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Automatic displacement monitoring data interpretation – the next step towards an expert system for tunneling

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ABSTRACT: For more than twenty years, absolute displacement monitoring has been standard practice for tunneling 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.

1. INTRODUCTION

Absolute displacement monitoring in tunneling has superseded relative measurement methods for nearly twenty years.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 deform-ability 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].

Already Vavrovsky and Schubert [12] 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.

The European standard 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 behavior
- Observe abnormal trend developments; and,
- 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 that consistently checks the entire displacement characteristics against typical displacement trends in an unbiased way.

2. DEFINITIONS

Diagrams, illustrations and explanations in this paper apply the following terms and algebraic sign convention:

(a) Displacement component, see Fig. 1 (a):

L Longitudinal displacement (positive in direction of excavation)

H Horizontal (transversal) displacement (positive to the right, looking in direction of excavation)

S Settlements (negative downwards)

(b) Orientation of the displacement vector:

L/S Ratio of longitudinal displacement and settlement

H/S ratio of horizontal displacement and settlement

L/H ratio of longitudinal and horizontal displacement

(c) 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

(d) Change of the displacement trend, see Fig. 1 (b) and Fig. 1 (c):

- 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.

3. CHARACTERISTIC DISPLACEMENTS

It is an established fact that the geologic structure strongly influences the displacement characteristics of a tunnel. For assessing the "normality" of the system behavior and detecting deviations from the "normal behavior", 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.

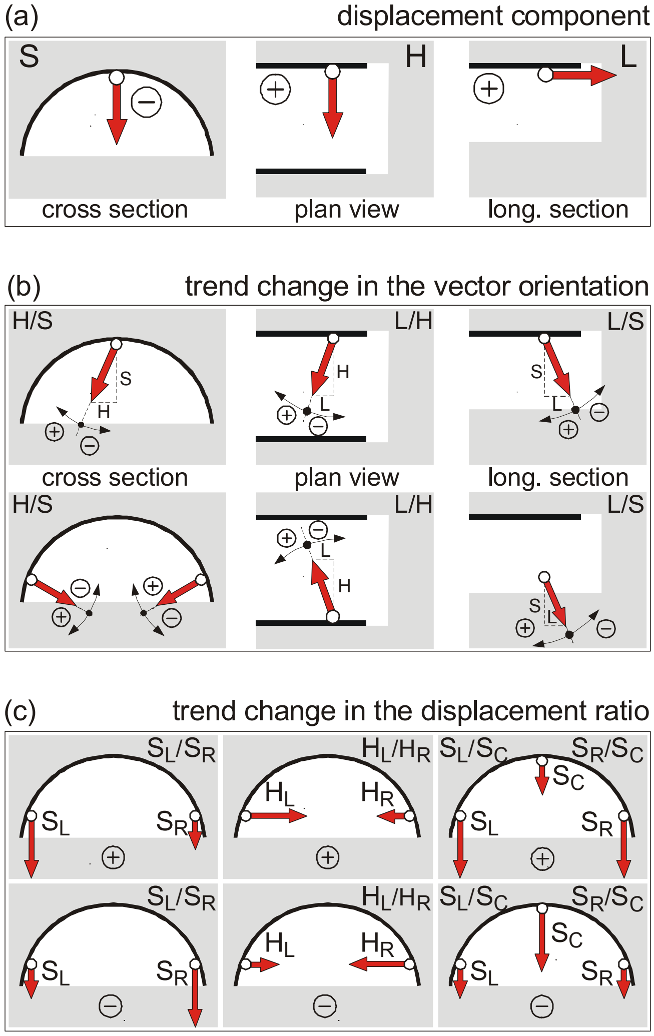

Fig. 1. Sign convention for (a) the displacement components S, H and L, (b) trend change in the vector orientation and (c) trend change in the displacement ratio.

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 smoothened - data were used.

Figure 2 depicts the determination of normal behavior from monitored displacement data in a Flysch formation of the Wienerwald tunnel. The 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].

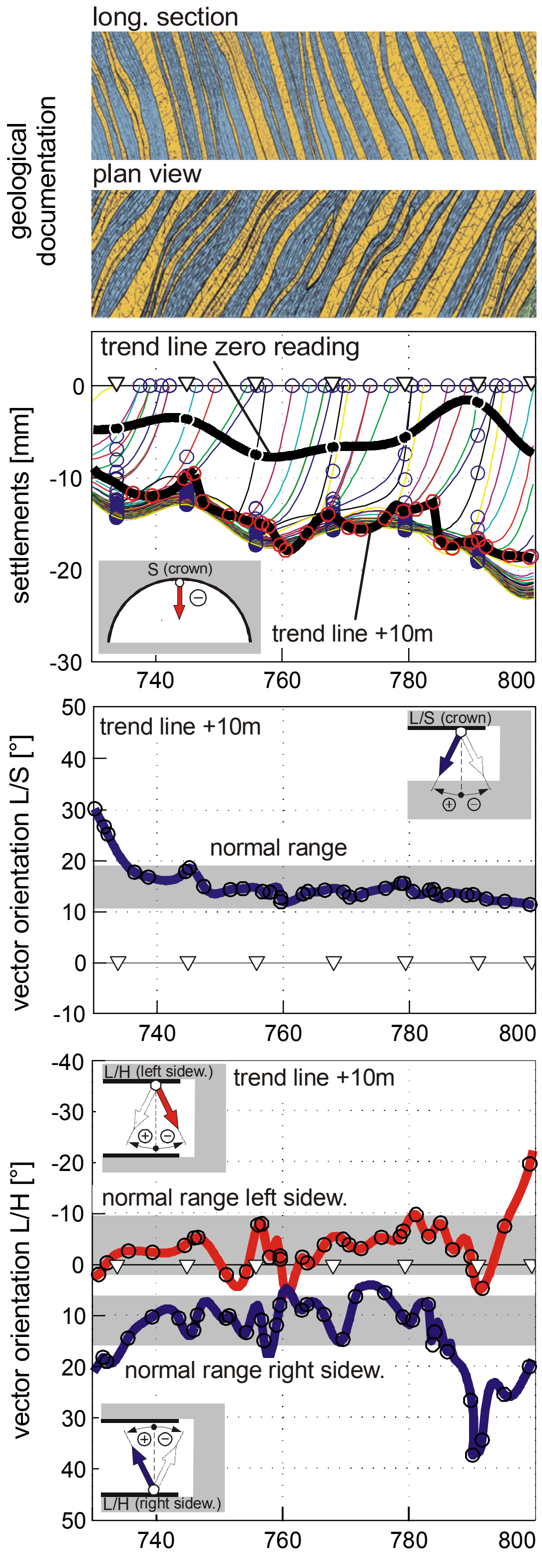

Fig. 2. Comparison of the geological documentation and several displacement trends.

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, 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 approx. 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 3 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. Nearly 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.

4. 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 modeled parameters to characteristic geotechnical conditions allows comparisons between actual monitoring results and this knowledge base.

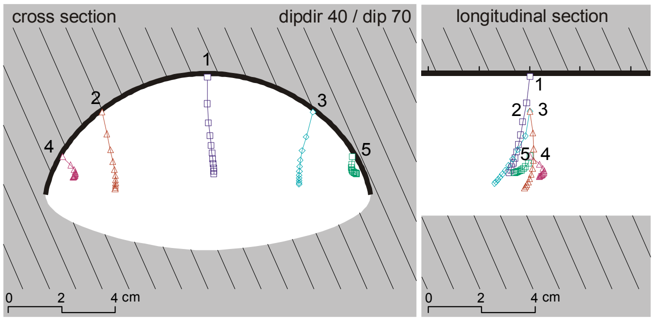

Fig. 3. Spatial orientation of displacement vectors as a consequence on the influence of bedding plane orientation; results gained from numerical simulations utilizing ubiquitous joint model.

Figure 4 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 for the transition to stiffer rock units. For each transition type, typical and characteristic displacement trends were established [21]. Figure 5 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 L/H 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.

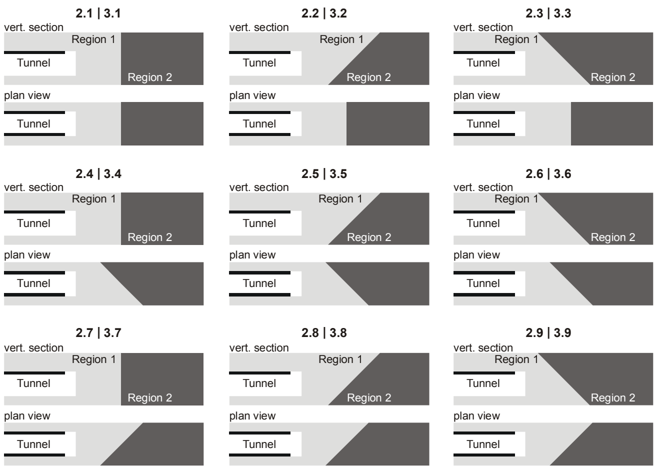

Fig. 4. Basic types of changing ground with contrasting stiffness as specified in [21].

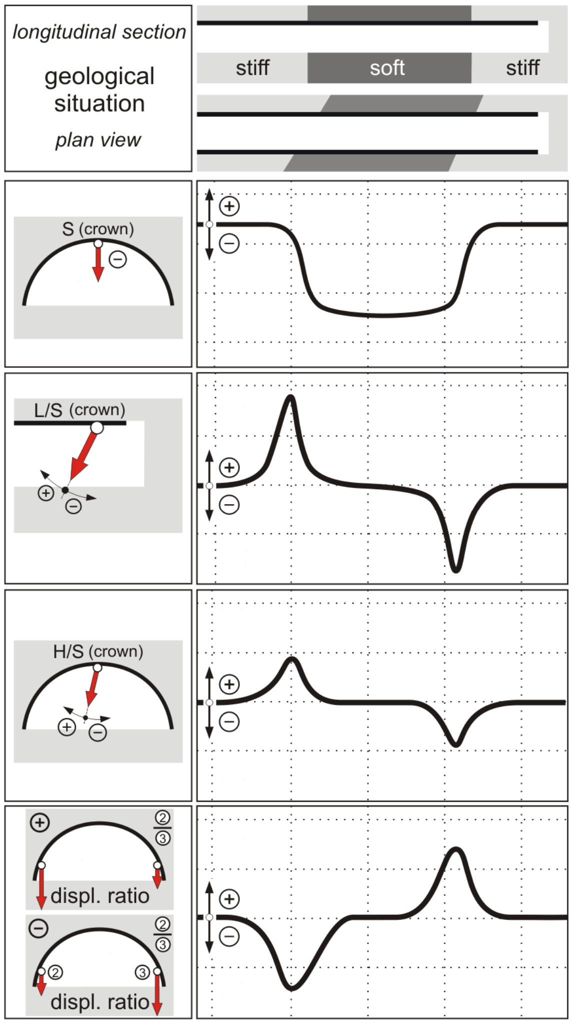

Fig. 5. Displacement trends when tunneling through a fault zone [8, 9, 11, 21].

5. 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)
- 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)

ground conditions change				no change	transition to softer rock unit								
					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

Fig. 6. Displacement trend reference matrix when advancing softer rock mass, modified based on [21].

ground conditions change				no change	transition to stiffer rock unit								
					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

Fig. 7. Displacement trend reference matrix when advancing stiffer rock mass, modified based on [21].

Figure 6 and 7 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 behavior) 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 pre-diction 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 our 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 particular 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.

6. 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 particular 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.

trend						transition to softer rock unit									transition to stiffer rock unit								
basic type				input vector	1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
vector orientation	crown	L/S	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	1	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10
		H/S	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	left sidewall	L/H	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	1	0	0	0	0	0	0	0	0	0	5	10	10	5	10	10	5	5	5	0
		L/S	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	1	0	0	0	0	0	0	0	0	0	0	10	10	5	10	10	5	5	5	5
	right sidewall	L/H	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	1	0	0	0	0	0	0	0	0	0	0	10	10	5	5	5	0	10	10	5
		L/S	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-	1	0	0	0	0	0	0	0	0	0	0	10	10	5	5	5	0	10	10	5
displacement ratio		S_L/S_R	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	10	10	10	0	0	0	0	0	0	10	10	10	0	0	0	0	0	0
			-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		H_L/H_R	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	10	10	10	0	0	0	0	0	0	10	10	10	0	0	0	0	0	0
			-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S_L/S_C	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	10	5	5	5	0	5	10	10	5	10	5	5	5	0	5	10	10	5
			-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S_R/S_C	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	10	5	5	10	10	5	5	0	5	10	5	5	10	10	5	5	0	5
			-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
actual rating					40	40	30	30	15	10	15	15	10	10	90	80	60	55	50	30	55	50	30
avr. rating					40	21									56								
max. rating					100																		
correlation [%]					40	40	30	30	15	10	15	15	10	10	90	80	60	55	50	30	55	50	30

Fig. 8. Application of the established trend correlation matrix and determination of the basic type showing the highest correlation to the trends observed, modified after [21].

Figure 8 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 percent. 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 evaluation software will allow automating the entire process.

Tests with the evaluation tool on several case histories showed promising results. However, the rock mass fabric and primary stress conditions in many cases strongly influence the deformation characteristics of a tunnel. Thus, it is important to identify the characteristic deformation pattern either by numerical simulations or by evaluating monitoring data from similar situations. Once characteristic behaviors for typical geotechnical conditions are established, and a certain tolerance established to account for data noise and insignificant changes in the rock mass conditions, deviations from this normal range can be assessed and used for the prediction.

Results of such measurement data interpretation procedures do not always provide a unique result. Further, a clear indication of the length of a fault zone cannot be obtained, as a short zone with very poor ground can produce a similar displacement trend, as a longer one with not so poor ground [9].

7. CONCLUSION

It is possible to automate the interpretation of displacement monitoring data. Even though the system does not always give definitive answers, 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 re-moving measurement errors.

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