The Importance of Displacement Prediction

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ABSTRACT: Tunnel construction in faulted and/or heterogeneous rock mass is in general associated with stability problems, high deformations and frequently changing stress conditions. Depending on the encountered conditions, different strategies for excavation and support of the tunnel must be applied. The decisions on site thereby are widely influenced by the magnitude and development of the tunnel displacements.

To allow for a reliable and relatively accurate prediction of displacements, the program GeoFit® was developed. GeoFit® is based on analytical functions which simulate the face advance effect and the time-dependent behaviour of the rock mass and support. Several parameters are used to describe the complex system behaviour. The program allows considering several options, including the installation of supports, sequential excavation, and non-steady tunnel advance. It provides several options of displaying measured and predicted data, thus allowing a continuous control of the “normality” of the displacements, and reacting in time in case the measured values deviate from the predicted ones. In addition the follow-up of trends of function parameters and displacements enables for short term prediction of the geological condition ahead of the face. This again increases the quality of decisions on site, increases safety and economic efficiency, and reduces the uncertainties.

The paper will show some basic principles of the displacement prediction and methods of data evaluation. Selected case histories will be used to illustrate the evaluation techniques and the benefit gained from these methods.

1 INTRODUCTION

The prediction of the magnitude and development of the expected displacements has a considerable impact on a large number of issues during tunnel construction.

On the one hand, excavation and support methods are influenced by the magnitude of displacements. On the other hand, the over-excavation has to be adjusted to the expected displacements to guarantee the clearance after stabilisation. In case of a misjudgement of displacements serious consequences have to be expected.

When underestimating the displacements, the danger of destruction of the lining exists by exceeding the deformability. Figure 1 illustrates such a case where shearing of the shotcrete occurred at the right side wall. In addition displacements in excess of the anticipated ones may lead to the necessity of reshaping, a process which in general costs as much as the original excavation and support.

In case of overestimation of displacements the remaining volume between primary lining and planned inner lining has to be filled with concrete. This also causes additional costs.

To allow for a safe and economic construction, the accurate prediction of displacements and conditions ahead of the face is essential.

Figure 1. Damaged lining after excessive displacements and exceeded deformability of the shotcrete.

2 ADVANCED EVALUATION OF DISPLACEMENT MONITORING DATA

Prediction of rock mass behaviour, in particular when tunnelling under high overburden is a most challenging task, during design as well as during construction. Heterogeneous rock mass conditions significantly increase the difficulties in prediction of the tunnel performance.

Although the general geological situation may be known, changes of rock mass stiffness or structure ahead of the face, to a great extent influencing stresses in the vicinity of the tunnel and thus deformations, generally cannot be determined with sufficient accuracy. Exploration by drilling ahead or questionable results from geophysical methods are time consuming and costly.

The introduction of absolute displacement monitoring during tunnel excavation by geodetic methods to a large extent has replaced relative displacement measurements (Rabensteiner 1996). The resulting increase in the amount of available information has led to additional possibilities in data visualisation. Plots of deflection curves, trend lines along the tunnel axis and displacement histories have become common practice in many countries. The improved tools have led to a better understanding of geomechanical processes during tunnel excavation, and valuably assist the geotechnical engineer on site in his daily work.

2.1 *Qualitative evaluation of the displacement vector orientation*

During the excavation of the Inntaltunnel Schubert (1993) observed that the ratio between longitudinal and radial displacements (L/S) considerably changes when the face approaches a zone of different stiffness. Using data from absolute displacement monitoring from different sites, Budil (Budil 1996, Schubert & Budil 1995) studied the phenomenon of longitudinal displacements. He found a relation between displacement vector orientation and rock mass heterogeneity. This work was continued by Steindorfer (Steindorfer 1998, Steindorfer & Schubert 1997), who in detail analysed the development of stresses and displacements in heterogeneous ground during tunnel excavation.

When tunnelling in homogeneous rock mass and primary stress conditions, the vector orientation (ratio between longitudinal displacements and settlements - L/S) shows a certain value which can be considered as “normal”. With different deformability of the ground, the absolute displacement values change but the ratios of the single components do not vary substantially. Different boundary conditions, like changes in the rock mass structure or in the primary stress situation, influence the stress distribution around the cross section of the tunnel as well as ahead of the face, which leads to deviations of the vector orientation from “normal”. When the excavation approaches a section consisting of "stiff" rock mass the vector orientation drops below "normal", which means an increasing trend of the vector orientation in the direction of excavation.

The opposite tendency can be observed when the face approaches a section consisting of "soft" rock. The vector orientation shows an increasing trend against the direction of excavation. A certain prediction of the extension of a fault zone is possible with the help of vector orientation trends.

Figure 2 illustrates the results from numerical simulations for tunnelling through rock mass with frequently changing stiffness. When the excavation approaches "stiff" rock (section 2) the vectors tends to point in the direction of excavation. Shortly after the excavation enters the "stiff" rock, the vector orientation shows an opposite tendency, which means an increasing trend against the direction of excavation. With further advance of the face into the relatively "stiff" section, the vector orientation does not normalise, but rather continues its increasing trend against the direction of the excavation. This deformation pattern indicates that rock mass conditions ahead of the face will change within one or two diameters and "soft" rock will be encountered.

After the face enters section 3 which consists of "soft" rock mass, the vector orientation tends back to "normal". When excavating in section 3 the vector orientation remains "normal", which is an indication that "soft" rock mass is ahead of the face for at least two or three diameters.

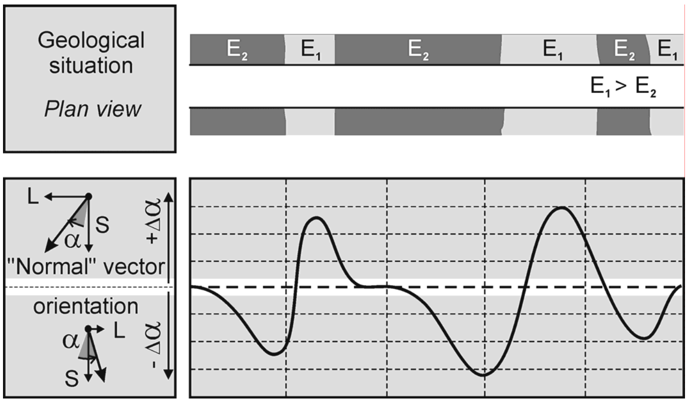


Figure 2. Variation in the vector orientation when tunnelling through rock mass with frequently changing stiffness.

The practical value of this information is obvious. When tunnelling through a rock mass with frequently changing stiffness at short distances, stresses will concentrate in the "stiff" sections. When these sections of "stiff" rock are comparatively narrow, they may become overloaded and already fail in the vicinity of the face or at some distance from the face. This again leads to a redistribution of loads to the previously "weaker" rock. This process may continue for a while, and in many cases is interpreted as creeping.

2.2 *Quantitative evaluation of the displacement vector orientation*

To quantify the influence of weak zones on stresses and displacements, further investigations with numerical simulations have been conducted by Grossauer (2001).

Figure 3 shows the deviation of the displacement vector orientation from “normal”, obtained from numerical 3D model for different stiffness contrasts between the fault zone and the adjacent rock mass. The amount of the deviation does not only depend on the stiffness contrast between the rock masses, but also on the width of the embedded zone. Figure 4 illustrates the increasing deviation with increasing fault zone length up to a certain critical length, beyond this no further increase of the vector orientation can be observed. This critical zone length was determined to be in between 2.5 and 4 tunnel diameters.

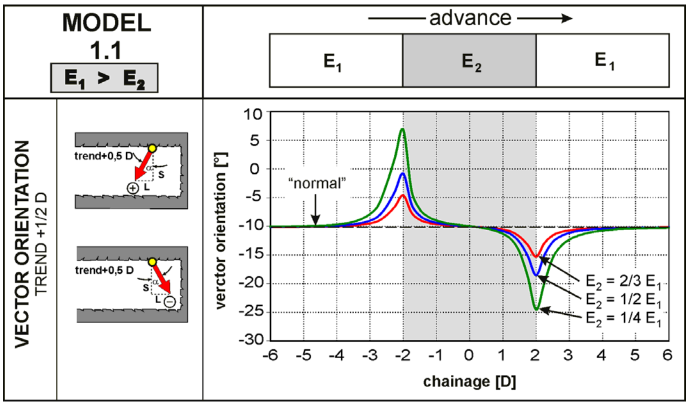


Figure 3. Deviation of the displacement vector orientation from “normal” for different stiffness contrasts.

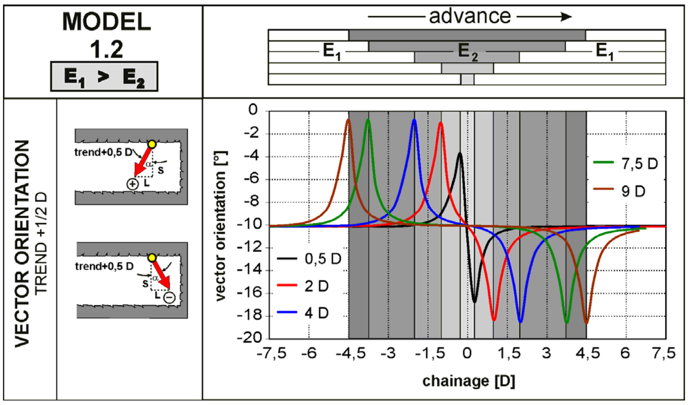


Figure 4. Deviation of the displacement vector orientation from “normal” for a certain stiffness contrasts and different fault zone widths.

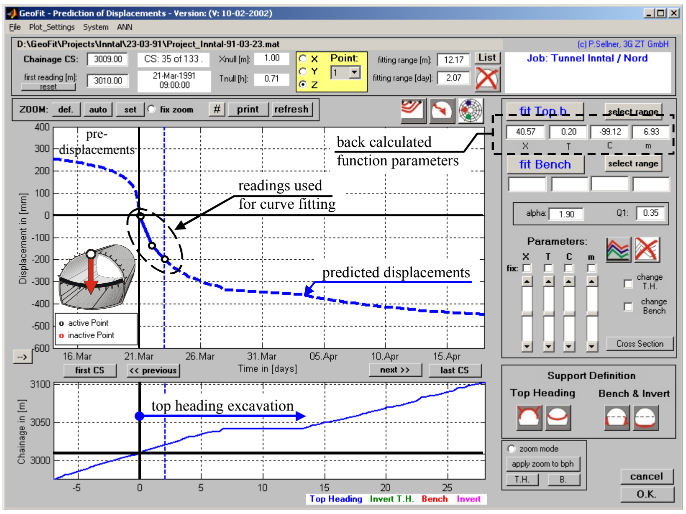
3 PREDICTION OF DISPLACEMENTS

Guenot et al. (1985) and Sulem et al. (1987) proposed a method based on analytical functions that describe displacements in a plane perpendicular to the tunnel axis 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 another two parameters (X, C) the face advance effect. These parameters can be back-calculated from case histories using curve fitting techniques. Artificial intelligence (neuronal networks) is planed to be involved to identify dependencies between the function parameters and the geological and geotechnical conditions encountered.

The system of these analytical functions was implemented in the program package called GeoFit® (Sellner 2000). It provides easy-to-use tools for back-calculating displacement monitoring data (curve fitting technique), for prediction of displacements and for handling the expert system. The application is acting interactively. Each change in the calculation assumptions is displayed on the screen immediately. Both monitored and predicted results are shown. This procedure allows to predict displacements for any time and point of the tunnel wall as well as the ground surface considering different construction stages and supports. Trend lines, deflection lines, displacement plots and spatial displacement vector orientations can be evaluated and displayed on the basis of monitored, calculated and predicted data, allowing a continuous comparison of the actually measured and predicted data.

3.1 *Prediction methods*

Basically, there are two possibilities for predicting displacements. The first, a very simple but accurate method is to predict final displacements after a few displacement readings at a given cross section. The rock mass behaviour is determined form previously excavated sections in combination with the short-term prediction gained from the evaluation of the monitoring data (Steindorfer 1998). By fitting the analytical displacement function to the measured displacements, a prediction for the future displacement development is possible. Figure 5 shows a displacement history plot for the crown settlement at the Inntaltunnel (cross section 3009). The readings of the first two days after the zero reading are used to back calculate the function parameters (X, T, C, m). The obtained function parameters represent the displacement behaviour of the observed section and the displacements can be calculated for any desired excavation advance. The dashed line shows the displacement prediction for this cross section. This method is called the “Extrapolating Prediction Method” (EPM). The accuracy of the prediction increases with the number of available displacement readings at the observed cross section.



GeoFit - Prediction of Displacements - Version: (V: 10-02-2002)

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Job: Tunnel Inntal / Nord

Chainage CS: 3009.00

CS: 35 of 133 .

first reading [m]: 3010.00

21-Mar-1991 09:00:00

Xnull [m]: 1.00

Tnull [h]: 0.71

Point: 1 ○ X ○ Y ● Z

fitting range [m]: 12.17

fitting range [day]: 2.07

X: 40.57 T: 0.20 C: -99.12 m: 6.93

alpha: 1.90 Q1: 0.35

Figure 5. Back calculation of the function parameters using the readings of the first 2 days and prediction of displacements.

The second method is used for sections ahead of the face, when no readings are available yet. The information required for the determination of the rock mass behaviour and support influence is gained from a database, which stores knowledge from back-calculated case histories. Information describing the geological and geotechnical conditions for the specific section is gained by modelling ahead, using the predicted geological conditions, as well as extrapolations of the observed behaviour on previous sections. Easy-to-obtain parameters such as overburden, joint parameters, RMR and weathering conditions are used as input parameters for the artificial neural network, which calculates the function's parameters and thus displacements. This method is called the "Pure Prediction Method" (PPM).

3.2 *EPM versus PPM*

While the latter method, the PPM, requires a database of back-calculated values to predict the function parameters, the first method, the EPM, only needs some a few displacement readings and information of the previously excavated tunnel sections. The EPM has been tested on several sites and shows a high accuracy and reliability. The prediction procedure is simple and quick and supports the site engineer in his daily work.

3.3 *Function parameters for prediction*

Following the ideas of the influence of the changing stress field in a heterogeneous rock mass on the displacements, it is obvious that the trends of the function parameters X, T, C, and m should reflect the geotechnical situation, and thus could be used for prediction. The results of numerical models with elastic rock mass behaviour were imported into GeoFit® and the function parameters obtained by curve fitting (Kim 2003). The back calculated function parameters X and C for a fault zone width of one tunnel diameter and a stiffness contrast of 2.0 between the two rock masses showed that the parameter X significantly increases already 15 m ahead of the transition between stiff and weak rock. The investigation of different fault zone widths showed larger increase of the parameter X for with increasing widths. Besides this increase of X well ahead of the weak zone, the results clearly show the influence of the fault zone length on the final displacements within the weak zone, which are reflected through the parameter C. With some experience in this kind of monitoring data evaluation, the combination of displacement vector orientation trends and distributions of function parameter trends can be used to predict quality and extension of weak zones ahead of the tunnel face, as well as the magnitude and development of the displacements.

4 CASE HISTORIES

During the last few years advanced methods were used on many tunnel sites to support the geotechnical engineer in the ongoing evaluation of the displacement monitoring data and to assist him in the interpretation of geotechnical situations and consequently in the decision making process.

To illustrate the evaluation techniques and the benefit gained from the methods explained in this paper, examples of two selected case histories will be shown.

4.1 *Inntaltunnel, Austria*

The 12.7 km long, double track railway tunnel bypasses the city of Innsbruck. During the excavation of the north heading with an overburden of approx. 300 to 350 m, a major fault zone was encountered.

The following figures (Figure 6 & Figure 7) will show the advantages of advanced monitoring data evaluation for chainage 3060 m up to 3200 m and the left sidewall point.

From chainage 3100 to 3135 the settlements dropped to about 5 to 10 mm. In contrast the trend of the vector orientation 20 m behind the face showed a significant increase against direction of excavation, indicating a zone of weakness outside the excavation area.

Shortly before the excavation entered the major fault zone, the settlements showed a slight increase, which did not provide a clear indication of changing rock mass conditions ahead of the face as the variation was within the usual range (Figure 7).

After the face entered the fault zone at chainage 3170, the vector orientation dropped to about 10° against direction of excavation which could be considered to be "normal" behaviour while settlements increased considerably due to the "soft" fault material.

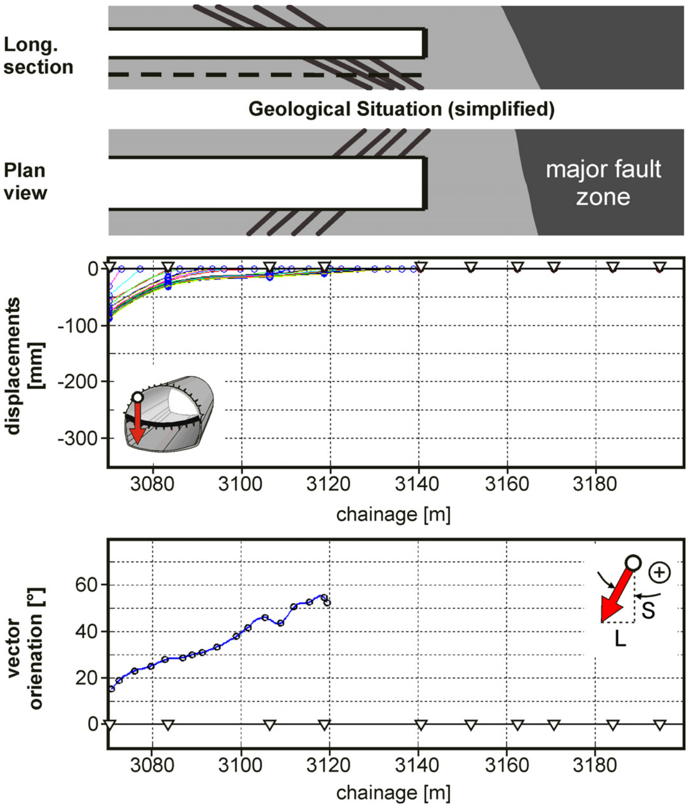


Figure 6. Development of settlement and displacement vector orientation trend (L/S), face position at chainage 3140 m.

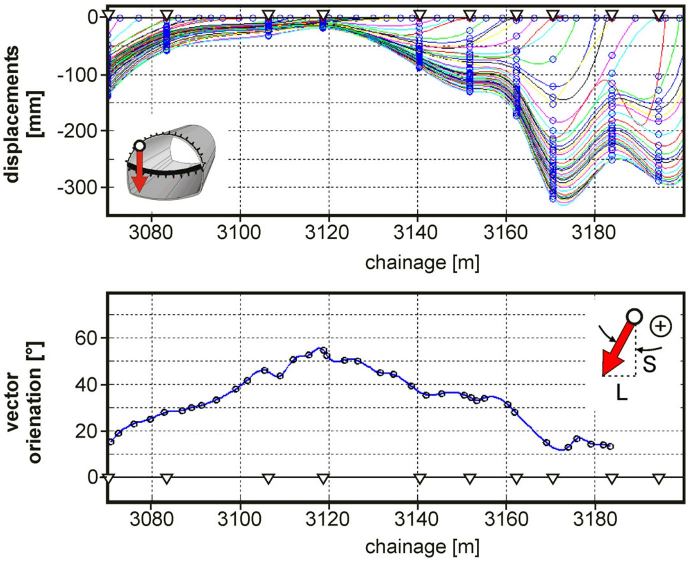


Figure 7. Settlement and displacement vector orientation (L/S) after entering the major fault zone.

4.2 *Strenger tunnel, Austria*

The Strenger tunnel, a twin tube, two lane road tunnel is located between Innsbruck and Bregenz in the western part of Austria. The geological situation is dominated by Quartzphyllite with an overburden up to 600 m. The foliation typically dips steeply to the south, which results in a strike oblique to parallel to the tunnel axis.

Figure 8 shows the development of the settlements and the trend of the vector orientation for the crown point of the south heading from the west portal, after entering a fault zone.

Similar to the case displayed above, a significant increase of the displacement vector orientation trend against direction of excavation could be observed well before the excavation entered the fault zone. In contrast, the development of the displacements don‘t show a significant increase until the fault zone was entered.

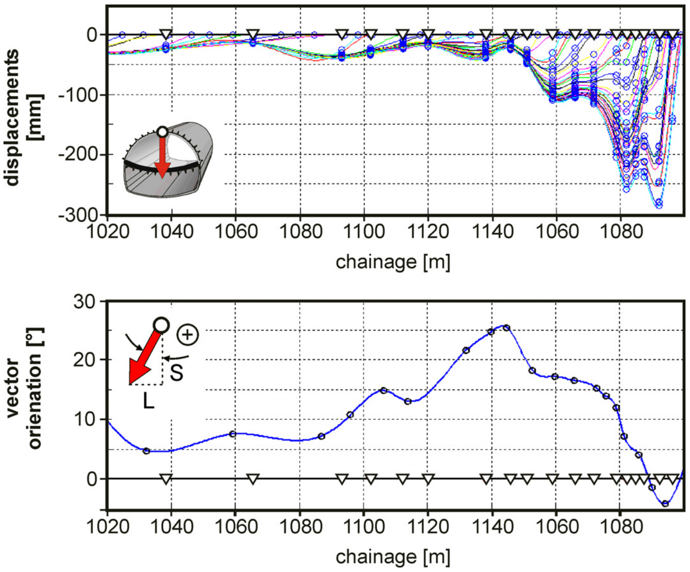


Figure 8. Settlements and displacement vector orientation trend after encountering a fault zone.

The next figure demonstrates the distribution of the four function parameters X, T, C and m back-calculated from the vertical displacements of nearly the same section described before.

Similar to the distribution of the displacement vector orientation, a significant increase in the trend of the parameter X can be observed well before the excavation encounters the fault zone at approx. chainage 1175.

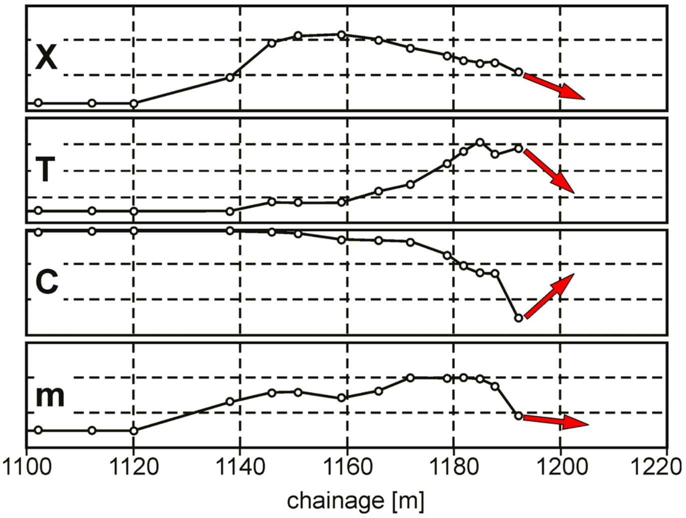
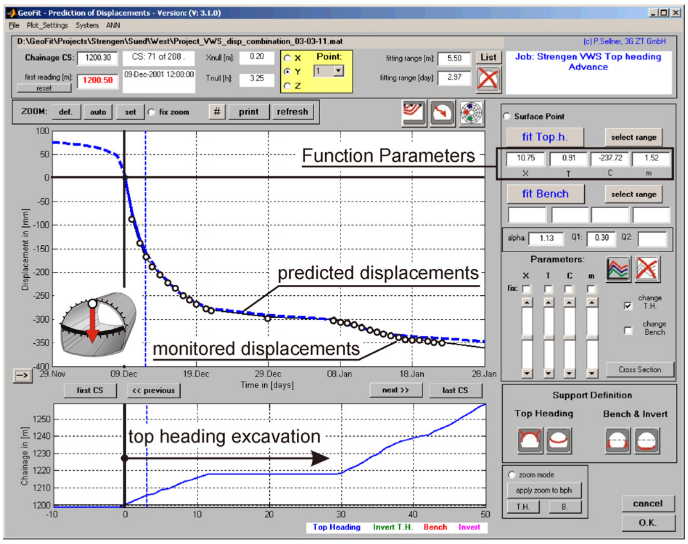


Figure 9. Distribution of the function parameter trends; extrapolation of the parameters for the next monitoring section.

Some experience in the field of the advanced evaluation of displacement monitoring data in combination with the distribution of the parameter trends allows for an extrapolation of these parameters for the next monitoring section. Figure 10 demonstrates the displacement history plot of the monitored settlements (circles) and the predicted ones (dashed line) for the crown point of cross section 1200. For the prediction of the displacements the function parameters, extrapolated from the section before, were used. After the third reading a fine adjustment of the predicted curve was made. Finally, the predicted displacements fit well to the displacements monitored on site.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D:\GeoFit\Projects\Strengen\Sued\West\Project_VWS_disp_combination_03-03-11.mat
(c) P.Sellner, 3G ZT GmbH
Chainage CS: 1200.30
CS: 71 of 208 .
first reading [m]: 1200.50
09-Dec-2001 12:00:00
Xnull [m]: 0.20
Tnull [h]: 3.25
○ X ● Y ○ Z
Point: 1
fitting range [m]: 5.50
fitting range [day]: 2.97
Job: Strengen VWS Top heading Advance
X: 10.75
T: 0.91
C: -237.72
m: 1.52
alpha: 1.13
Q1: 0.30
Q2:
fix: X ☐ T ☐ C ☐ m ☐
☑ change T.H.
☐ change Bench
○ Surface Point
○ fix zoom
○ zoom mode

Figure 10. Displacement history plot; comparison of the predicted an finally observed displacements for the crown point of cross section 1200.

5 CONCLUSION

The prediction of the geotechnical conditions ahead of the face and, especially the prediction of the expected displacements is a crucial issue for safe and economical tunnelling in faulted or heterogeneous rock mass.

Advanced methods of data evaluation have significantly improved the value of information gained from monitoring data. Experience with tunnels in Austria during the last decades has shown that the ratio between longitudinal and radial displacements can be used to identify zones of different stiffness ahead of the face. Based on analytical functions it is possible to back-calculate displacement monitoring data with curve fitting techniques and to predict displacements. The combination of displacement vector orientation trends and distributions of function parameter trends can be used to predict weak zones ahead of the tunnel face, as well as the magnitude and development of the expected displacements.

With the increasing number of projects evaluated with these methods in different geological environment and boundary conditions a knowledge base can be developed leading to a “smart” data evaluation tool.

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