Innovative Approaches in Monitoring Data Evaluation and Interpretation

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ABSTRACT: Uncertainties in the geological and ground models, as well as simplifications in the design in general lead to an inaccurate design of underground structures. Observations during construction are required to optimally adjust the construction method to the real ground behaviour. Increased safety, reduced costs and risk are the targets of an observational approach. Absolute displacement measurement with geodetic methods nowadays is common on many tunnel sites. The information contained in the measurement data can be used not only to assess the stability of an underground structure, but also to predict final displacements and the ground quality ahead of the face and around the tunnel.

To assist the engineers on site to optimally exploit the information contained in the displacement monitoring data, various tools have been developed, including an expert system, which allows an automatic assessment of changing ground conditions ahead of the face. In addition monitoring is is an essential part the safety management on site. The potential of advanced data evaluation methods is shown.

1 INTRODUCTION

The limited knowledge of the geological setup and ground characteristics of a project area, as well as the simplifications used in the simulation tools available in general lead to an inaccurate design of underground structures. As ground behaviour can vary in a wide range, and different failure modes require different construction strategies, it is not possible to account for the uncertainties with higher safety factors, as is usual for less complex structures. In addition, the adjustment of the construction methods to the real ground behaviour results in reduced costs and risk, as well as increased safety.

The measurement of displacements in space with geodetic methods has replaced the traditional convergence measurements on many sites around the world. With appropriate evaluation methods, more information can extracted from the measurement results. Besides assessment of the influence of the rock mass structure on deformation of the tunnel, the spatial deformation characteristics can be used to improve the ground model outside the visible area, e.g. ahead of the face and outside the tunnel perimeter. This allows reacting on changing ground conditions in time.

Another important issue is the prediction of the “normal” evolution of the systems displacements. Once the “normal” behaviour is defined, a comparison of the actual displacements with the predicted ones can be continuously compared, and deviations from the normal easily identified.

2 PREDICTION OF DISPLACEMENTS

Conventional tunnel designs usually provide information on the magnitude of the expected displacements in various construction stages, as well as stresses in supports. Very rarely, the transient development of the displacements with progressing face advance and in relation to the time is shown in designs with the required accuracy. Besides the ground characteristics, stresses, size and shape of the underground structure and support, also the rock mass structure strongly influences the spatial and time dependent evolution of the displacements.

The knowledge of the displacement evolution is essential on the one hand to determine the magnitude of the required overexcavation to account for the displacements, but also for the assessment of the utilization of the linings. Latter is particularly important in cases, where shotcrete linings are used, as the development of the strength among other factors depends on the time.

Figure 1 shows results of a numerical simulation of a tunnel excavation in foliated rock masses, where the dip

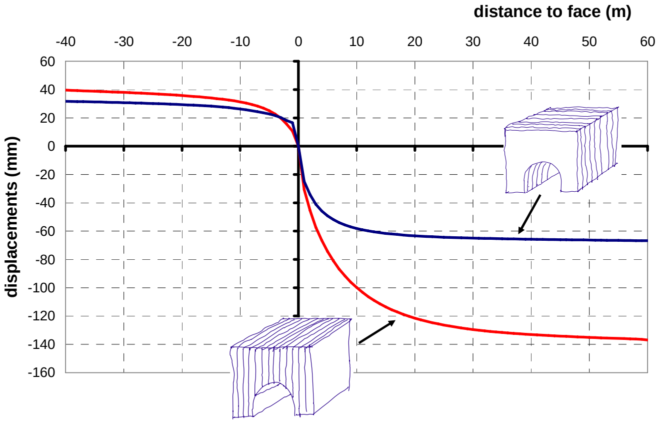


Figure 1. Influence of the relative orientation of the foliation to the tunnel axis on magnitude and evolution of displacements

of the foliation was vertical, and the strike parallel and normal to the tunnel axis. It can be seen, that not only the total magnitude of displacements is significantly different, but also the spatial characteristic of the displacement development. While for the case with the strike perpendicular to the tunnel axis the final displacements are reached practically 10 m behind the face, in the case with the foliation strike parallel to the tunnel axis, even 30 m behind the face the increase of displacements due to face advance can be clearly seen.

2.1 *Tool for prediction of displacements*

Guenot et al. (1985) and Sulem et al. (1987) proposed a method based on analytical functions that describe tunnel displacements as a function of time and the advancing face. Barlow (1986) and Sellner (2000) modified this approach. The displacement behaviour of the rock mass and support basically is represented by four function parameters. Two parameters (T, m) are used to simulate time dependency and two parameters (X, C) the face advance effect. These parameters can either be back-calculated from case histories using curve fitting techniques, or determined with analyses.

The system of these analytical functions was implemented in the program package GeoFit® (Sellner 2000). It provides easy-to-use tools for back-calculating displacement monitoring data by curve and for prediction of displacements. The code allows simulating staged excavation, as well as the installation of different types of support.

The analysis of thousands of measurements in different geotechnical conditions has shown that the measured displacements in general match the predicted ones perfectly. As new readings can immediately be compared to the predicted displacement evolution, any deviation from the "normal" behaviour can be identified immediately and the reasons analysed.

Shown in figure 2 is the predicted displacement evolution over time for a top heading bench excavation of a railway tunnel under the assumption of a steady advance. The prediction was made after only 2 readings. The dashed line represents the displacement development for the top heading with standard shotcrete and rock bolt support. The upper solid line shows the effect of a temporary top heading invert, which was installed close to the face. The lower solid line shows the effect of the bench excavation on the displacements. Due to a holiday break and organizational reasons, the actual advance was unsteady, leading to an unsteady displacement over time. Using the function implemented in GeoFit®, displacements are calculated according to the actual advance, so with a change in the advance rate also the development of the predicted displacements over time changes.

Figure 3 shows the comparison of the development of the calculated displacements under consideration of actual advance and time with the measured displacements, which are shown in the plot as circles. It can be seen, that even with very unsteady advance and staged excavation, the function produces very realistic results. Although the advance has changed considerably after the first prediction, the final displacements were predicted accurately at a very early stage. Note that the function parameters did not change.

Not only is this tool a valuable help for the engineers on site, it also allows to correlate the function parameters to rock mass structure and stress conditions, thus forming the basis for an expert system. Once enough quality data are available, this should allow determining the function parameters on the basis of the observed geological and boundary conditions.

Figure 2. Predicted displacement development for a top heading bench excavation and steady tunnel advance. Dashed line: displacements of top heading without temporary invert, solid line: top heading with temporary invert

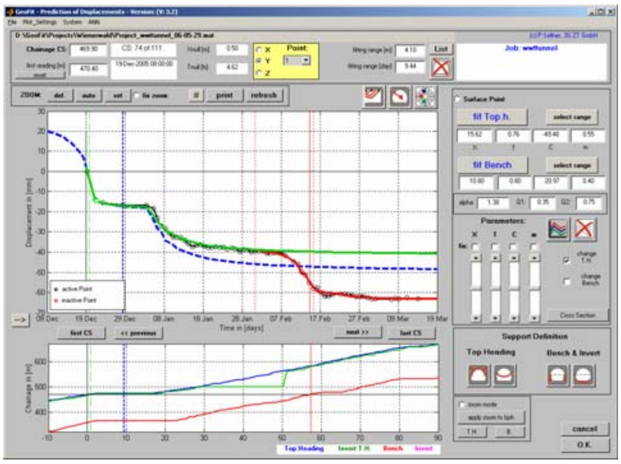


Figure 3. Comparison of the predicted to the measured displacements (circles)

3 PREDICTION OF ROCK MASS QUALITY AHEAD OF THE FACE

Due to the inevitably inaccurate geological model developed during the design phase, the exact location of changes in the ground quality or position of singular features, like faults cannot be known before construction.

On the other hand, "surprises" during tunnel excavation usually are costly and time consuming. When for example entering fault zones without prior warning, the displacement might exceed the allowance, requiring costly reshaping, or the support might be damaged, or even collapses might occur.

From this it follows that a good prediction of the ground quality ahead of the face can considerably reduce the potential of surprises and costly repair works. However, direct methods of investigation ahead of the face, like probe drillings are costly and delay the progress of excavation. Indirect methods, like geophysical methods have not yet been developed are also costly, and the reliability of the results at the present stage of development is not satisfying.

Experience from many tunnelling sites has shown that results from displacement monitoring can be used to predict the ground quality ahead of the face (Schubert et al. 1995, Budil, 1996, Steindorfer et al. 1995, Steindorfer, 1998). A number of theoretical studies have confirmed the observations on site (Grossauer, 2001, Mösslacher, 2006).

The idea is that as long as there are no major changes in the rock mass structure or quality in a representative volume around the tunnel, the spatial characteristics of the displacements will not change. If there is material in the vicinity of the tunnel with different properties, the strains and stresses will change, which again reflects in a changed displacement characteristic.

Recording changes in trends of certain displacement values or ratios of displacements, one is in a position to predict the type and approximate location and orientation of the “inhomogeneity”.

Many case histories and numerical analyses showed that significant changes in the stiffness of the ground ahead of the face show in a change of the ratio between longitudinal displacements and vertical displacements (Schubert, 1993, Budil, 1996, Steindorfer, 1998). However, a clear trend can be only achieved in cases where the angle of intersection between the tunnel axis and the transition is somewhere between 90° to 45°. If the angle of intersection is smaller, additional evaluations are required to identify the change.

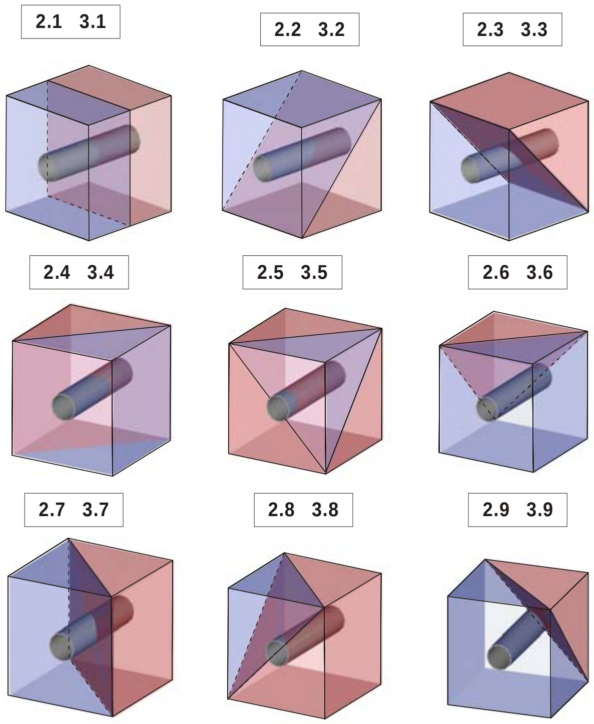


Figure 4. Basic cases of changes in ground quality (Lenz, 2007)

Based on the evaluation of a number of case histories and the results from numerical simulations, Lenz (2007) established typical displacement trends for the different transitions shown in figure 4.

A reference table considering following displacement parameters was established:

- Vertical displacements of crown and sidewalls
- Horizontal displacements of crown and sidewalls
- Longitudinal displacements
- Ratio of longitudinal to vertical displacements
- Ratio of longitudinal and horizontal displacements
- Ratio of vertical displacements left to right sidewall
- Ratio of horizontal displacements left and right sidewall
- Ratios of vertical displacements right and left sidewalls to the crown

Figure 5 shows a characteristic development of different displacements and ratios of displacement components, when the tunnel is excavated through a weak zone. While the radial displacements show a change only in the immediate vicinity of the weak zone, the displacement vector changes already some distance ahead of the transition. Also horizontal displacements of the crown and the ratio of the vertical displacements of the sidewalls show significant changes, when the excavation approaches the weak zone.

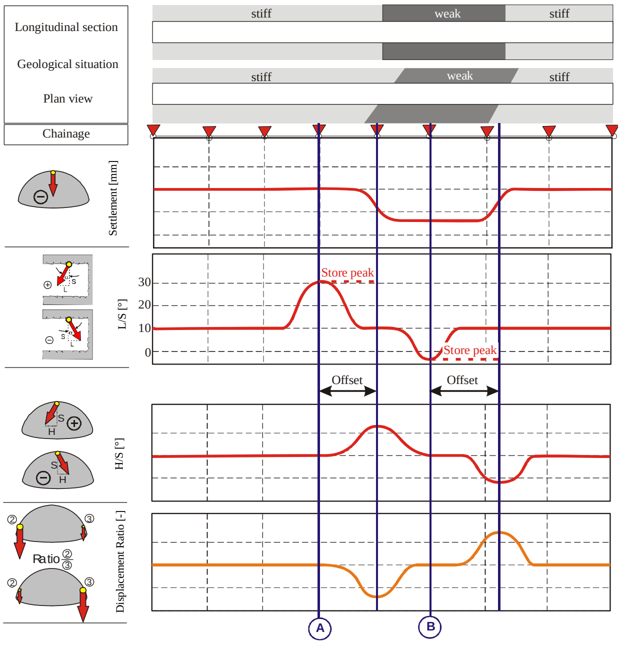
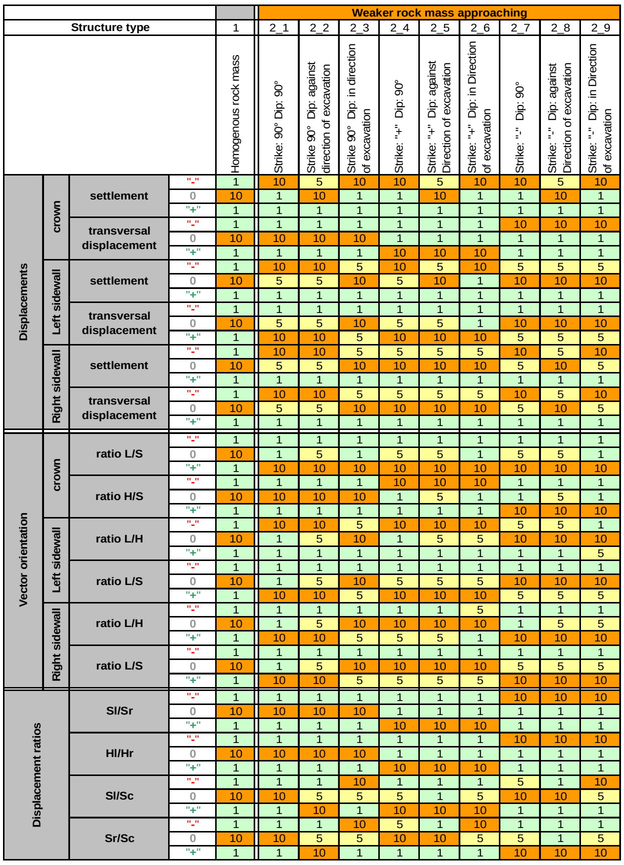


Figure 5. Typical trends of different displacement components and ratios when tunneling through a weak zone (Lenz, 2007)



					Weaker rock mass approaching								
Structure type				1	2_1	2_2	2_3	2_4	2_5	2_6	2_7	2_8	2_9
				Homogenous rock mass	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
Displacements	crown	settlement	"-"	1	10	5	10	10	5	10	10	5	10
			0	10	1	10	1	1	10	1	1	10	1
			"+"	1	1	1	1	1	1	1	1	1	1
		transversal displacement	"-"	1	1	1	1	1	1	1	10	10	10
			0	10	10	10	10	1	1	1	1	1	1
			"+"	1	1	1	1	10	10	10	1	1	1
	Left sidewall	settlement	"-"	1	10	10	5	10	5	10	5	5	5
			0	10	5	5	10	5	10	1	10	10	10
			"+"	1	1	1	1	1	1	1	1	1	1
		transversal displacement	"-"	1	1	1	1	1	1	1	1	1	1
			0	10	5	5	10	5	5	1	10	10	10
			"+"	1	10	10	5	10	10	10	5	5	5
	Right sidewall	settlement	"-"	1	10	10	5	5	5	5	10	5	10
			0	10	5	5	10	10	10	10	5	10	5
			"+"	1	1	1	1	1	1	1	1	1	1
		transversal displacement	"-"	1	10	10	5	5	5	5	10	5	10
			0	10	5	5	10	10	10	10	5	10	5
			"+"	1	1	1	1	1	1	1	1	1	1
Vector orientation	crown	ratio L/S	"-"	1	1	1	1	1	1	1	1	1	1
			0	10	1	5	1	5	5	1	5	5	1
			"+"	1	10	10	10	10	10	10	10	10	10
		ratio H/S	"-"	1	1	1	1	10	10	10	1	1	1
			0	10	10	10	10	1	5	1	1	5	1
			"+"	1	1	1	1	1	1	1	10	10	10
	Left sidewall	ratio L/H	"-"	1	10	10	5	10	10	10	5	5	1
			0	10	1	5	10	1	5	5	10	10	10
			"+"	1	1	1	1	1	1	1	1	1	5
		ratio L/S	"-"	1	1	1	1	1	1	1	1	1	1
			0	10	1	5	10	5	5	5	10	10	10
			"+"	1	10	10	5	10	10	10	5	5	5
	Right sidewall	ratio L/H	"-"	1	1	1	1	1	1	5	1	1	1
			0	10	1	5	10	10	10	10	1	5	5
			"+"	1	10	10	5	5	5	1	10	10	10
		ratio L/S	"-"	1	1	1	1	1	1	1	1	1	1
			0	10	1	5	10	10	10	10	5	5	5
			"+"	1	10	10	5	5	5	5	10	10	10
Displacement ratios		Sl/Sr	"-"	1	1	1	1	1	1	1	10	10	10
			0	10	10	10	10	1	1	1	1	1	1
			"+"	1	1	1	1	10	10	10	1	1	1
		Hl/Hr	"-"	1	1	1	1	1	1	1	10	10	10
			0	10	10	10	10	1	1	1	1	1	1
			"+"	1	1	1	1	10	10	10	1	1	1
		Sl/Sc	"-"	1	1	1	10	1	1	1	5	1	10
			0	10	10	5	5	5	1	5	10	10	5
			"+"	1	1	10	1	10	10	10	1	1	1
		Sr/Sc	"-"	1	1	1	10	5	1	10	1	1	1
			0	10	10	5	5	10	10	5	5	1	5
			"+"	1	1	10	1	1	1	1	10	10	10

Figure 6. Example of correlation matrix with different weighting factors depending on the relevance of the trend for specific geotechnical conditions, Lenz, 2007

Depending on the relevance of each trend for a certain geotechnical situation a weight was introduced. Steady, increasing, and decreasing trends of certain displacement components are considered in the correlation matrix (figure 6).

Monitoring results are continuously evaluated with the tunnel progress, and developments recorded. A 0/1 switch is used as an input vector. This vector now is multiplied with the weighted relevance factor for each geotechnical model. This is done for all observed trends. In the next step the values of each column are added up. The column with the highest result vector shows the most probable geotechnical situation to be expected. Figure 8 shows an example of such an evaluation. Where significant trends are observed, the input vector is set to 1. For this case, the maximum correlation is obtained for the situation, where stiffer rock mass can be expected ahead of the face, dipping steeply and striking to the tunnel axis approximately perpendicularly.

In case of an acute angle between tunnel axis and the interface of the zones with different quality, there will be a longitudinal offset in the individual trends. The amount of offset is used to determine the spatial position of the interface.

Currently the evaluation of the trends and the input vectors is still done manually. A next step will be to implement a trend analysis tool into the evaluation software with the aim to automatize the whole process. This would put also less experienced engineers in a position to make relatively reliable predictions on changes in the rock mass quality ahead of the face. The tool has been successfully tested on several case histories.

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 a “normal” characteristic for typical geotechnical conditions is established, and a certain tolerance established to account for data noise and insignificant changes in the rock mass quality, deviations from this normal range can be assessed and used for the prediction.

It is quite obvious that the results of such measurement data interpretation procedures do not always provide a unique result. In addition a clear indication of the length of a fault zone cannot be obtained, as a short zone with very poor ground can have the produce a similar displacement trend, as a longer one with not so poor ground (Grossauer, 2001).

4 ASSESSMENT OF LINING LOAD

Once data are recorded and stored, one should make the maximum use of the information contained in the data. One of the methods to increase the level of information is to analyse stresses in the lining and compare them to the strength. Rokahr and Zachow (1997) have done pioneering work in this field and the model is practically applied (Rokahr et al. 2002). An-other model, simulating the complex behavior of shotcrete is currently under development, and has been tested on one site so far (Hellmich et al. 1999, Macht 2002).

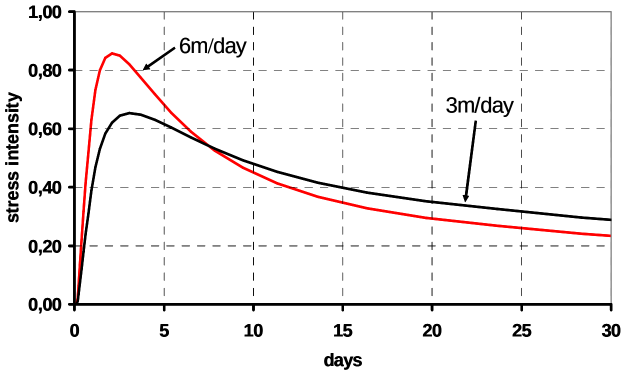
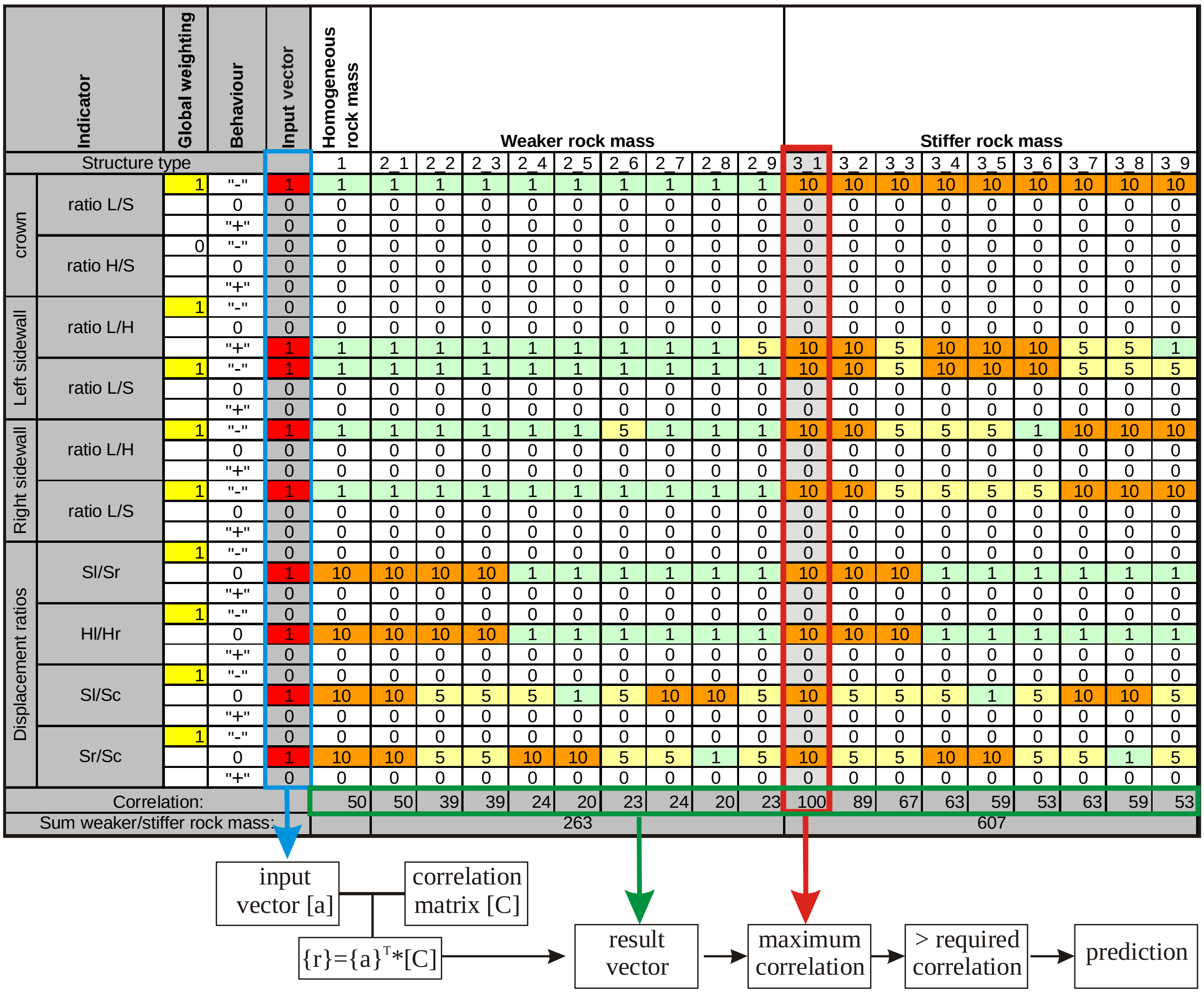


Figure 7.Development of utilization of a shotcrete lining with different excavation rates

Especially for tunnels with low overburden, where the shotcrete lining is the predominant support and the rock mass plays a minor role in the stress redistribution, the knowledge of the development in the stress intensity index is an important decision aid. With higher overburden the integrity of the shotcrete lining usually looses importance, because in most cases the natural “rock arch” can compensate the loss in lining capacity,



	Indicator	Global weighting	Behaviour	Input vector	Homogeneous rock mass	Weaker rock mass									Stiffer rock mass								
Structure type					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
crown	ratio L/S	1	"-"	1	1	1	1	1	1	1	1	1	1	1	10	10	10	10	10	10	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ratio 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	0	0
Left sidewall	ratio L/H	1	"-"	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
			"+"	1	1	1	1	1	1	1	1	1	1	5	10	10	5	10	10	10	5	5	1
	ratio L/S	1	"-"	1	1	1	1	1	1	1	1	1	1	1	10	10	5	10	10	10	5	5	5
			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
Right sidewall	ratio L/H	1	"-"	1	1	1	1	1	1	1	5	1	1	1	10	10	5	5	5	1	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ratio L/S	1	"-"	1	1	1	1	1	1	1	1	1	1	1	10	10	5	5	5	5	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Displacement ratios	Sl/Sr	1	"-"	0	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	1	1	1	1	1	1	10	10	10	1	1	1	1	1	1
			"+"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hl/Hr	1	"-"	0	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	1	1	1	1	1	1	10	10	10	1	1	1	1	1	1
			"+"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sl/Sc	1	"-"	0	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	1	5	10	10	5	10	5	5	5	1	5	10	10	5
			"+"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sr/Sc	1	"-"	0	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	1	5	10	5	5	10	10	5	5	1	5
			"+"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Correlation:					50	50	39	39	24	20	23	24	20	23	100	89	67	63	59	53	63	59	53
Sum weaker/stiffer rock mass:						263									607								

Figure 8. Example of trend evaluation using the correlation matrix. The highest result vector is in the column 3.1, representing stiffer rock mass ahead with a more or less vertical dip and a strike perpendicular to the tunnel axis. (Lenz, 2007)

under the condition that is has still reserves or is properly reinforced by rock bolts.

In both routines measured displacement data are used and strains in the lining calculated. Considering the strain development and transient properties of the shotcrete, the stresses can continuously be compared to the actual strength, leading to a stress intensity factor. Not only the magnitude of displacements, but also their timely development influences the stresses in the lining. It can be seen in Figure 7 the advance rate influences the displacements, which again determine the stresses. The higher the displacement rate in the beginning, the higher is the initial utilization of the lining. Due to larger creep magnitudes the stress intensity then decreases more rapidly than with a slower progress.

Using tools to predict displacements (for example GeoFit©) allows also a prediction of the stress intensity factor. The influence of different advance rates on the future stresses can be evaluated and thus the progress controlled in a way that the stresses in the lining remain within acceptable limits.

5 CONCLUSION

The use of methods to measure the absolute displacements of tunnels has increased the potential to extract more information from the monitored data.

The use of methods to measure the absolute displacements of tunnels has increased the potential to extract more information from the monitored data. Using relatively simple empirical functions, the development of the displacements as a function of the face advance and time can be reliably predicted. Software has been developed allowing the prediction of displacements for staged excavation and different support types. The application of this method on a large number of projects has allowed establishing correlations between specific geotechnical situation and the function parameters.

By predicting the transient displacements at an early stage, monitored data can continuously be compared to the prediction, and deviations immediately be recognised. This decreases reaction time in case of an unfavourable evolution of the system und consequently contributes to safer and more economical construction.

Absolute displacement monitoring data can also be used to assess the stresses in linings. This is of particular importance for shotcrete lined tunnels with shallow overburden, where serious damages can be caused in case of a failure of the lining.

The collection of a huge amount of monitoring data in different geotechnical conditions has allowed establishing an expert system, which supports the prediction of ground conditions ahead of the tunnel face. Typical trends of displacement components have been identified. The combination of different trends then is used to identify changing ground conditions ahead of the face. Appropriately used, this tool can help reducing "surprises" during tunnel excavation, which in general are costly and time consuming.

It appears that only integrated approaches, considering on site experience can advance tunnelling technology towards safer and more economical construction.

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