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Prediction of subsidence during tunnel construction

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ABSTRACT: Stress redistribution, ground loss and change of groundwater table in the course of tunnel excavation cause surface settlements. These surface movements may cause damage to structures above and beside the tunnel. Experience shows that the timely and spatial influence of underground excavations on the surface settlements varies in a wide range. The domain of influence mainly depends on the ground structure and properties, the quality and quantity of the tunnel support as well as on tunnel dimension and the construction method. In some cases the surface movements are limited to some meters ahead and aside of the tunnel and stabilisation is reached within a few days after excavation. In other cases an extended surface area is influenced for a long period and the stabilisation process is slow. Accurate predictions of surface movements are difficult in the design phase. To enable a timely adjustment of the construction method an extensive observation program in the tunnel and on the surface is established in many cases, and warning and alarm criteria defined to ensure safety and serviceability. These levels and criteria of the observed properties should consider not only fixed values – such as maximum settlements – but account for the evolution of these parameters (i.e. settlement path or history). It is indispensable to consider the timely development of surface movements in all three dimensions over the time and as a function of the tunnels progress. Efficient and easy to use procedures to predict and check the surface movements are required to ensure a safe and economical construction. Numerical methods require a more or less time consuming input, calculation time and interpretation work, limiting their applicability for the day-to-day use.

An efficient way to predict displacements caused by tunnel excavation is to use analytical functions that describe the movements as a function of time and the face advance. A procedure based on analytical functions has been developed to support the prediction of the tunnel performance and surface movements. The tool can also be used to study the influence of variations of the tunnel progress and support on the surface movements. In this way the construction planning can be optimized in a way to minimize damage to surface structures. Two case histories from shallow tunnels in Austria are used in this paper to illustrate the application of the prediction tool.

1 INTRODUCTION

To prevent surface structures from (excessive) damage due to surface movements (subsidence) an extensive observation program in the tunnel and on the surface is established in many cases. The measurements describe the actual state of the system consisting of ground and support. The monitored values can be compared to values from the design allowing judging whether the system behaviour is in a "normal range" or in an "abnormal one" (see the design procedure described in ÖGG, 2001). Considering the time depending evolution of displacements and to ensure an adequate reaction time usually warning levels and alarm levels or criteria are defined, dependent on local requirements. Those levels are determined at a rather cautious level at the beginning of construction work and are updated with increasing knowledge of the system behaviour. Additionally, the observation of trends may be used as a criterion for "normal" or "abnormal" behaviour.

To ensure safe and economic tunnel projects a detailed description of the system behaviour and its "normal" range is indispensable and has to be defined during the design phase. For the judgment of the systems state and to check the efficiency of different measures routine predictions are required during the construction which describe the expected reactions of the ground to the excavation and support. These predictions are compared to the observed behaviour on a daily basis. Any deviation between prediction and observation must be related to either a wrong estimation of the geological model in combination with wrong or inaccurate material parameters and/or an inadequate prediction to the construction's response to the stress redistribution. In both cases measures have to be established in time to ensure safety and economy.

The definition, the prediction and the comparison of the system behaviour requires a calculation method which considers various inputs as ground properties, support properties and construction methods. This calculation method should also allow estimating the efficiency of additional measures or mitigation measures in time.

2 STATE OF THE ART & METHODS REQUIRED

During design the expected normal system behaviour is determined and various alarm levels and alarm criteria defined and continuously updated during construction, if required. The use of displacement monitoring data is quite effective for describing, predicting and controlling the system behaviour. Additionally other parameters like pore water pressures, lining stresses, ground stresses and so on can be monitored.

Practice has shown that sometimes the projects success is hampered by shortcomings in the definition, the prediction and the observation of the system's behaviour. A few points which have to be considered when dealing with surface settlements in tunnelling are listed below:

- Sometimes certain values are compared to a predefined fixed threshold instead of accounting for the evolution of the displacement. Especially when differential settlements of the surface areas (subsidence troughs across as well as along the tunnel axis) may damage or reduce the serviceability of an object, it is indispensable to consider the timely development of surface movements in all three dimensions over the time and as a function of the tunnels progress.
- During the construction the tools or techniques used for the prediction are time consuming and therefore costly. This may or will lead to a low frequency in the update of the prediction and consequently to a late identification of unacceptable displacement trends. Efficient and easy to use procedures to predict and check the surface movements are required to ensure a safe and economic construction.
- Current prediction techniques such as analytical solutions (see Park 2005, Chou & Bobet 2002) are limited in their prediction accuracy due to simplifications. Although an extended surface area is influenced for a long period and the stabilisation process is slow (Burland 2001), common analytical methods can only be used for estimating the maximum settlement trough perpendicular to the tunnel axis. In addition such methods do not consider relevant influencing factors, such as excavation rates and methods, different support types and ground conditions leading to inaccurate predictions. Certain counter measures (as additional bolting, installation of temporary top heading invert, etc.) can not be judged with regard to their efficiency. To be on the safe side the tunnel engineer has to overdesign the support accepting cost increase. Thus the prediction tools should account for the ground properties, the supports, and the excavation rate and method.
- The commonly pure empirical assessment of the system behaviour may lead to problems in the case of change of personnel on site. Former experience is difficult to communicate if no consistent rules are established. Thus such rules have to be developed, which describe the timely and spatial local development of certain values and allow predicting the system's state.

In the design phase mostly numerical simulations are used to predict subsidence. These time consuming simulations may consider influencing parameters as size of the structure, overburden, ground structure and quality, ground water conditions, excavation method, supports and progress rate. However, the knowledge of the parameters of the ground, the ground-support interaction, quality of construction, the influence of ground water disturbance etc. is limited during the design phase. In addition, numerical models contain simplifications and constraints regarding the material parameters and the difficult choice of an appropriate material law (see Kofler 2002, Potts & Zdravkovis 2001), which further decrease the accuracy of the prediction. Due to computational limitations surface and subsurface structures are rarely integrated in the numerical model and consequently the ground model needs to be updated during construction and the real behaviour controlled by monitoring. These drawbacks, as well as the effort required make numerical simulations unsuitable for a day-to-day updating of the geological-geotechnical model and its alarm levels. Quick, flexible and easy to use tools are required to continuously predict and control the system behaviour.

3 PROPOSED METHOD

An efficient way to predict the system behaviour of underground excavations is to use analytical functions, which describe the displacements as a function of time and the face advance (tunnel progress). The displacement behaviour of the rock mass and support basically is represented by function parameters. These parameters can be back-calculated from data of case histories. Using those function parameters the development of displacements of the tunnel wall and the ground surface can be predicted. Artificial intelligence methods (expert systems) interlink the function parameters and appropriate ground and support features. Special visualization techniques of the results allow an easy recognition of critical conditions. The tool can also be used to study the influence of variations of the tunnel

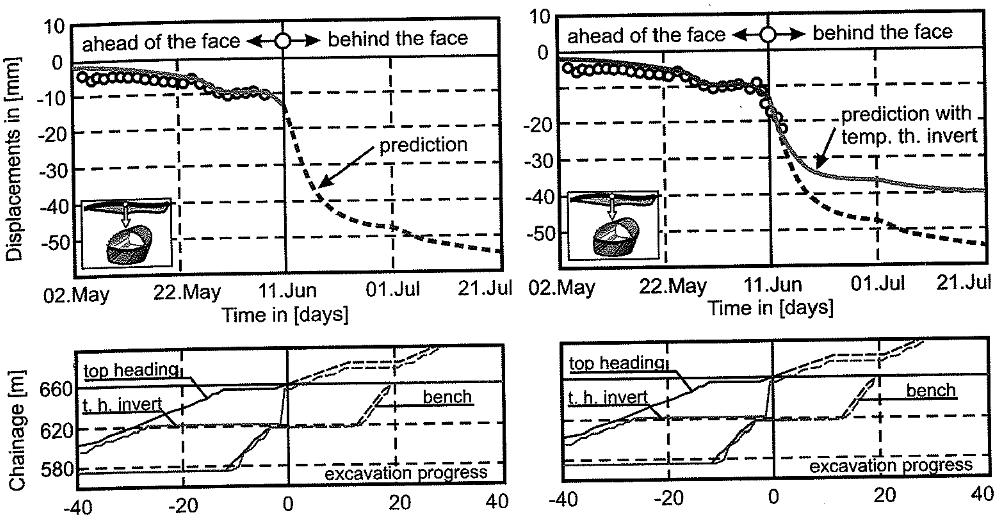


Figure 1. Time – displacement history plot for the surface point. Measured and predicted displacement history some days before (left side) and after (right side) the face passes the monitoring section 661.

progress rate and support type on the surface movements. In this way the construction planning can be optimized in a way to minimize damage to surface structures. The proposed method (GeoFit©) provides the following major advantages (Sellner, 2000):

- it predicts and simulates the evolution of displacements over time depending on the tunnel progress,
- it is an efficient, quick and easy to use procedure using graphical user interfaces and calculation takes a few seconds only,
- it considers relevant inputs, such as supports, excavation sequence and ground conditions,
- it allows to establish certain "rules" predicting critical system states in advance by considering both, the evolution of the function parameters and displacements over time or tunnel advance, and
- a continuous comparison of the monitoring results to warning levels is possible.

4 PRACTICAL APPLICATION

4.1 *Prediction technique and how to set counter measures*

The first example illustrates the technique for the subsidence prediction of points above a shallow tunnel which underpasses a freeway. The tunnel is situated in a tectonic melange and is excavated according to the NATM. The prediction technique proposed is demonstrated on the monitoring section 661.

Figure 1 shows the time – displacement history plot for the considered surface point in the upper axis system and the construction advance in the lower diagram. The zero reading was done approximately 110 m before the tunnel face passed the monitoring section on 11th of June. The circles in the displacement plots represent the monitored subsidence, which are used to back calculate the four function parameters X, T, C and m. The solid grey line shows the back calculation ("fitting") and the dashed line represents the predicted displacements according to the back calculated function parameters and a progress rate, which was extrapolated for the next few days.

In this case, the subsidence prediction for this monitoring section is done three days before the tunnel face reaches this section (see left side of Figure 1). It can be seen, that the settlements will reach a maximum value of about 60 mm. The accuracy and reliability of the prediction can be checked by looking on the development of the function parameters along the alignment.

Figure 2 (left side) shows the back calculated function parameters for the system behaviour which should show a reasonably "smooth" trend as they are correlated to certain geological-geotechnical properties of the ground (Grossauer, Schubert & Kim, 2002; Schubert, Button, Sellner & Solak, 2003). Abrupt changes in magnitude are most unlikely except there are abrupt changes of ground conditions. In this case the back calculated function parameters follow a rather consistent trend which increases the prediction's accuracy and reliability. If changing rock mass conditions are expected, the parameters can be modified accordingly. Methods for short term prediction of rock mass conditions are described by Steindorfer (1998) and Sellner & Steindorfer (2000).

If expected displacements exceed the acceptable range additional measures can be set in time. The

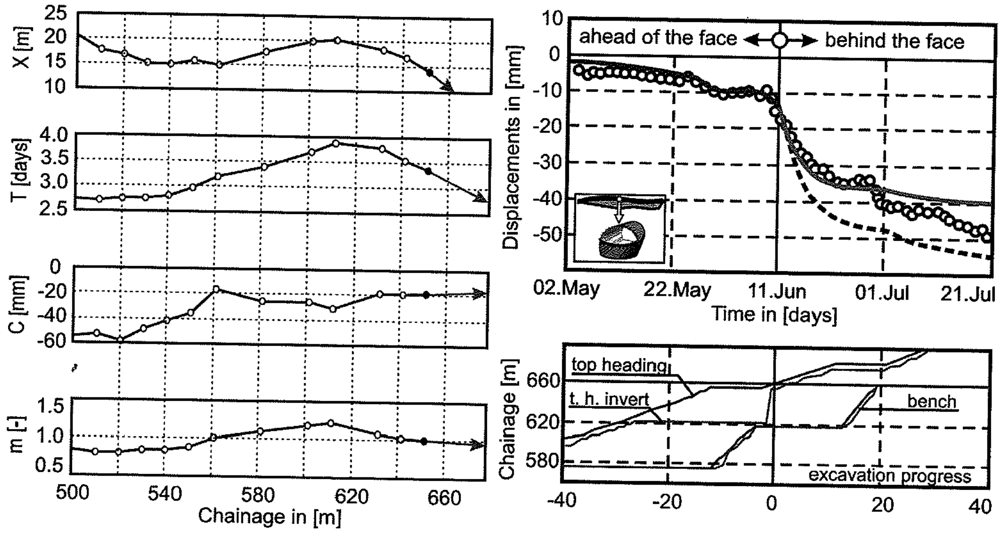


Figure 2. Trend of the function parameters X, T, C and m along the tunnel axis (left side) and the comparison of predicted and observed subsidence (right side) for monitoring section 661.

efficiency of such counter measures is shown in figure 1 (right side). The grey solid line shows the expected settlements considering that a temporary top heading invert is installed. The final displacement on the surface will be reduced by approximately 20 mm.

The right side of figure 2 shows a comparison of the finally observed and the predicted surface settlements due to top heading excavation. The prediction fits the monitoring with a high degree of accuracy until the 28th of June. On this day the bench excavation reaches the monitoring section resulting in additional displacements. For this excavation step an analogous prediction can be performed but is not shown here.

4.2 *Early detection of problem areas*

The next example shall demonstrate the potential of detecting critical situations in time and check the effectiveness of mitigation measures. The example is derived from a tunnel at shallow depth in very poor ground conditions. An intense observation program was conducted. The left part of figure 3 shows the observed subsidence (circles) and predicted (solid line) subsidence of a single observation point on the surface. The right part of figure 3 shows the outline of surface structures and the tunnel alignment. The dark dots represent the monitoring points on the surface. When the tunnel face has reached chainage 785 m a displacement prediction is performed (shown here as contour plot) which represents the surface settlements when the face will be located at chainage 825 m. The dark area ahead of the tunnel indicates settlements exceeding the defined alarm level.

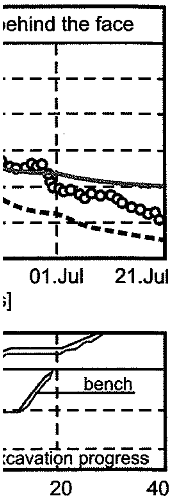
To meet displacement restrictions, countermeasures have to be taken. In this case a temporary top heading invert is installed and the bolt density increased. The efficiency of these measures is predicted and shown in figure 4. The left part shows the settlement of the surface point in case of installing the temporary top heading invert and intensifying bolting (solid line). For comparison the settlements without additional measures are shown too (dashed line). Due to the installation of the top heading invert and the denser bolting pattern the settlements are significantly reduced and the defined alarm level will not be exceeded.

The prediction of subsidence can be performed for any time or chainage and visualized with movies, contributing to detect critical areas in advance. A better understanding of the timely and spatial influence of the construction on the subsidence can be archived.

The visualisation as plan view or three dimensional surface plots is of significant importance when dealing with surface inclinations. A two dimensional evaluation of observations along a monitoring sections will not show the total inclination but the projection of the inclination which is of lower quantity.

5 CONCLUSION

Considering subsidence, two main features can be found. Firstly, they can be measured and observed long before the tunnel passes the domain of interest. Secondly, they may cause damage on surface structures due to a variety of settlements, movements,



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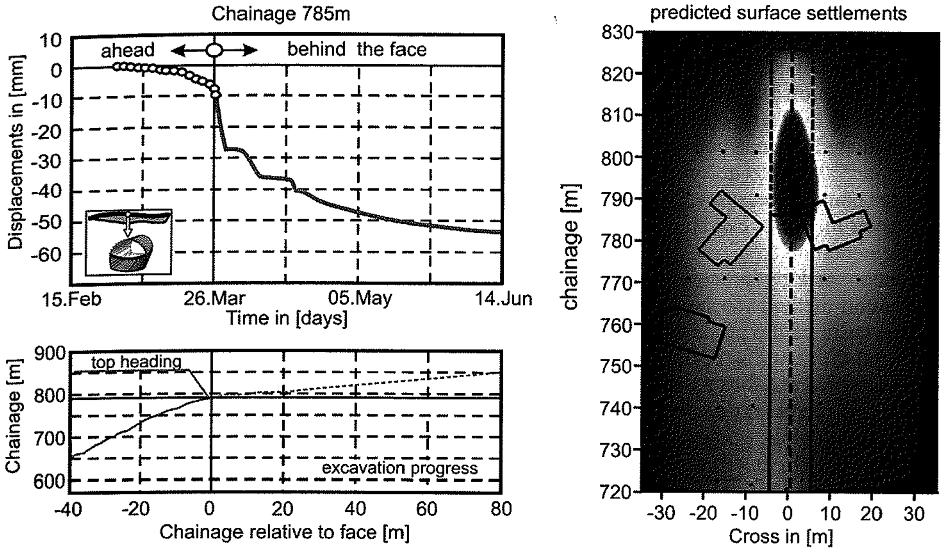

Figure 3. Left side: Settlement prediction for a single point on the surface; right side: outline of surface structures, tunnel alignment and contour plots of predicted subsidence without additional measures.

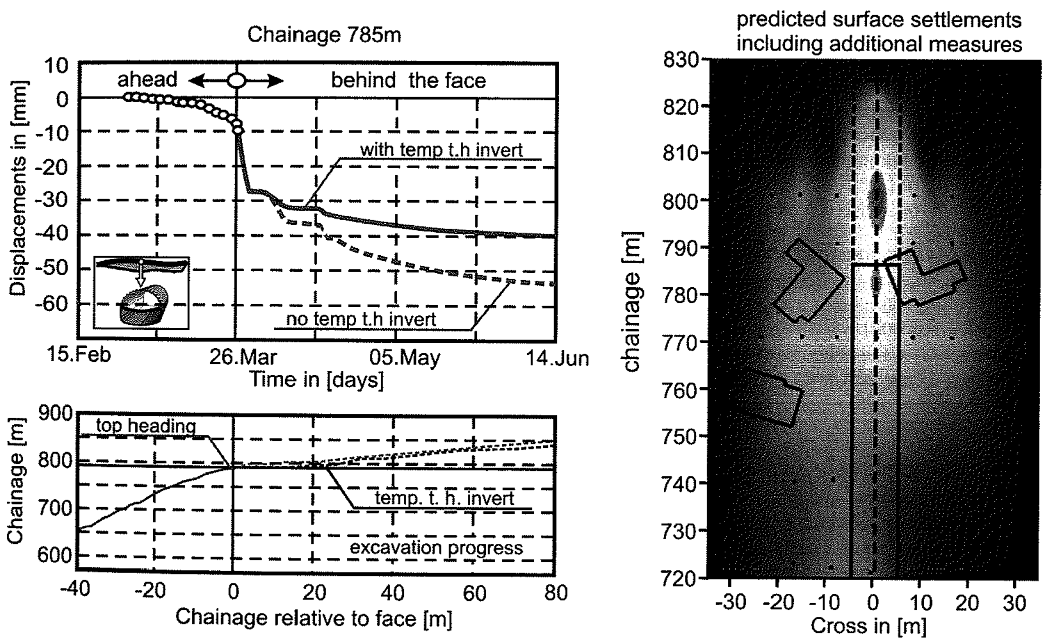

Figure 4. Left side: Settlement prediction for a single point on the surface; right side: outline of surface structures, tunnel alignment and contour plots of predicted subsidence considering additional measures.

rotations, and deflections. This requires that the engineers permanently control the settlement trough above an advancing tunnel and its compatibility to surface structures. The degree of damage is reduced by predicting displacements and establishing measures to reduce or compensate them. As a matter of fact, pre-displacements can be observed and used to back calculate the displacement behaviour of the ground in an early stage resulting in a better understanding of the ground's reaction to tunnelling and thus in a better quality of the subsidence prediction for any stage of the tunnel project.

The proposed method provides tools for back calculation and prediction of subsidence and supports the tunnel engineer in his daily work. A permanent comparison of predicted "normal behaviour" and observed "real behaviour" allows to detect critical domains in time and to set counter measures. The efficiency of the planned counter measures can be checked "virtually" before implementation.

The decision making process regarding support and construction method can be supported with this method. The basis of the predictions – the function parameters and the resulting definition of the system behaviour – is stored and thus reproducible. This storage of decisions represents a specific knowledge, a correlation of geological, geotechnical and construction parameters, which can be used for further sections and projects.

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