Methods for the evaluation and interpretation of displacement monitoring data in tunnelling

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ABSTRACT: Absolute displacement monitoring has become common practice on many tunnel sites. Those data in combination with the information on geological and boundary conditions have a tremendous potential to enhance the insight into mechanical processes around the tunnel and the ground-support interaction. Different methods of data evaluation are used for specific purposes. Displacement history plots can be used to evaluate the stabilization process or to predict the final displacements rather than to predict geotechnical conditions ahead of the face. For such a request the use of more advanced evaluation methods are required.

To describe the spatial and transient development of displacements during tunnel excavation, analytical functions are used. The daily evaluation process will be enormously improved by comparing the currently monitored displacements to the expected displacement characteristic, determined using the analytical function. Any deviation from the normal behaviour can be identified in time. Critical displacement trends can be automatically detected as well as typical trends used to predict the ground conditions ahead of the face.

1 INTRODUCTION

The introduction of absolute displacement monitoring using geodetic methods has significantly improved the basic concept of the observational approach for tunnel construction. Rabensteiner (1996) already described the scope of optical displacement monitoring and the procedure to determine reliable 3D coordinates of monitoring points installed at the circumference of the tunnel. The huge amount of displacement data which are commonly produced on a daily basis require appropriate evaluation methods in order not to get lost in data tables, as well as to extract as much information as possible. In the mid of the last decade, several authors have given an overview of useful evaluation methods to improve the understanding of geomechanical processes during the tunnel excavation (Schubert & Steindorfer 1996, Vavrovsky & Schubert 1994, 1995). They also have introduced new techniques for the prediction of geological conditions ahead of the tunnel face by interpreting the trend of the displacement vector orientation (Schubert & Budil 1995). During the last decade, these evaluation methods have been applied on many sites primarily during tunnel projects in the Alps. The experience continuously gained led to further improvement in the interpretation reliability.

The following chapters will give a rough overview on the basic evaluation procedure as well as on the different main evaluation methods and their applicability with regard to specific questions. Finally, with the help of a case history from Austria the interpretation process will be shown using a combination of different methods.

2 EVALUATION PROCEDURE

Depending on the expected ground characteristics and boundary conditions different levels of sophistication of measurement data evaluation will be applied. In relatively good and homogeneous rock mass, where small displacements are expected, the routine evaluation will be in the form of time displacement plots. Those are used to check if the actual behaviour is within the expected range.

In cases of complex or weak rock mass conditions, where higher displacements are expected, and/or restrictions in displacements due to the presence of buildings or other infrastructure have to be observed, more advanced evaluation procedures will be required.

A typical daily evaluation procedure during the tunnel excavation consists of two main categories:

- The evaluation and assessment of the tunnel stabilization process, and
- the interpretation of the displacement results with regard to the prediction of the geological-geotechnical conditions ahead and outside the tunnel profile.

2.1 *Assessment of the stabilization process*

The interpretation of the time-displacement curve for one displacement component, mainly the settlements for the crown and sidewall points as well as the transversal component of the sidewall points, is the most significant evaluation method for this purpose. The condition for a satisfying stabilization, respectively the stress redistribution is a steadily decreasing displacement rate, in case of homogeneous rock mass conditions and continuous advance rate. When the rock mass is heterogeneous or the advance rate not constant, the time displacement plot only does not provide conclusive evidence of the stabilization process. Schubert et al. (2002) exemplarily illustrated the influence of varying excavation progress rates on the development of the settlements versus time. For the examples the formula for the time dependent closure of tunnels, developed by Guenot et al. (1985) and Sulem et al. (1987) was used.

This method is based on analytical functions that describe displacements in a plane perpendicular to the tunnel axis as a function of advancing face and time. 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 and m) are used to simulate the time dependency and another two parameters (X and C) the face advance effect. These parameters can be back-calculated from case histories using curve fitting techniques.

The system of these analytical functions was implemented in the program package called GeoFit® (Sellner 2000, GeoFit 2001). It provides easy-to-use tools for back-calculating displacement monitoring data by curve fitting and for the prediction of displacements. Both monitored and predicted results are shown and can be compared at any time. This procedure allows predicting displacements for any time and point of the tunnel wall as well as the ground surface considering different construction stages and supports.

With some experience appropriate function parameters (X, T, C and m) can be reliably determined. Grossauer et al. (2003 & 2005) described a method using the development of typical displacement trends and the function parameters along the tunnel axis to extrapolate a parameter set for newly installed monitoring sections. Thus the expected "normal" displacement development in relation to time, progress, construction sequence and support can be predicted after only a few readings. The continuous comparison of the actually measured and the predicted data allows an easy identification of any deviation of the actual from the predicted behaviour. With this information additional investigations can be performed to clarify the reasons for the deviation and/or appropriate countermeasures taken in time.

The following case histories from two tunnel projects in Austria should exemplify the assessment of the stabilization process by means of time displacement plots. The geological settings as well as supplementary information for the case histories can be found in Sellner & Grossauer (2002).

The upper part of Figure 1 shows the development of the settlements versus time for the upper left sidewall monitoring point at a certain cross section in the top heading. Both, monitored displacements (zero reading and two subsequent readings - displayed as black circles) and predicted displacements (grey lines) are displayed. The dark-grey dashed line represents the expected displacement development over time for the top heading excavation, while the light-grey dashed line corresponds to the predicted displacements considering an additional support in the form of a temporary top heading invert. The predicted displacements have been established using the analytical functions described above (Sellner 2000). The lower part of this figure shows the associated construction phase, e.g. the progress of the top heading (dark-grey line) and the subsequent temporary top heading invert installation (light-grey line). The solid lines represent the already accomplished part of the respective construction phases while the dashed lines the scheduled ones.

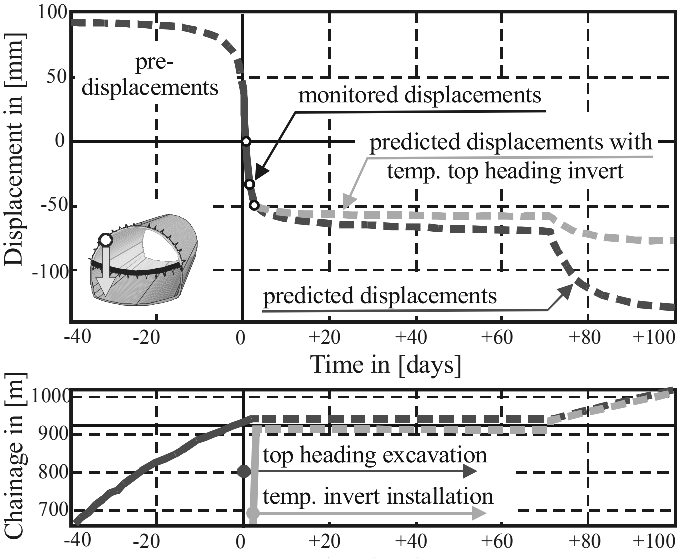

Figure 1. Displacement history plot for settlements of the upper left sidewall point; comparison of the actually monitored displacements (circles) and predicted displacements (dark-grey and light-grey dashed lines) – associated construction phase diagram.

The excavation has been stopped approximately two days after the installation of the measuring section for operational reasons. The settlement reached about 30mm one day after installation of the target, and about 50mm after two days, when the excavation was stopped. These two readings were used to predict the displacement development (dark-grey dashed line). As the prediction showed rather high displacements after the planned restart of the top heading excavation 50 days after the stop (approximately 140 mm total), a temporary shotcrete invert was installed in the top heading. The predicted displacement with the temporary invert is represented as light-grey dashed line in Figure 1. During the period of the bench excavation far behind the monitoring section no construction activities were planned in the vicinity of the top heading face. Therefore only a slight increase in the settlements for the observed point due to creep of rock mass and support was predicted. The additional displacements after restart of the top heading were predicted with approximately 20mm, reducing the total displacements from 140mm to about 80 mm.

Figure 2 shows the comparison of both, the actually observed settlements and the predicted ones. The predicted displacement history coincides quite well with the finally observed curve even with the unsteady excavation rate including a construction stop over a period of approx. 50 days and the excavation restart and further progress.

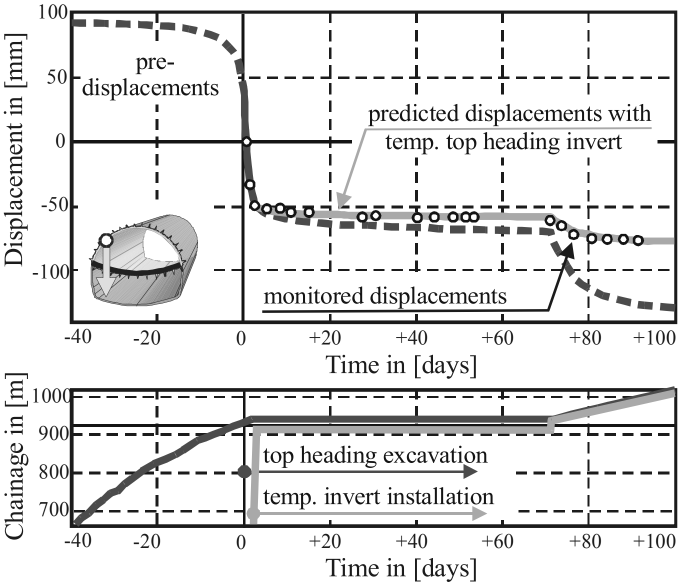

Figure 2. Comparison of actually observed settlements (circles) and the predicted settlements (grey lines).

Figure 3 shows a similar situation as described above on a different tunnel site. Displayed is the development of both, the measured and predicted settlements versus time for the crown point. The predicted displacement curves are shown for the influence of top heading excavation (dark-grey dashed line) as well as the effect of the temporary top heading invert (light-grey solid line). Analogue to the prior example, the top heading excavation was stopped 2 days after the monitoring section has been installed and restarted after a period of about 20 days. The installation of the temporary top heading invert was done close to the face and alternately to the top heading excavation. The development of the settlements shows a similar characteristic as the prior example but lower displacement values. In the first two days the settlements reached about 20mm, followed by slight increase during the stop. The restart of the top heading excavation caused a pronounced increase in the crown settlements up to approx. 40mm in total. With increasingly distance between the monitoring section and the face, a decreasing displacement rate indicated a satisfying stabilization. Up to this point, no significant deviation of the monitored settlements from the predicted normal displacement development can be identified. A sudden increase of about 10mm (marked with the dashed ellipse) occurred approximately 32 days after the zero reading, clearly indicating an abnormal system behaviour calling for an investigation of this situation and, if necessary the implementation of countermeasures to guarantee the tunnel stability.

The shotcrete had settled during the stop and lost its ductility, thus behaving relatively brittle also close to the face. As no visual damage of the lining of the crown could be identified, the reason for the increase of displacements could either be a failure of the temporary invert or a failure in the surrounding rock mass. To be able to judge the stability of the system, two scenarios were considered. In the first case - failure of temporary invert - it could be expected, that the displacement development would follow the predicted one for the case with no temporary invert installed (dark-grey dashed line in Figure 3). In the case of a failure in the rock mass it could be expected, that the displacements would exceed those of the system without temporary invert. This situation might be classified as critical and additional remedial measures would have to be taken.

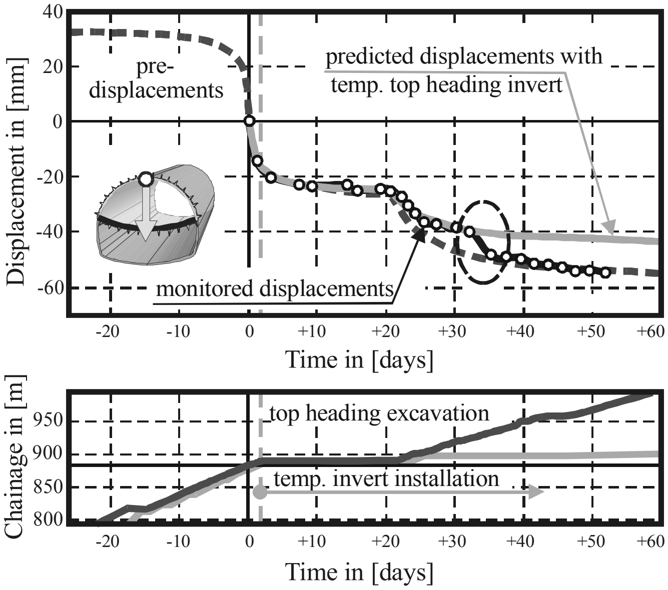

Figure 3. Displacement history plot for settlements of the crown point; comparison of the actually monitored displacements (circles) and predicted displacements (dark-grey dashed line and light-grey solid line) – associated construction phase diagram.

As shown in Figure 3, the measured displacements followed the predicted path for the case without temporary invert, indicating that the temporary invert had failed. In this case, the prediction of the displacement development with and without the consideration of the temporary top heading invert provided a valuable assistance in the judgment of the unexpected situation.

Both case histories have shown that the definition of the expected normal behaviour is one of the crucial issues assessing the tunnel stabilization process.

2.2 *Interpretation of displacement monitoring data in combination with the geological-geotechnical conditions*

A tunnel excavation in homogeneous and isotopic rock mass with uniform primary stress conditions will cause a more or less symmetric displacement pattern in the profile, as well as a certain and regular characteristic development in the longitudinal direction. Any changes in the rock mass structure or in the primary stress state influence the stress distribution around the tunnel and ahead of the face, which again result in a change in the displacement pattern.

Figure 4 shows the monitored displacement characteristic for the top heading excavation as vector plot in a plane perpendicular and parallel to the tunnel axis of a tunnel in Austria, which has been excavated in Flysch, consisting mainly of a series of clay- and siltstones. The relevant geological structure in terms of displacements is the bedding, dipping steeply in excavation direction and striking almost perpendicular to the tunnel axis. The displacement pattern can be described as symmetrical in the cross section with slightly increased displacements on the left side. The plot in longitudinal direction shows displacement vectors tending against the excavation direction with a curved path after the first few readings.

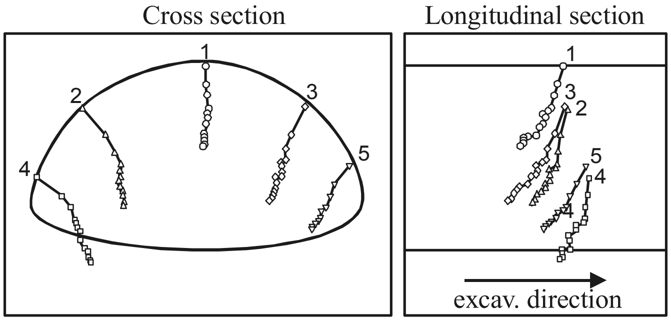

Figure 4. Observed displacement vector plot in cross sections both perpendicular (left) and parallel to the tunnel axis; situation characterized as Flysch with a main structure nearly dipping vertical and striking nearly perpendicular to the tunnel axis from right to the left in an angle of approx. 80°.

Numerical simulations using Flac 3D with a ubiquitous joint model have shown that the influence of a vertically dipping and perpendicularly striking foliation results in a displacement characteristic more or less identical to the situation described above. Figure 5 shows the related displacement vectors in a cross- and longitudinal section. Additional cases with various anisotropy orientation settings have been investigated and the results compared to observed displacement data on site. Considering the site specific and displacement relevant geological structures, the actually observed and the simulated displacement characteristics showed a clear correlation. Goricki et al. (2005) and Button et al. (2006) show a couple of displacement plots for sites constructed in Austria with regard to the anisotropy orientation and compare the plots with different synthetic examples from numerical simulations.

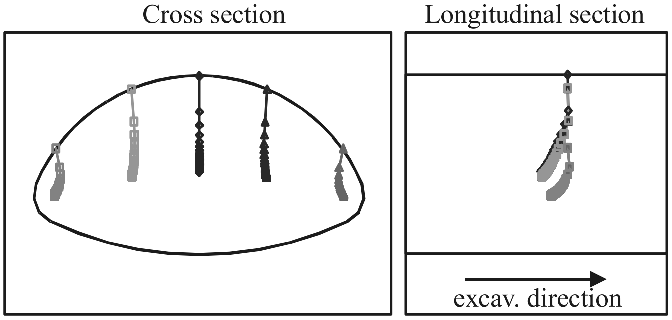

Figure 5. Displacement vector plot gained from 3D numerical investigations using a ubiquitous joint model; joint orientation dipping vertical and striking perpendicular to the tunnel axis.

Using the knowledge about the influence of the anisotropy orientation on the displacement development, the geological structure encountered on site can be used to predict the expected spatial displacement vector orientation. Any significant deviation from this normal behaviour will thus reflect an abnormal behaviour. In case the reason for the abnormality does not originate from a failed support system, the type of deviation can be used to predict changes in the rock mass condition ahead of the tunnel. The evaluation of data gained from the excavation of tunnels constructed in Austria showed, that the ratio between radial and longitudinal displacement varied in a wide range. Matching the observed phenomena with the geological documentation, it was found that deviations of the ratio appeared when zones of different deformability were approached with the excavation (Schubert 1993). To verify the hypothesis, numerical 3D simulations have been performed. The results showed that changing rock mass conditions ahead of the tunnel face clearly influence the displacement vector orientation (Steindorfer 1998). To quantify the influence of weak zones on stresses and displacements, further research has been conducted by Grossauer (2001) and later on by Jeon (2005). The amount of the deviation depends on the stiffness contrast between the rock masses and also on the width of the fault zone. The deviation increases with increasing fault zone length up to a certain critical length, above which no further increase of the vector orientation can be observed. This critical zone length is in between 2.5 and 4 tunnel diameters, as shown in Figure 6 for 3 different stiffness contrasts.

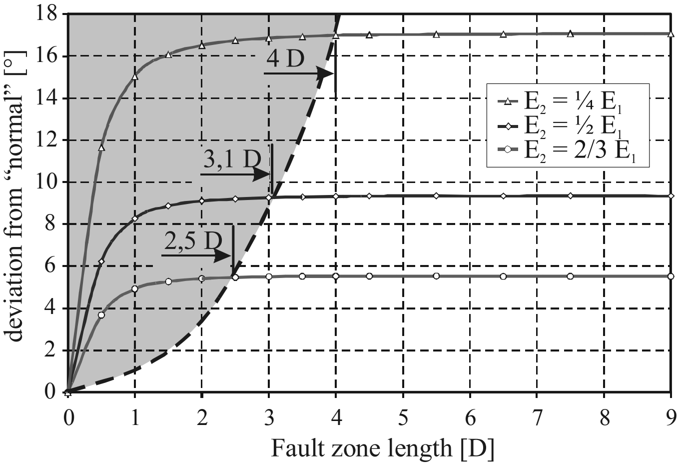

Figure 6. Deviation of the displacement vector orientation from 'normal' at the transition from intact rock mass to the fault zone, depending on the stiffness contrast and the width of the fault zone.

Research activities performed during the past decade with regard to the determination of the influence of specific geological features on the displacement behaviour of tunnels have significantly improved the displacement monitoring data evaluation capabilities on site.

3 EVALUATION METHODS

The following chapter shows a set of different evaluation methods chosen for the geotechnical interpretation with regard to the geological conditions.

3.1 *Value of evaluation methods*

Before interpreting the particular displacement curves, the applicability and information capability of the single evaluation methods have to be considered. Vavrovsky & Schubert (1994) have given an overview of the geomechanical relevance of some monitored parameters. Schubert et al. (2002) summarized the different displacement monitoring data evaluation methods and rated their value with regard to specific questions. Table 1 shows a brief and preliminary listing of the applicability of the single evaluation and display methods and the appropriate information values. It has to be pointed out, that usually a combination of evaluation methods is required to obtain a clear understanding of the geotechnical situation and the rock mass and tunnel behaviour. The achievable accuracy using trigonometric measurements for the determination of the displacements of targets mounted on the tunnel wall under the consideration of an acceptable effort is in a range of about +/- 1mm. This takes into account numerous possible sources of error and the extremely dynamic environment during tunnelling. Several evaluation methods are based on the ratios of displacement components, e.g. the ratio between longitudinal displacements and settlements. For situations with monitored displacements of less than 1cm, an error of +/- 1mm will lead to a considerable variation in vector orientations and thus might lead to misinterpretations.

3.2 *Combination of different evaluation methods*

To obtain a complete picture of the mechanisms occurring around a tunnel, in general different methods of monitoring data evaluation have to be used.

Figure 7 shows a set of evaluation methods in combination with the simplified geological situation for a 200m long section of the Inntal tunnel, Austria. The overall rock mass in this area can be described as a fault zone consisting of Quartz Phyllite, intensely sheared in different degrees. The hatching indicates the intensity of faulting. Narrow hatching signifies intense faulting. Polygons are used to indicate zones with block-in matrix-rocks.

The interpretation of the displacement characteristic of the 200m long area has been done using the following evaluation methods:

- Deflection curve diagram for the settlements of the crown point,
- trend line of the displacement vector orientation (H/S for the crown point, L/S for both, the crown and left sidewall point), and
- trend line of the displacement ratios calculated for the horizontal, as well as the vertical displacements.

H/S … ratio of horizontal displacements and settlements, expressed as an angle in degrees - reflects the deviation of the displacement vector from the vertical direction in a vertical plane perpendicular to the tunnel axis.

L/S … ratio of longitudinal displacements and settlements, expressed as an angle in degrees - reflects the deviation of the displacement vector from the vertical direction in a vertical plane parallel to the tunnel axis.

All trend lines have been generated in a distance of 12m behind the top heading face. The displacement ratios have been evaluated for the horizontal displacements of the left and right sidewall point. The last diagram shows the displacement ratio evaluated for the settlements of the crown and left sidewall point.

In the case of the horizontal displacements (diagram E), a ratio of 1 denotes equal horizontal displacement magnitudes on both measuring points. Positive values higher than 1 signify that the horizontal displacements of point 2 (left sidewall point) are larger

Table 1. Overview of the value of evaluation methods for specific questions (Schubert et al 2002): + = good; o = limited; - = no value.

	Evaluation of stabilisation process	Prediction of final displacements	Stress redistribution longitudinal	Detection of stiffness contrasts outside the profile, kinematics	Prediction of geological conditions ahead	Estimation of stress intensity in the lining
Displacement history	+	+	-	o	-	+
Deflection lines, trends	o	-	+	o	o	-
Trends of relative displacement values	-	-	-	+	-	-
Vectors in cross section	-	-	-	+	-	+
Vectors in longitudinal section	-	-	-	o	+	-
Spatial vector orientation	-	-	+	+	+	-

than the one of point 3 (right sidewall point). Negative values stand for the case of lager horizontal displacements of point 3 than point 2. In the case of the vertical displacements ratios (diagram F in Figure 7), positive values indicate larger crown settlements than sidewall settlements. The plotted values show the ratio of displacements between the two points.

The settlements evaluated for the crown point (deflection curves, diagram A) show magnitudes ranging from 20cm up to maximum 50cm. On the average the vertical displacement in the section shown are around 35cm. Starting the displacement interpretation from the left hand side, a pronounced deviation of the trend lines from a normal range can be observed in the displacement ratio diagrams E and F. The normal range is indicated in both diagrams by the hatched area.

In diagram E, the horizontal displacement ratio of the left and right sidewall point shows relatively high displacements at the right sidewall at tunnel chainage 4040. A quasi identical trend development can be observed for the settlement ratio of the crown and left sidewall point (diagram F). Both displacements ratio trends reflect an asymmetric displacement pattern, with larger displacements at the right sidewall. This characteristic can also be observed in the trend development of the crown vector orientation H/S (diagram B). From a more or less vertical orientation, the vector increasingly points to the left, reaching a value of about 5°. The vector orientation L/S of the left sidewall point (diagram C) also shows a clear deviation from the normal range. The vector orientation increasingly tends against the excavation direction, indicating weaker rock mass ahead (Schubert & Steindorfer 1996, Steindorfer 1998). The moderately dipping fault above the crown, which crosses the tunnel axis in an acute angle influences the stress distribution due to the tunnel excavation. The result is a stress concentration at the right sidewall and the crown of the tunnel, leading to increased displacements. The "abnormal" displacement characteristic in the section between 4020m to 4040m clearly indicates a weak zone outside the visible tunnel profile; the fault is visible in the tunnel profile only at around station 4060m. The value of observing displacement ratio trends is obvious, as it shows also the effect of non-visible geological features, allowing a timely adjustment of excavation and support. It is interesting to note that although weaker ground is ahead of the face, the vector orientation trend L/S for the crown (diagram C) remains within the normal orientation of about 5° against the excavation direction, while usually a larger deviation would be expected (Golser & Steindorfer 2000, Grossauer 2001, Steindorfer 1998). In contrast to steeply dipping faults, smoothly inclined faults dipping in the direction of excavation do not result in a significant change in the displacement vector orientation in the crown. A slight trend deviation in the vector L/S (diagram C) can be observed at approx. 4070m. The reasons for this vector deviation tending against the excavation direction, is probably caused by the relative weak rock mass at chainage 4095, embedded between the 2 intensely faulted zones. Crown settlements monitored at this section show magnitudes of 50cm.

The next relevant deviations of trends from the normal range can be observed in diagram E at chainage approx. 4090 as well as 4120. Both trends indicate larger horizontal displacements of the left sidewall than the right and are caused by weaker material on the left side. At the end of the section displayed here, similar trends as discussed in the beginning can be observed in diagrams E and F, which indicate another weak zone in a similar orientation as that one crossing the tunnel at 4060m.

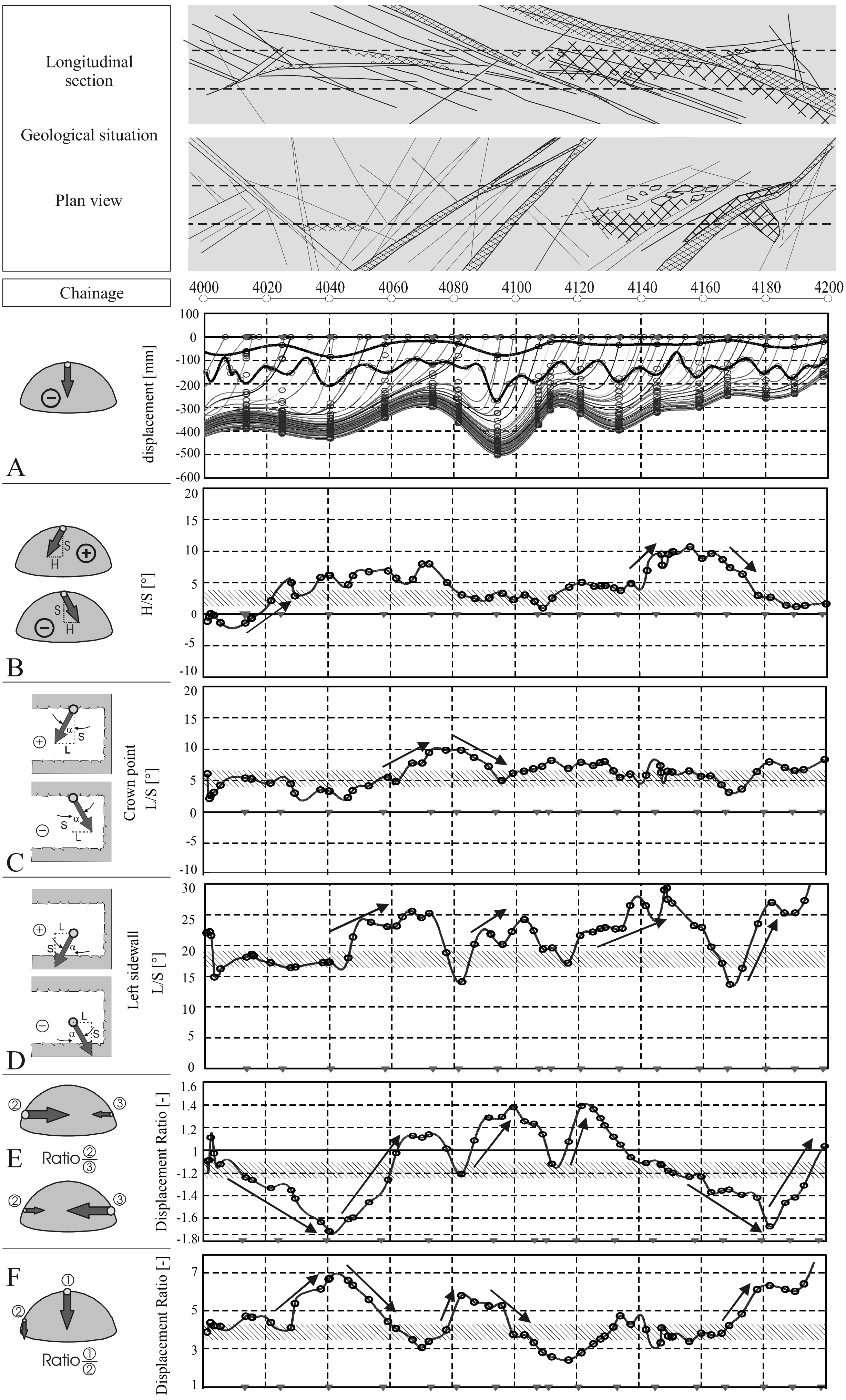

Figure 7. Development of different trend lines evaluated for a 200m section of the Inntal-tunnel - associated geological situation.

4 CONCLUSION

The most common way to assess the tunnel stability is by evaluating time-displacement plots. However, the value of information of this evaluation is limited, as the face advance plays a major role in the displacement development. Tools for the prediction of displacements with respect to tunnel advance and time have been developed. Once a "normal" behaviour is predicted, the observed displacements can be compared to the predicted ones, and deviations identified, and appropriate measures taken.

In particular in complex rock mass conditions, the evaluation of displacement histories is not sufficient to allow a timely reaction to the changing ground conditions. To be able to observe the influence of geological features outside of the tunnel profile, trends of displacements and trends of ratios of different displacement components can be used. In this way, the geotechnical conditions ahead of the face and outside the visible area in the tunnel can be predicted.

The daily interpretation of a huge number of diagrams requires extensive experience and profound understanding of rock mechanics. A research program is currently undertaken on the Institute for Rock Mechanics and Tunnelling at the Graz University of Technology with the aim to establish an expert system, which evaluates the different trends and provides an interpretation automatically. This tool combined with the monitoring data evaluation software will ease the day to day work of geotechnical engineers on site, and make tunnelling in complex geological conditions less risky.

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