

Is it possible to Automate the Interpretation of Displacement Monitoring Data?

By Karl Großbauer and Gerold Lenz

Absolute displacement monitoring in tunneling has superseded relative measurement methods for nearly twenty years. With the increased amount of 3D measurements, data utilization has also evolved. Modern data interpretation techniques have far surpassed the prior abilities to make reliable predictions of tunnel performance (1, 2). Deflection curve diagrams, trend lines, and vector plots supplemented the preceding evaluation methods with time-displacement curves.

During the 1990s, on-site observations together with insights gained from the evaluation of numerical simulations, increased the knowledge of how certain geological conditions influence the displacement development. For example, the ratio between radial and longitudinal displacements was found to vary over a wide range and reflect contrasting stiffness ahead of the advancing face (3, 4, 5, 6, 7, 8). Methods were subsequently developed to reliably predict domains of different deformability ahead of and outside the tunnel. A number of additional theoretical studies have confirmed the relationships between the ratio of radial to longitudinal displacements and corresponding ground conditions (9, 10, 11).

Schubert and Vavrovsky (12) already describe the geomechanical relevance of different monitoring parameters. In (13) the authors evaluate various available methods for displacement data evaluation with regard to tunnel performance prediction, and the applicability of the various evaluation methods. The result is a table, which guides the user in choosing the appropriate evaluation method.

Eurocode 7 (14) specifies conditions for the application of the observational method. Derived from these specifications, the general demands for the evaluation methods relate to the ability to:

- ◇ Control the tunnel stability,
- ◇ Predict the final displacement magnitude and its transient development,
- ◇ Compare actual to predicted displacement behaviour,
- ◇ Observe abnormal trend developments,
- ◇ Predict geotechnical conditions ahead and outside the tunnel.

State of the art displacement evaluation methods are capable of fulfilling these demands. In addition, extensive knowledge of data evaluation is already available. What is missing is a system

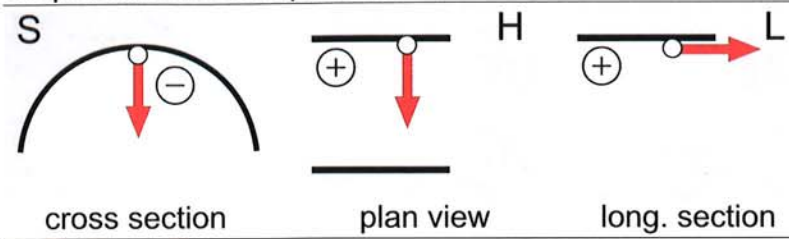
Ist eine Automatisierung der Interpretation von Verschiebungsmessdaten möglich?

Seit über zwei Jahrzehnten sind absolute Verschiebungsmessungen integraler Bestandteil beinahe bei allen Tunnelvortrieben. Während dieser Zeit wurde ein großer Erfahrungsschatz in der Auswertung und Interpretation von Verschiebungsmessdaten angehäuft. Mittlerweile sind zumindest der qualitative Einfluss von geologischen Strukturen sowie der Einfluss von Störungszonen auf die zeitliche und räumliche Entwicklung der Verschiebungen weitestgehend untersucht und bekannt. Das erworbene und strukturiert aufbereitete Wissen kann nun dazu verwendet werden, einen Teil der täglichen Auswerte- und Interpretationstätigkeit zu automatisieren. Trendverläufe der Verschiebungsvektoren wurden für 18 geologische Situationen, die verschieden orientierte Übergänge von weichem auf steifes beziehungsweise steifem auf weiches Gebirge darstellen, erarbeitet und in einer Korrelationstabelle zusammengestellt. Aktuell ausgewertete Trendverläufe können laufend mit den in der Korrelationstabelle definierten Trendverläufen verglichen werden. Eine zahlenmäßige Bewertung der Anzahl von übereinstimmenden Trends erlaubt eine Identifikation der wahrscheinlichsten geologischen Situation. Es ist somit möglich Regelmäßigkeiten

in den Trendverläufen, die für bestimmte Situationen abgespeichert sind, in den täglich aktualisierten Messdaten wieder zu finden und daher automatisch typische Situationen zu identifizieren.

For more than twenty years, absolute displacement monitoring has been standard practice for tunnelling projects in Europe. By correlating the monitoring results to specific geological conditions, it is now possible to forecast ground conditions ahead and in the vicinity of the tunnel face. To improve this forecasting, 18 characteristic scenarios, wherein transitions from soft to stiff ground occur (and vice versa), have been established and input to a monitoring data correlation matrix. By continuously comparing actual monitoring results to the reference cases in the correlation matrix, the prediction of variations with respect to ground conditions ahead of the face is greatly facilitated. The monitoring data trends in the correlation matrix are weighted according to their relevance for specific geologic situations, with the most compelling trends yielding the highest weighting factors. An automated monitoring data evaluation tool can be achieved by incorporating the results summarized herein to a computer code. It is believed that such a tool will significantly aid the work of onsite engineers with regard to data evaluation and interpretation activities.

displacement component



trend change in the vector orientation

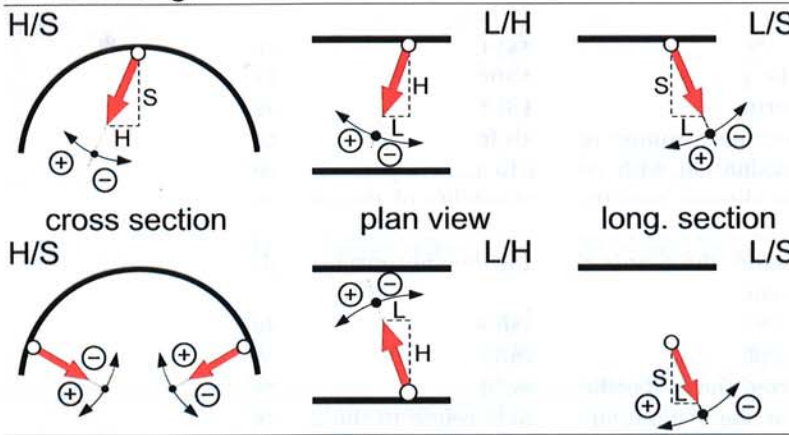


Fig. 1 Sign convention for the displacement components S, H, and L (upper part), and for the trend change in the vector orientation (lower part).

Bild 1 Vorzeichenregelung für die Verschiebungskomponenten S, H und L (oberer Teil) und für die Trendänderung der Vektororientierung (unterer Teil).

that consistently checks the entire displacement characteristics against typical displacement trends in an unbiased way.

Definitions

The following terms and algebraic sign convention are used in this paper:

- Displacement component (Figure 1):
 - ⊖ L: Longitudinal displacement (positive in direction of excavation),
 - ⊖ H: Horizontal (transversal) displacement (positive to the right, looking in direction of excavation),
 - ⊖ S: Settlement (negative downwards).
- Vector orientation:
 - ⊖ L/S: Ratio of longitudinal displacement and settlement,

trend change in the displacement ratio

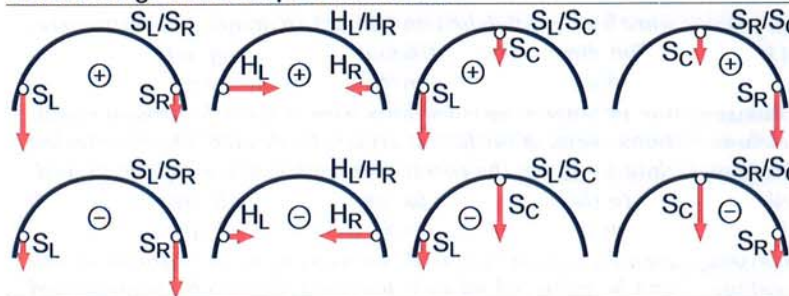


Fig. 2 Sign convention for the trend change in the displacement ratio.

Bild 2 Vorzeichenregelung für die Trendänderung der Verschiebungsverhältnisse.

- ⊖ H/S: Ratio of horizontal displacement and settlement,
- ⊖ L/H: Ratio of longitudinal and horizontal displacement.
- Displacement ratio:
 - ⊖ S_L/S_R: Settlement ratio of left and right sidewall,
 - ⊖ H_L/H_R: Horizontal displacement ratio of left and right sidewall,
 - ⊖ S_L/S_C: Settlement ratio of left sidewall and crown,
 - ⊖ S_R/S_C: Settlement ratio of right sidewall and crown.
- Trend deviation (Figures 1 and 2):
 - ⊖ -: No characteristic change,
 - ⊖ +(L/S): Clockwise rotation, looking toward left sidewall,
 - ⊖ +(H/S): Clockwise rotation, looking at tunnel face,
 - ⊖ +(L/H): Deviation against direction of excavation,
 - ⊖ +(S_L/S_R): Relative increase of settlement at left sidewall; or relative decrease at right sidewall,
 - ⊖ +(H_L/H_R): Relative increase of horizontal displacement at left sidewall; or relative decrease of at the right sidewall,
 - ⊖ +S_L/S_C: Relative increase of settlements at the left sidewall; or relative decrease at the crown,
 - ⊖ +S_R/S_C: Relative increase of settlements at the right sidewall; or relative decrease at the crown.

Characteristic displacements

It is an established fact that the geological structure strongly influences the displacement characteristics of a tunnel. For assessing the "normality" of the system behaviour and detecting deviations from the "normal behaviour", characteristic displacements and their relation to ground characteristics need to be established in the design phase. This includes the spatial orientation of the displacements, as well as their transient development with face advance and time. Updating of the established characteristics during construction increases the reliability of performance predictions.

Appropriate evaluation of monitoring data requires removing erroneous data and measurement accuracy thresholds. This includes the consideration of initial readings taken at different times and distances to the face, as well as removing inaccuracies from the measuring process itself. To address the shortcomings, software was utilized for mathematical fitting of the measured values and noise attenuation (15). For the further evaluation, the fitted - and thus smoothed - data were used.

Figure 3 depicts the determination of normal behaviour from monitored displacement data in a Flysch formation of the Wienerwald tunnel. The

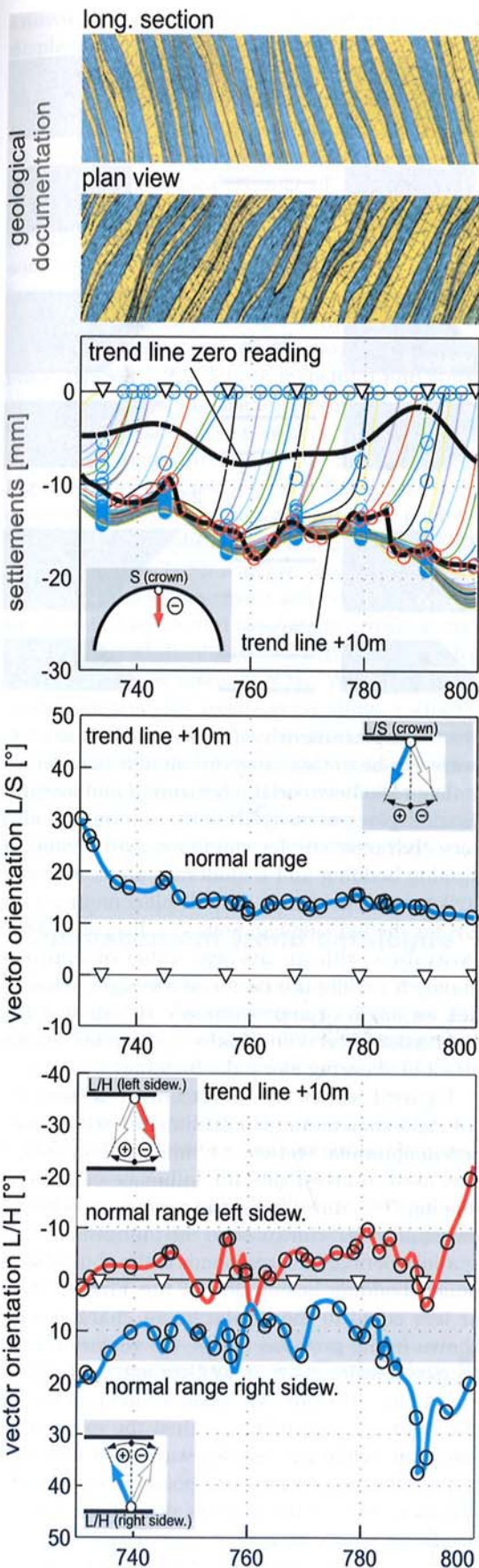


Fig. 3 Geological documentation, deflection curves for crown settlements and significant vector orientations for a 70 m long section of the Wienerwald tunnel (16).

Bild 3 Geologische Dokumentation, Zustandslinien der Firstsetzung und signifikante Vektororientierungstrendlinien für einen 70 m langen Abschnitt des Wienerwald Tunnels (16).

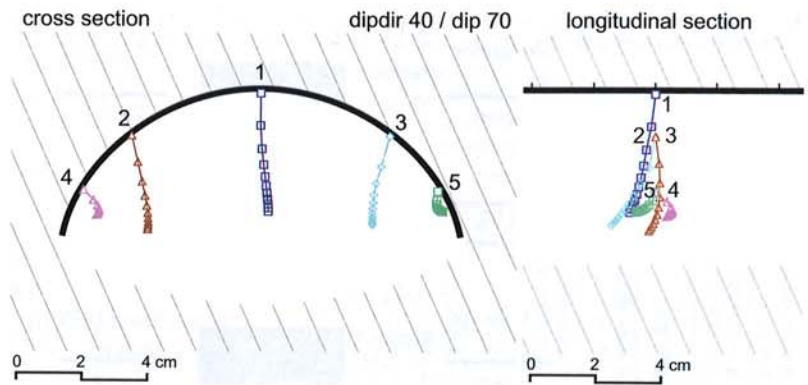


Fig. 4 Influence of the bedding on the displacement vectors shown in cross section and longitudinal section; results obtained from a numerical 3D simulation using the ubiquitous joint model.

Bild 4 Einfluss der Schichtung auf die Verschiebungsvektoren, dargestellt im Quer- und Längsschnitt; Ergebnisse aus einer numerischen 3D Simulation und der Anwendung des ubiquitous joint model.

angle between the strike of the regularly bedded sandstones and silt- and mudstones and the tunnel axis is about 50°, while the dip is between 70° and 80° in direction of excavation (16).

It can be seen that the crown settlement in the section is rather uniform in the range between 10 and 20 mm. The trend of the displacement vector orientation in the crown (L/S) in this section varies in a range of 10° to 20° from the vertical against the excavation direction. Consequently,

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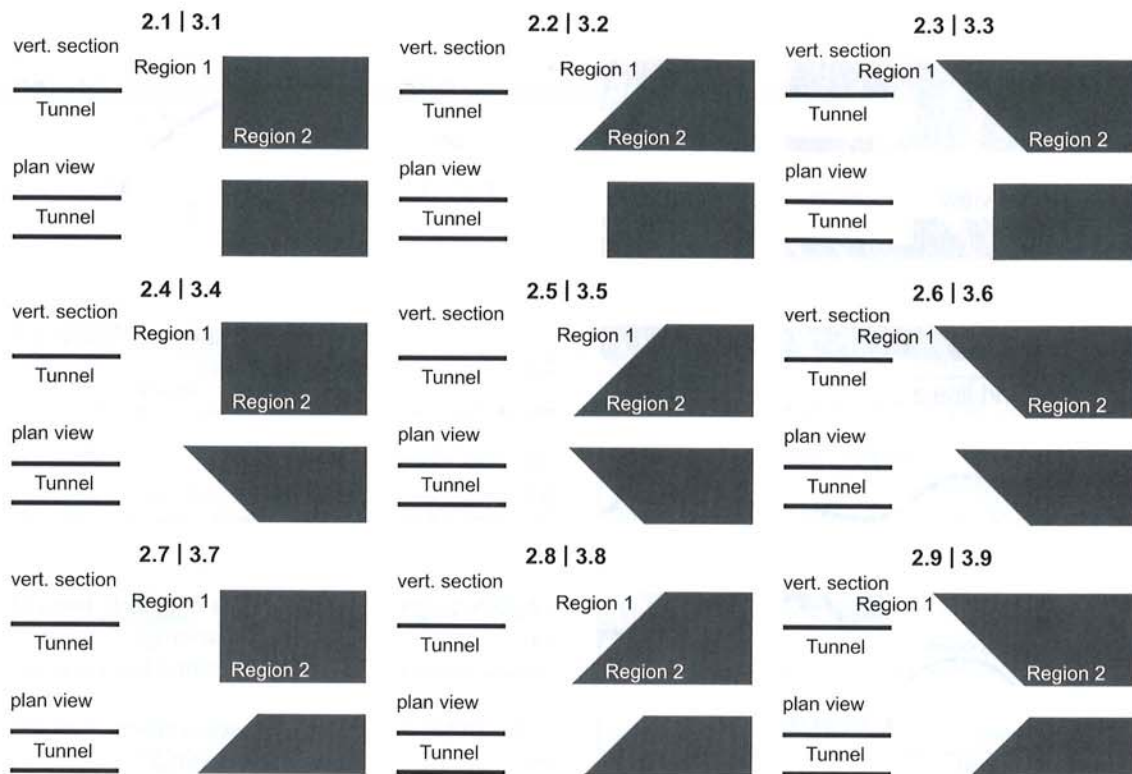


Fig. 5 Nine different basic types of ground conditions with contrasting stiffness (21).

Bild 5 Neun verschiedene Grundtypen mit der Änderung in der Gebirgssteifigkeit (21).

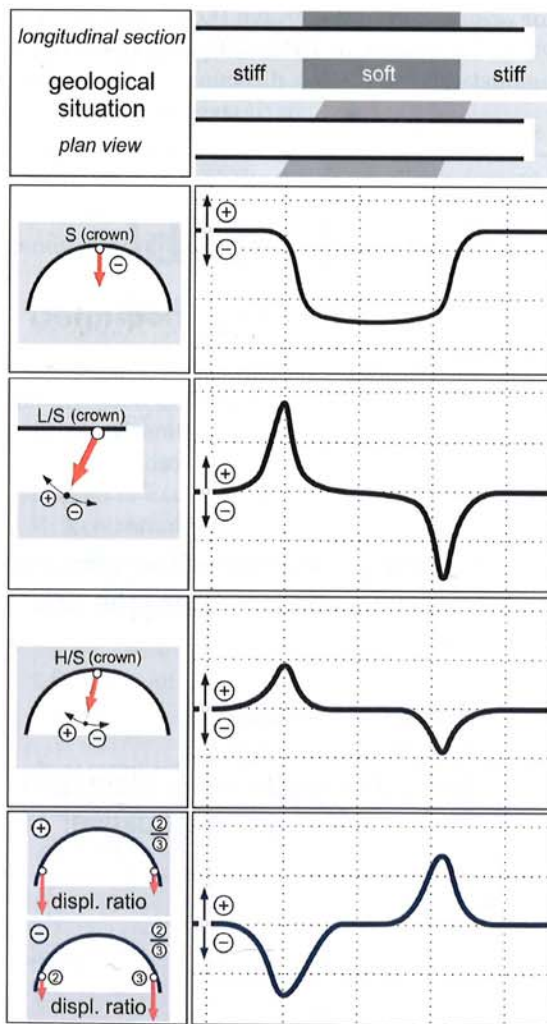


Fig. 6 Typical displacement trends when tunnelling through a fault (soft) zone (8, 9, 11, 21)

Bild 6 Typische Verschiebungstrendlinien für den Tunnelvortrieb durch eine Störungszone (8, 9, 11, 21).

crown displacement vector orientations are expected to be in this range for similar conditions.

The ratio between the horizontal and longitudinal displacements (L/H) at the sidewalls is also very characteristic for conditions with a steeply dipping bedding and a moderate angle between strike and tunnel axis. The displacement vector L/H for the left sidewall points in direction of the excavation with an average value of approximately 5°, while the vector of the right sidewall has an angle of approximately 10° against the excavation direction. This is interpreted as the effect of shearing along the bedding.

Figure 4 shows the displacement vectors resulting from a numerical 3D simulation in a cross and longitudinal section. A ubiquitous joint model was used to investigate the influence of bedding dipping 70° in the direction of excavation. The dip direction is 40° clockwise to the tunnel axis. This spatial orientation corresponds to the above-mentioned bedding orientation of the Flysch. More or less equal to the displacement characteristic shown in the previous figure, the vectors L/S for both sidewalls show a well-pronounced difference in the direction. The displacement vector for the right sidewall points against the excavation direction, while the left sidewall point develops in the other way round and points in excavation direction. In (17) the authors describe a similar displacement characteristic caused by an inclined schistosity striking the tunnel in an acute angle.

Ground structure and displacement characteristics

A thorough evaluation of displacement data from many case histories has increased the

knowledge on the relationship between tunnel displacements and geological conditions. A considerable number of numerical simulations for typical geological settings confirmed and supplemented the observations made on site (8, 9, 10, 11, 18, 19, 20).

Correlating typical trends of several measured values and modelled parameters to characteristic geotechnical conditions allows comparisons between actual monitoring results and this knowledge base.

Figure 5 depicts nine different basic types of ground conditions with contrasting stiffness. The basic types 2.1-2.9 denote transition into softer rock units, 3.1-3.9 transition to stiffer rock units. For each transition type, typical and characteristic displacement trends were established (21). Figure 6 shows a set of trends for a tunnel excavation through a fault zone, which in terms of the definitions used here is a sequence of basic type 2.7 and 3.7. Shown are the characteristic developments of the crown settlements, the vector orientation L/S and H/S for the crown as well as the vertical displacement ratio between the left and the right sidewall, S_L/S_R . While the radial displacements (for example S) show a change only near the weak zone, the displacement vector changes (L/S and H/S) already some distance ahead of the transition. Also the displacement ratio of the sidewalls (S_L/S_R) change significantly when the excavation approaches the weak zone.

Displacement trend catalogue

The consequent data evaluation led to the compilation of a displacement trend catalogue. For all nine basic types, both for transitioning from stiff to soft rock units and vice versa, the following displacement trends were established:

- ◇ Ratio of longitudinal displacements and settlements for the crown and sidewall points (L/S),
- ◇ Ratio of horizontal displacements and settlements for the crown and sidewall points (H/S),

Table 1 Reference table for the displacement trend change when advancing a softer rock unit according to the different basic types of changing ground conditions (modified after 21).

Tabella 1 Referenztafel der Änderung der Verschiebungstrends für den Vortrieb auf weiches Gebirge; dargestellt für die neun verschiedenen Grundtypen im Übergang der Gebirgsverhältnisse und für gleichbleibende Verhältnisse (angepasst nach 21).

ground conditions change		transition to softer rock unit										
		no change	Strike: 90° Dip: 90°	Strike: 90° Dip: against direction of excavation	Strike: 90° Dip: in direction of excavation	Strike: "+" Dip: 90°	Strike: "+" Dip: against direction of excavation	Strike: "+" Dip: in direction of excavation	Strike: "-" Dip: 90°	Strike: "-" Dip: against direction of excavation	Strike: "-" Dip: in direction of excavation	
basic type		1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	
vector orientation	crown	L/S	+ ↑	■	■	■	■	■	■	■	■	■
		H/S	+ ↑	■	■	■	■	■	■	■	■	■
	left sidewall	L/H	+ ↑	■	■	■	■	■	■	■	■	■
		L/S	+ ↑	■	■	■	■	■	■	■	■	■
	right sidewall	L/H	+ ↑	■	■	■	■	■	■	■	■	■
		L/S	+ ↑	■	■	■	■	■	■	■	■	■
displacement ratio	S_L/S_R	+ ↑	■	■	■	■	■	■	■	■	■	
	H_L/H_R	+ ↑	■	■	■	■	■	■	■	■	■	
	S_L/S_C	+ ↑	■	■	■	■	■	■	■	■	■	
	S_R/S_C	+ ↑	■	■	■	■	■	■	■	■	■	

most likely trend development
 possible trend development

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Table 2 Reference table for the displacement trend change when advancing a stiffer rock unit according to the different basic types of changing ground conditions (modified after 21).

Tabelle 2 Referenztafel der Änderung der Verschiebungstrends für den Vortrieb auf steiferes Gebirge; dargestellt für die neun verschiedenen Grundtypen im Übergang der Gebirgsverhältnisse und für gleichbleibende Verhältnisse (angepasst nach 21).

ground conditions change		transition to stiffer rock unit										
		no change	Strike: 90° Dip: 90°	Strike: 90° Dip: against direction of excavation	Strike: 90° Dip: in direction of excavation	Strike: "+" Dip: 90°	Strike: "+" Dip: against direction of excavation	Strike: "+" Dip: in direction of excavation	Strike: "-" Dip: 90°	Strike: "-" Dip: against direction of excavation	Strike: "-" Dip: in direction of excavation	
basic type		1	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	
vector orientation	crown	L/S	+ ↑	+	+	+	+	+	+	+	+	+
		H/S	- ↓	-	-	-	-	-	-	-	-	-
	left sidewall	L/H	+ ↑	+	+	+	+	+	+	+	+	+
		L/S	- ↓	-	-	-	-	-	-	-	-	-
	right sidewall	L/H	+ ↑	+	+	+	+	+	+	+	+	+
		L/S	- ↓	-	-	-	-	-	-	-	-	-
displacement ratio	S_L/S_R	+ ↑	+	+	+	+	+	+	+	+	+	
	H_L/H_R	- ↓	-	-	-	-	-	-	-	-	-	
	S_L/S_C	+ ↑	+	+	+	+	+	+	+	+	+	
	S_R/S_C	- ↓	-	-	-	-	-	-	-	-	-	

■ most likely trend development
□ possible trend development

- ◇ Ratio of longitudinal and horizontal displacements for the sidewall points (L/H),
- ◇ Ratio of vertical displacements (left and right sidewall) (S_L/S_R),
- ◇ Ratio of horizontal displacements (left and right sidewall) (H_L/H_R),
- ◇ Ratio of vertical displacements (left as well as right sidewall to the crown) (S_L/S_C), (S_R/S_C).

Table 1 and Table 2 show the evaluation results in terms of trend deviations for the nine previously mentioned basic types when tunneling from stiff to soft rock units and from soft to stiff rock units, respectively. In addition, the first row of each table shows the trend development for basic type 1 (rock mass with consistent behaviour) as a reference case. The black solid squares indicate the most likely development of the displacement trends for the respective

change in the ground conditions. White squares correspond to trends that are not clearly indicative, but at the same time cannot be ruled out.

The further use of the reference tables as a prediction tool requires a weighting process. Trend developments, which are typical for a given situation, receive a weight of 10, while possible trend developments are assigned the value 5. The relative values are based on experience and the authors' judgment. Clear and indicative trends are of double relevance than trends that are not clearly indicative.

Stiffness transitions in an acute angle to the tunnel axis, as for example slightly dipping faults, cause a steady increase (or decrease) in the respective trends rather than an abrupt change. The reference tables consider such trend developments with the above mentioned white squares. This process is applied for all cases mentioned above.

The combination of both reference tables including the weighting factors yield in the displacement trend correlation matrix.

Proposed automation method

On site a continuous evaluation of monitoring results allows characteristic trend developments to be identified. In a next step, the input vector for each trend type in the correlation matrix is set to 1 for the observed trend development in the corresponding box. The input for the respective trends is kept 0 if no clear development is observed. This input vector in each row is then multiplied with each weight in the correlation matrix. Adding the values of each column provides a result vector for each basic type. The column with the highest result vector represents the most likely geological condition ahead of the face.

Table 3 demonstrates the application of the correlation matrix. Setting the input vector in the appropriate boxes, the maximum correlation is obtained for the situation, where stiffer rock mass can be expected ahead of the face, dipping steeply and striking approximately perpendicular to the tunnel axis (basic type 3.1).

The example shown matches the observed trends and the expected trends for type 3.1 with 90 %. However, experience from case histories showed that the trends do not always follow the theoretical expectations. Reasons for such deviations among others may be local imperfections in construction or relative displacements between lining and ground. To avoid unreliable results, the minimum correlation factor necessary is proposed at 75 %. The evaluation of several case histories showed that a correlation factor less than 75 % does not reliably allow predicting the appropriate ground conditions ahead.

Currently this evaluation tool requires manual evaluation of the trends and setup of the input. Using trend analysis tools implemented into the

it at least provides a consistent correlation to the displacement trends observed.

The consistent collection and evaluation of monitoring data and correlation to the geological situations allowed the establishment of typical trend developments for different geological situations. This forms the backbone of the proposed method. The comparison of actually observed displacement trends to reference trends allows the detection of similar situations on site. Hence, complex interrelations of different trend characteristics from multiple monitoring points and certain geological features become comprehensible. The day-to-day data evaluation using the presented method facilitates the prediction of ground conditions ahead and outside the tunnel. This allows for timely intervention, when necessary, and aids in the reduction of unforeseen conditions during construction. It also enables the use of the entire displacement data set. The vast amount of data gathered daily and the subsequent evaluation generates a flood of information, which challenges even very experienced engineers. It is not always easy to find the context between several trends and the geotechnical conditions by only visually inspecting a number of diagrams.

The method proposed can be a useful assistance for the displacement data interpretation. It will support in getting an insight in the geological conditions around the tunnel, in detecting zones of different rock mass stiffness in time and hence to adapt excavation and support to the changing conditions. However, the method is not a viable substitute for detailed geotechnical analysis and onsite decisions by the geotechnical engineer.

The presented reference tables for the displacement trends will be extended in the future. Using additional investigation and monitoring results relative to different geological situations will increase the reliability of the tool. Nevertheless, the applicability is a function of data quality and quantity. To increase the accuracy and reliability of automated evaluation tools, readings should be taken in short intervals and in sufficient density. Quality of data has to be assured by removing measurement errors.

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Authors

Dipl.-Ing. Karl Großbauer, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria, E-Mail grossauer@tugraz.at; Dipl.-Ing. Gerold Lenz, iC Consulten, Zöllhausweg 1, A-5101 Salzburg, Austria, E-Mail g.lenz@ic-salzburg.at

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