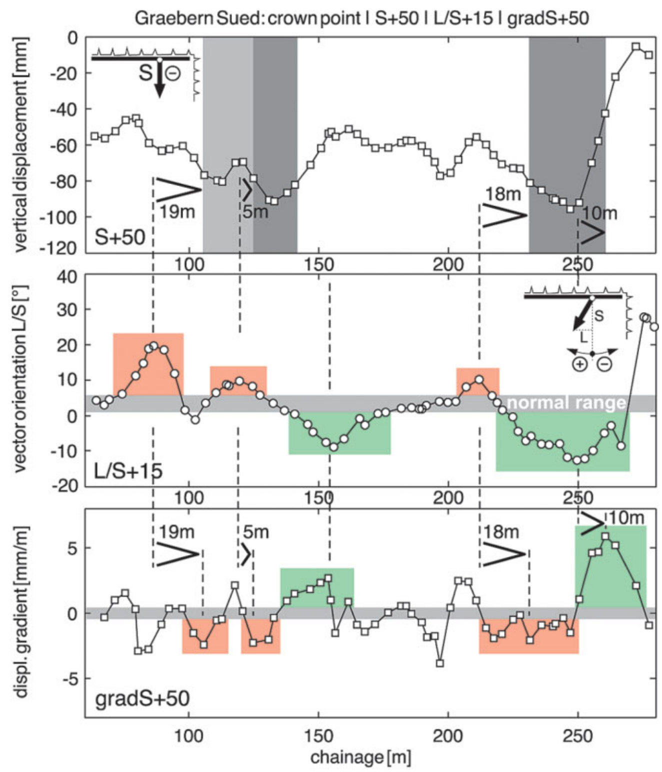

Fig. 8. Graeberntunnel, crown point – development of trend lines for the settlements S+50, vector orientation L/S+15 and displacement gradient grad S+50
Bild 8. Gräberntunnel, Firstpunkt – Verlauf der Trendlinien für die Setzungen S+50, die Vektororientierung L/S+15 und die Verschiebungsinkremente grad S+50

3.5 Frequently changing conditions

The last example demonstrates the displacement situation when tunnelling through heterogeneous rock mass and originates from the Graebern tunnel, south heading. Figure 7 shows the crown point trend lines 10 m behind the face for the settlements, as well as the displacement vector orientation L/S, right before entering a zone of relatively stiffer ground. As already shown with the case history before, the trend line for L/S clearly deviates from the normal range and indicates a zone with relatively stiffer rock mass. The settlement trend line, though, does not show any clear indication for changing conditions.

Figure 8 finally demonstrates the displacement trend lines for the crown settlements S+50 (upper part) and the associated displacement gradient gradS+50 (lower diagram), as well as the displacement vector orientation L/S+15 (middle diagram). The deviations of L/S from the normal range and the associated variation in the displacement gradient are highlighted with red shaded rectangles. Once more, all three relative maxima in the L/S trend line indicating softer rock mass ahead, are followed by relative minima of the displacement gradient trend line with an off-set of around 18 and 5 m, respectively. In contrast, the green shaded areas refer to relatively stronger ground ahead. Again, both cases clearly show a correlation between changes in L/S trend lines and changes in the settlements with no distinct off-set at chainage 150 m, and an off-set of around 10 m at the L/S deviation at chainage 250 m.

4 Conclusion

The introduction of absolute displacement monitoring and the development of evaluation methods have definitely increased the information which can be extracted from these data. When properly evaluating these data, the frequency of "unexpected" events can be considerably reduced. However, the analysis of the data should not serve as a unique and stand alone tool in tunnelling. It should rather supplement and extend the existing pool of geological and geophysical methods in order to improve the knowledge about the ground conditions ahead. Keeping in mind that the displacement data are available anyway, their intrinsic prediction potential should be specifically utilized to plan explorations ahead of the face, which are time consuming and costly.

Within the framework of displacement data evaluation, the displacement vector orientation has proved to be a helpful tool for identifying changing ground conditions ahead of the face. Even though it is not presently yet possible to quantitatively predict the stiffness, strength or extent of a fault zone ahead of the face, the method has a high potential. Summarizing the experience gained during the last decade by the evaluation of data from tunnel sites as well as supplementing numerical simulations, the following major findings with regard to the displacement vector orientation can be concluded:

- Deviations in the displacement vector orientation trend from a certain normal range do not occur arbitrarily; they are the result of changing conditions, either changing ground conditions and/or changes in the influencing factors.
- The larger the stiffness contrast between adjacent rock masses, the larger is the deviation of the displacement

Table 2. Summary of changes in the displacement vector orientation trends and changes in the final top heading settlement magnitudes of the ground ahead for the case histories shown
Tabelle 2. Änderungen der Orientierung der Verschiebungsvektoren und Änderungen der Größenordnung der Setzung nach dem Kalottenvortrieb für die gezeigten Fallbeispiele

Normal range of vector orientation L/S+15	Type of L/S deviation	Magnitude of L/S deviation	Off-set to ground quality change	Final settlement change (increase/decrease)	
7°–11° (pointing backwards)	rotation against excavation direction	~20°	8 m	increase	factor +5–6
		~6°	10 m		factor +1.5
		~15°	15 m		factor +6
		~15°	19 m		factor +1.4
		~5°	5 m		factor +1.2
		~5°	18 m		factor +1.6
7°–11° (pointing backwards)	rotation in excavation direction	~15°	9 m	decrease	factor –5
1°–5° (pointing backwards)		~11°	0 m		factor –1.5
		~17°	10 m		factor –10

vector orientation and accordingly the greater the extent of an embedded stiff or soft zone, the larger is the deviation.

– The peak of the vector orientation deviation occurs well before significant changes in the displacement magnitudes can be observed. Hence, changes in the displacement vector orientation allow an early identification of changing conditions.

Table 2 summarizes the magnitude of deviation of the displacement vector orientation from normal for the case histories shown. The table also lists the order of magnitude in the change of the settlements, which were finally observed for the top heading excavation.

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