ADVANCED ANALYSIS AND PREDICTION OF DISPLACEMENTS AND SYSTEM BEHAVIOUR IN TUNNELLING

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ABSTRACT

Economic and safe tunnelling requires a continuation of the detail design into the construction phase. Besides a prediction of the geological conditions ahead of the face a reliable prediction of the behaviour of the compound system of rock mass and support (system behaviour) is required. With the knowledge of the ”normal” behaviour of the system the measured displacements can be compared to the predicted values in order to detect deviations in the behaviour in time. An additional benefit of such a prediction is the determination of the required overexcavation in squeezing rock and the continuous control of the tunnel stability.

To provide a reliable and accurate procedure for prediction of displacements the program “GeoFit” was developed. It considers several options, including the installation of support, sequential excavation, and non-steady tunnel advance.

1. INTRODUCTION

Interpretation of displacement monitoring data in the past on most sites has been limited to “have a look” on displacement graphs. As shown in Rokahr et al. (2002), this visual examination of graphs has a number of shortcomings. One of the tasks of a geotechnical engineer on site is to do the final design of tunnel excavation and support on a day-to-day basis. The required decision-making is mainly supported by information from the geological documentation and the displacement monitoring data. The quality of the decision making process considerably can be improved by using advanced methods to interpret the monitored displacement data (Steindorfer 1998). To be able to continuously evaluate the stabilisation process the prediction of the “system behaviour” is required. Latter requires a special displacement prediction based on rock mass properties, stress field, installed support and excavation procedure. A recently developed procedure to predict displacements and thus system behaviour in tunnelling is shown in this paper.

2. BASICS OF GEOFIT

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 are used to simulate time dependency and another two parameters to simulate the face advance effect. These parameters can be back calculated from case histories using curve fitting techniques. Artificial intelligence (neuronal networks) may 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 one to predict displacements for any time and point of the tunnel wall as well as of 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.

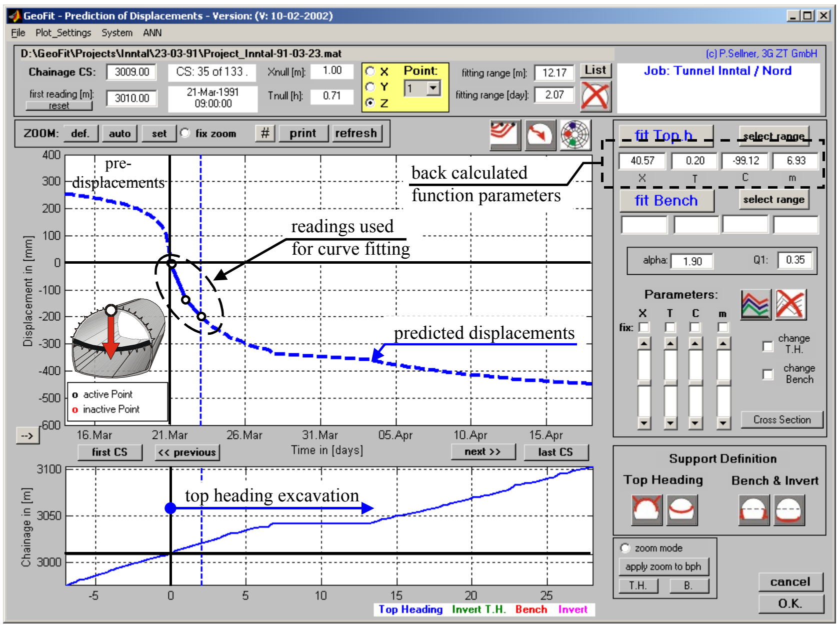
2.1 Prediction Methods

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 and from short-term prediction of rock mass behaviour (Steindorfer 1998). By fitting the analytical displacement function to the measured displacements, a prediction for the future displacement development is possible. Figure 1 shows the displacement history for the crown settlement for a tunnel in squeezing rock. 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 in figure 1 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.

The second method is used for sections ahead of the face, when no readings are available yet. The information required for 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*).

2.2 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, needs some 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. In the following section three case histories of different tunnel projects are given to show the capabilities and possibilities of GeoFit.



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

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Chainage CS: 3009.00

first reading [m]: 3010.00

CS: 35 of 133 .

21-Mar-1991 09:00:00

Xnull [m]: 1.00

Tnull [h]: 0.71

Point: 1

fitting range [m]: 12.17

fitting range [day]: 2.07

Job: Tunnel Inntal / Nord

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

alpha: 1.90

Q1: 0.35

pre-displacements

back calculated function parameters

readings used for curve fitting

predicted displacements

top heading excavation

Figure 1. Back calculation of the function parameters and displacement prediction

3. CASE HISTORIES

3.1 Railway Tunnel "Unterwald", Austria

The project area is situated within the Rannach Series, a metamorphic rock unit of Permo-mesozoic age characterised by a high content of quartz. The rock mass consists of predominating foliated quartzite and quartz-phyllite; subordinating intercalations of sericite- and chlorite-phyllite and carbonaceous phyllite. A few minor faults cross the tunnel at an obtuse angle. The alignment of this double track railway tunnel with a length of 1076 m is almost parallel to a hillslope with shallow overburden. Steel pipe umbrellas and temporary top heading invert are the main support elements in the first and last section of the tunnel. The tunnel is constructed in a top heading bench sequence according to the NATM.

Until approximately station 920 the tunnel was excavated in fractured quartz-phyllites with quite good rock mass conditions. From 922 m to 930 m a shear zone (faulted quartz-phyllites with clayey fault gouge) was encountered. The following case history shows the displacement behaviour (settlements) of a point located in the left sidewall at chainage 931 m. On October 30th the first day displacement was monitored with some 30 mm and the second day reading was approximately 50 mm. The previously excavated sections had an average first day displacement of some 15 mm. The over-excavation was defined with 150 mm for this section and the displacement prediction showed, that final displacements due to top heading excavation only would be in the range of 140 mm without any additional measures (see figure 2) which seemed to be to much to meet clearance restrictions. Thus the influence of additional rock bolting and installation of a temporary top heading invert was investigated to meet displacement restrictions. Figure 3 shows the displacement prediction for the top heading using these additional supports.

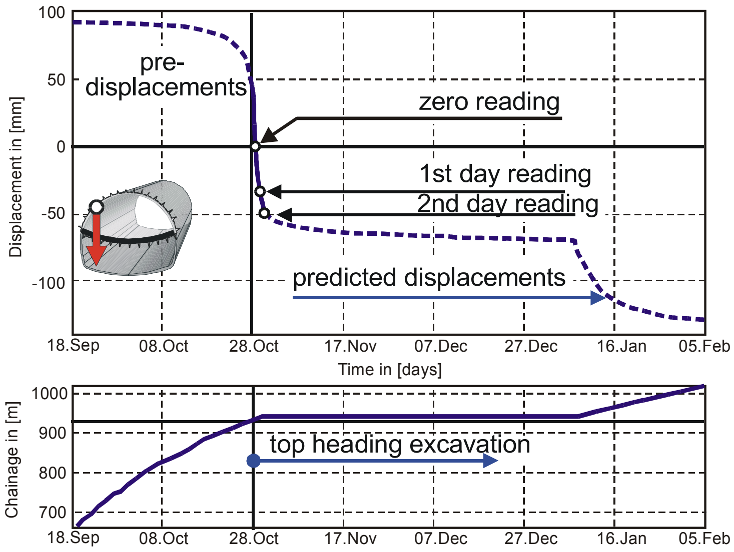

Figure 2. Prediction of settlements without any additional measures.

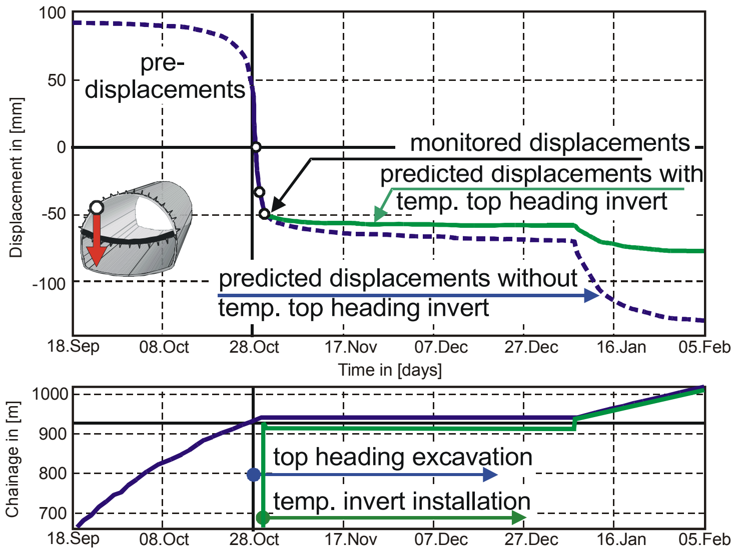

Figure 3. Displacement prediction using additional supports.

The solid line represents the time-displacement history for the settlements using additional supports, while the dashed line represents the displacement history without any additional supports. It can be seen that the final displacements due to top heading excavation would be in the range of 75 mm with the additional support. Therefore the additional support was installed on a length of approximately 20 meters from the face back. At station 940 m the top heading excavation was stopped for organizational reasons and bench and invert excavation proceeded until Christmas holydays.

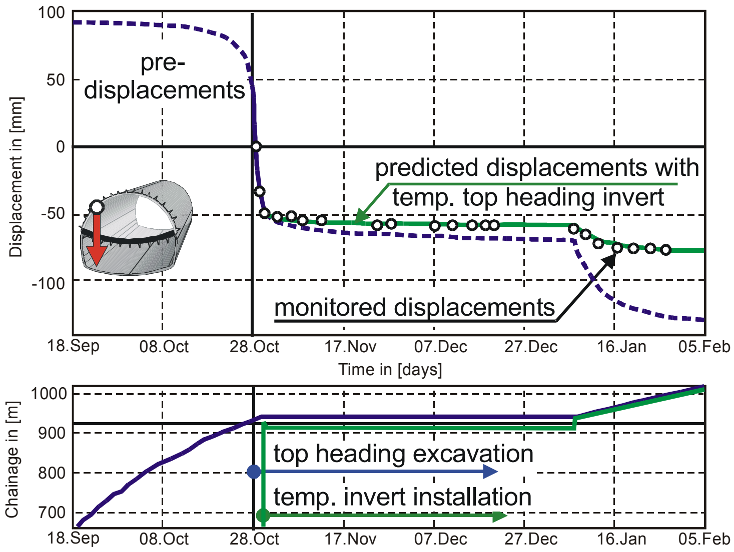

Figure 4. Comparison of predicted and finally observed displacements

In January 2002 the top heading excavation was restarted after a total stop of approximately two months. Two basic questions had to be answered: First of all, is the observed displacement behaviour of the “old” and stiff lining in a “normal” range when excavation proceeds and secondly, are the displacements within the tolerance dictated by the overexcavation chosen. GeoFit was used to investigate these two questions: Figure 4 shows the time history of the predicted and finally monitored displacements. It can be seen that the observed displacements were almost exactly as the predicted during excavation, construction stop, restart of excavation and further advance. Any significant deviation of the monitored displacements from the predicted behaviour would have been interpreted as an abnormal behaviour (for example overstressing and failure of the temporary top heading invert). In that case additional measures would have been required in order not to exceed the displacement limit. The big benefit of GeoFit was to predict the system behaviour using different supports for a discontinuous advance.

3.2 S6 Motorway Tunnel “Spital”, Austria

This tunnel is situated on the S6 Semmering motorway and consists of two 10 m diameter tubes with a distance of approximately 50 m and a length of 2.5 km. The alignment is almost parallel to the slope. The overburden is shallow with a maximum of 89 m and an average of 30 m. The tunnel alignment runs along a major fault zone. Strongly heterogeneous rock mass conditions are characteristic for this area (Püstow et al. 2000).

The following case history shows the crown settlements at station 882 m of the north tube. On December, 20th, excavation reached station 882 and two days later the ring closure was done by installing the temporary top heading invert. Due to Christmas break the construction was stopped for about two weeks. Measurements taken during the break showed only insignificant creep. The crown settlements reached a value of approximately 25 mm until the excavation was restarted on January 10th. Due to the further advance the settlements increased to a value of some 40 mm and showed normal displacement behaviour.

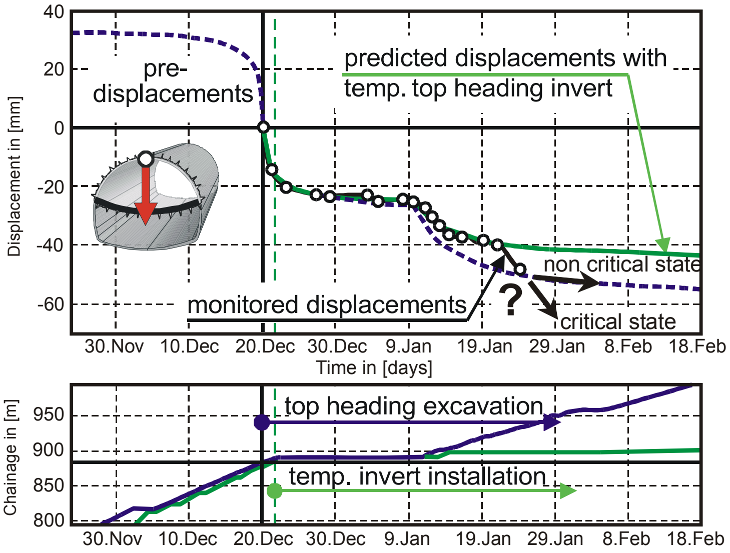

Figure 5. Predicted displacements with and without at temporary top heading invert.

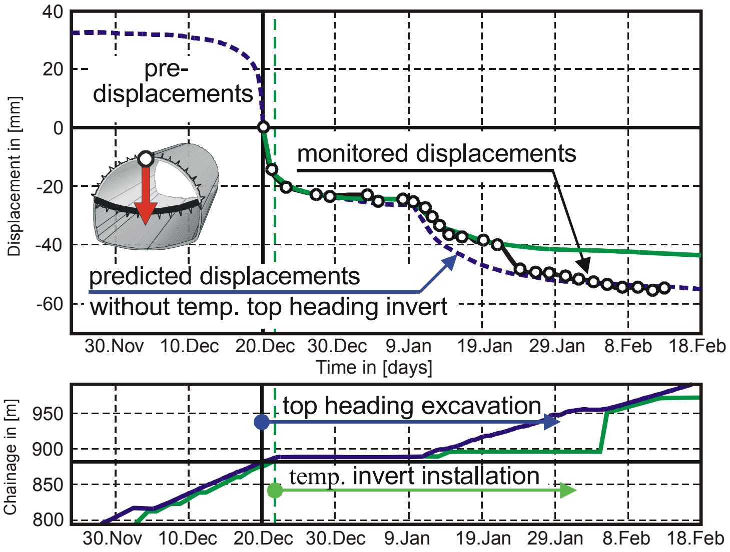

Figure 6. Comparison of the observed and the predicted displacements.

Figure 5 shows the time history of the crown settlements at station 882 m. The solid line represents the predicted behaviour of the tunnel using a temporary top heading invert, the dashed line shows the predicted displacement path without a temporary invert and the circle markers displays the monitored displacements.

On January 21st the settlements showed a deviation from the predicted value and suddenly increased to about 50 mm. This significant displacement increment of more than 10 mm within one day was a clear indicator of abnormal system behaviour. Reasons for this behaviour had to be found and the tunnel stability to be judged.

The shotcrete had settled during the stop and lost its creeping capacity, 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 rock mass. To be able to judge the stability of the system, two scenarios were developed.

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 (dashed line in figure 5). In the latter case (failure in the rock mass), the displacements would exceed those of the system without temporary invert. In figure 5 the arrows symbolize the predicted system behaviour for the first and non-critical state and for the probably critical state. As can be seen from figure 6, the measured displacements soon followed the predicted path for the case without temporary invert. The lining had lost part of its capacity, but the overall stabilisation process was back to normal again. In this case study the prediction of the displacements provided a valuable aid for the decision making process to predict the system behaviour, to identify an abnormal behaviour and its reasons and to judge the "new" system behaviour.

3.3 "Lainzer" Tunnel, Vienna, Austria

The Lainzer Tunnel is a 12.8 km new strategic linc between the Westbahn, the Suedbahn and the Donaulaendebahn. Two single track tunnels (780 m and 940 m long) underpass several surface constructions. The tunnels are constructed using NATM, the mean overburden is approximatelly 10 m thick. The geological conditions are characterised by a typical 10 m thick alluvium layer above claystones, sandstones and marls, which are partly in good conditions, but mostly tectonised, in sections completely altered to soil (Moritz . et al. 2002). This case history deals with the underpass of a large supermarket. The situation is characterised by a concrete pile wall about three meters beside the tunnel. During the construction phase the main railway line was operated on a newly constructed concrete slab just beside the pile wall.

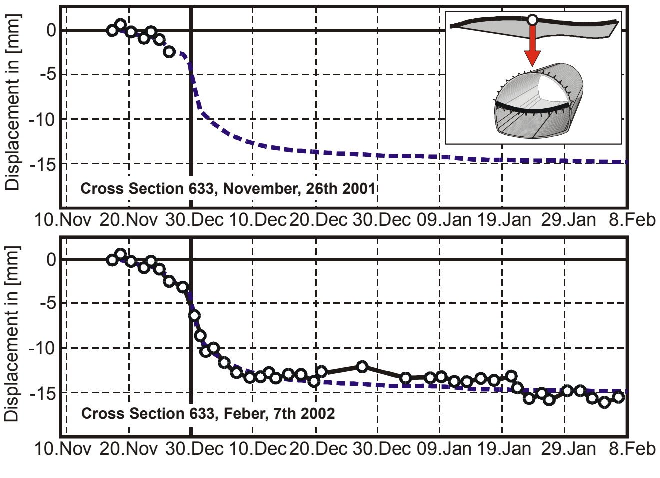

Figure 7. Comparison of predicted and finally observed displacements.

GeoFit was not available at site. It was used afterwards to check the prediction accuracy for surface settlements. The following example shows a surface point approximately 10 m above the crown of the tunnel at cross section 663 m.

The readings used to predict the influence of the underpassing were taken between Nov. 17th and Nov. 26th. Figure 7 (upper plot) shows the observed (small circle symbols) and predicted (dashed line) surface settlements when the tunnel face was approximately 6 meters ahead of the monitoring section. The accuracy of this prediction is shown in the lower plot of figure 7. Both, the quality and quantity of the predicted displacement history meets the monitored results sufficiently.

GeoFit can be used to predict surface settlements for shallow tunnels, too. An additional benefit in such a case is to predict the angular distortion to prevent damages on surface constructions and set additional measures (if required) in time.

4. CONCLUSION

GeoFit has been used, developed and updated permanently on site over the last years to meet the requirements of the geotechnical engineer. It was used for both, displacement prediction and system behaviour prediction on several sites in Austria. The accuracy of GeoFit’s predictions has been increased to a high level due to experience gained concerning the dependency between encountered conditions and the function parameters. It is a promising tool for the site engineer’s daily decisions making process. It allows one to predict the system behaviour and to continuously compare it with monitored data. Thus “abnormal” behaviour can be identified in time to define appropriate countermeasures. Besides, the influence of these countermeasures can be investigated in advance using GeoFit.

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