THE ROLE OF ON-SITE ENGINEERING IN UNDERGROUND PROJECTS

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In the planning and design phases of underground structures, the information on geological setup, the rock mass structure and characteristics necessarily is incomplete and inaccurate. To allow for a safe and economical construction, a continuous updating of the ground model and an adjustment of the construction methods to the actual site conditions is required. For a smooth construction process, the conditions ahead of the face have to be predicted, and the ground surrounding the tunnel characterized. Based on this updated model the ground behaviour can be assessed, and the final layout of the construction determined. The expected interaction between ground and support (system behaviour) forms the basis for the monitoring program and the safety management plan, which includes warning and alarm criteria.

As all decisions on site have to be made quickly, data acquisition, processing and analysis have to be well organized. Highly qualified and experienced geotechnical personnel, as well as appropriate site organization and contractual conditions are required to allow for a short reaction time to changing conditions.

A number of tools and methods have been developed, which contribute to a more reliable assessment of rock mass structure and behaviour, which again enables a more precise determination of excavation and support methods. Digital stereo photos allow a precise evaluation of the rock mass structure, while advanced software for the evaluation of displacement monitoring data and prediction of displacements assists in predicting and controlling the performance of the underground structure. Up to date methods of monitoring data evaluation and interpretation will be demonstrated with the help of case histories.

A key issue is the accurate prediction of the displacements in their development and final magnitude. Appropriate software can support engineers in assessing displacements and stresses of tunnel supports.

The experience of on-site personnel in general is limited, and may not cover specific problems encountered on site. In the past experts had to be brought to the site and briefed on the conditions to solve such problems. This is slow and inefficient, as the level of information might be not sufficient or time consuming to upgrade. With the Internet nowadays an exchange of information is easy, allowing experts to give a profound advice, even if they are not on site.

Keywords: tunnel design, monitoring, face mapping, on-site-engineering.

1. Introduction

Even with a good geological and geotechnical investigation and an up to date design, the adjustment of excavation and support to the local conditions has to be done on site in order to achieve an economical and safe tunnel construction. The uncertainties in the ground model increase with increased overburden and the complexity of the geological conditions. Considerable effort and expertise is required to continuously update the ground model, predict ground conditions ahead of the face, identify possible failure modes, determine appropriate excavation and support methods, and predict and verify the system behavior. The increased information gathered during construction allows a more precise ground characterization, and thus an optimal adjustment of the construction method to the ground behavior and required system behavior.

Many serious problems during tunneling arise from so called unexpected geological conditions. This may involve the late detection of faults and fault zones, but also the inflow of ground water. To minimize damages and losses due to such conditions, efficient and continuous site engineering is required.

To allow successful implementation of an observational approach, several technical and organizational conditions have to be fulfilled. First of all consistent procedures for the investigation, ground characterization, and design have to be devised (OeGG, 2001). Then the range of possible ground behaviors have to be assessed and the limits of acceptable system behaviors defined. On site the implementation of a monitoring program targeted to the expected behavior must be implemented in an appropriate density. Processing, evaluation and interpretation of monitoring results has to be done sufficiently rapidly to allow mitigation measures to be implemented in time. Last, but not least, the site organization shall allow an efficient decision making process and a rapid implementation of required measures.

2. The role of on-site engineering

Although the general nature of the ground may be known prior to construction, an accurate prediction of the internal structure is impossible. Thus the ground model has to be continuously improved during construction. Monitoring and data collection have to focus on the specific problems associated with project. An important part of the on site activities of geologists and geotechnical engineers is the prediction of the ground conditions in a representative volume ahead of the tunnel face and around the tunnel. Only if a relatively accurate model exists, can appropriate excavation and support methods be selected, and the expected system behavior predicted. A second very important task is the monitoring of the system behavior after excavation, and the assessment of its compliance with the prediction.

2.1. *Geological tasks*

On many sites the site geologist is used only to document the actual geological conditions. This usually is done in the form of face maps, with a later compilation into longitudinal sections and plan views. This may help in defending or supporting claims, but is not sufficient to allow for a reasonable adaptation of the construction to the actual conditions. To fulfill the requirements of an observational approach, the geologist has to continuously update the geological model, incorporating the observations on site. As many of the decisions during construction have to be made prior to the excavation, like round length, overexcavation, lining thickness, etc. the geologist also has to predict the ground conditions ahead of the face and in a representative volume around the tunnel. To enhance the accuracy of the prediction, a continuous observation of trends of certain parameters is required. For efficient data management and evaluation data base systems with advanced statistical and probabilistic features can be used (Liu et al. 1999).

2.2. *Geotechnical tasks*

The information gathered by the site geologist is further processed by the geotechnical engineer, forming the basis for decisions on construction method, monitoring layout and reading frequency, to name a few tasks only. To allow decisions to be taken in time, all data recording and evaluation has to be done quasi in real time, and the relevant data have to be always available to all parties involved in the construction. Internet based information platforms can be used for that purpose, allowing also off-site experts to keep track with the information flow. Based on the geological model, the geotechnical engineer has to update the ground model by assigning properties to the geological features. Then the ground behavior (ground reaction on excavation without support) for the section ahead is evaluated, possible failure modes identified, and excavation and support methods assigned. To support the geotechnical modeling, the monitoring results of the previously excavated sections can be used. In a next step, the system behavior (combined behavior from ground and construction measures) is predicted and compared to the requirements, like serviceability, compliance with limitations (subsidence, vibrations, etc). Based on the recommendation of the geotechnical engineer the Engineer under consideration of contractual aspects fixes the construction measures. In case those deviate from those recommended by the geotechnical engineer, the expected system behavior has to be re-evaluated.

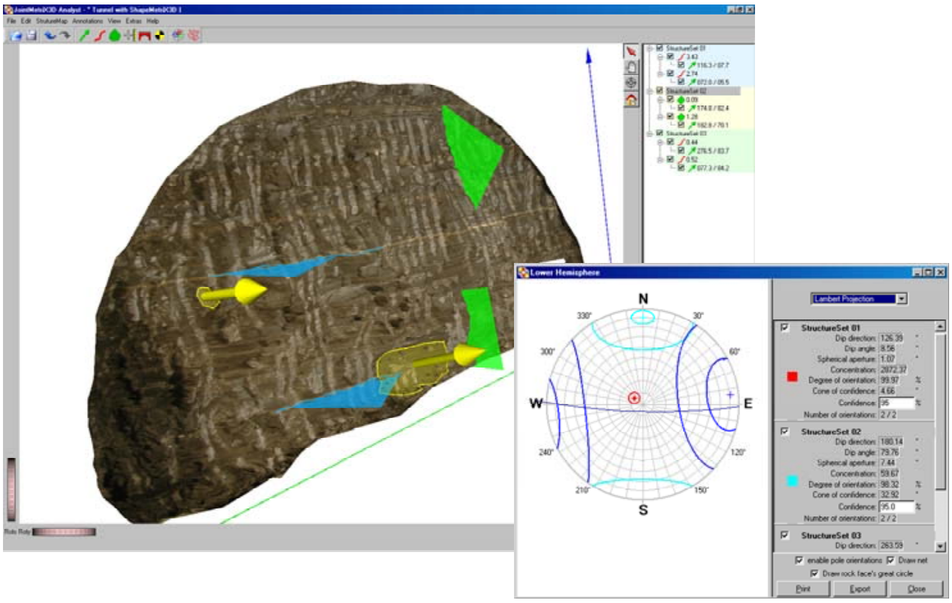
The geotechnical engineer also has to determine the monitoring layout and program, which should be targeted to capture the expected behavior. Once the expected system behavior is determined and the monitoring conducted, the observed behavior is compared to the predicted one. Deviations from the normal or predicted behavior have to be assessed, and in case of unacceptable developments mitigation measures proposed. Warning and alarm criteria and respective mitigation measures are laid down in a geotechnical safety management plan, jointly developed by the designer and geotechnical engineer on site.

3. Tools to assist in data collection and evaluation

3.1. *Prediction of ground conditions*

Predicting the ground conditions can be separated into two parts, the geological modeling and the geotechnical prediction, which is mainly based on evaluating and interpreting displacement monitoring data. A close co-operation between the disciplines is required to be able to produce a reliable prediction of the ground conditions ahead.

Basis for the geological modeling ahead of the face in general is the observation of trends of structures, recorded in the excavated section. Traditional manual face mapping increasingly is supported by up to date 3D image systems (Gaich et al. 2004, 2005). Figure 1 shows an example of a 3D model of a tunnel face with measurements of discontinuity orientations taken from the



Lambert Projection

☑ StructureSet 01
Dip direction: 126.39 °
Dip angle: 8.56 °
Spherical aperture: 1.07 °
Concentration: 2872.37
🟥 Degree of orientation: 99.97 %
Cone of confidence: 4.66 °
Confidence: 95 %
Number of orientations: 2 / 2

☑ StructureSet 02
Dip direction: 180.14 °
Dip angle: 79.76 °
Spherical aperture: 7.44 °
Concentration: 59.67
🟦 Degree of orientation: 98.32 %
Cone of confidence: 32.92 °
Confidence: 95.0 %
Number of orientations: 2 / 2

☑ StructureSet 03
Dip direction: 263.59 °

☑ enable pole orientations ☑ Draw net
☑ Draw rock face's great circle

Fig. 1 3D image of a tunnel face with measurements of discontinuity positions and orientations, and statistical evaluation of discontinuity data with JointMetrix3D Analyst image. In this way an unbiased evaluation of the geological situation is possible. In contrast to hand sketches, and discontinuity orientation measurements with the compass, with the images the information is complete and accurate, as the images are calibrated and metric. Orientations of joints can be measured from joint planes or joint traces. The evaluation software also offers options to measure bedding thicknesses, joint bridges, areas and distances.

A series of evaluated images of successive excavation faces allows predicting the rock mass structure and quality of a representative volume ahead of the face and around the tunnel by extrapolation. This, combined with the structural geological evaluation can lead to a pretty reliable geological model, forming the basis for predicting ground behavior, which again is the basis for the determination of required construction measures.

3.2. *Advanced analysis of displacement monitoring data*

The geological modeling preferably is supplemented by an analysis of the monitored displacements. It has been shown, that the trend of the spatial orientation of the monitored displacement vector can be used to identify changes in the rock mass quality ahead of the tunnel face (Schubert et al. 1995, Steindorfer 1998, Grossauer et al. 2003). Figure 2 shows the results of a series of numerical simulations, where the development of the stresses, displacements, and displacement vector orientations for a tunnel crossing a weak zone are shown.

Figure 3 shows an example of an Alpine tunnel, where the displacement vector orientation trend (L/S) significantly changes already when the face is several tens of meters ahead of a fault zone. At this project, the normal displacement vector orientation in quasi homogeneous ground was in the range of 4° to 9° against the direction of the advance. From about station 1100m a deviation of the vector orientation from the normal range can be observed. The peak of the deviation is reached right at the transition between sound rock and fault zone. With further progress of the excavation through the fault zone, the trend of the displacement vector orientation first tends to the normal range again. When the heading is within the fault zone, the trend of the displacement vector orientation deviates to the opposite side of the normal range, indicating the stiffer rock mass behind the fault zone. For extended fault zones, the displacement vector orientation generally returns to the “normal” range again, until the influence of the boundary to the more competent rock mass is indicated by another deviation. This information can be used to estimate fault zone extensions.

As a general rule it can be stated, that the higher the stiffness contrast between faulted rock and neighboring rock mass, and the longer the fault zone is, the larger is the deviation of the displacement vector orientation from the normal range. It has been shown by Grossauer (2001), that this is valid up to a certain critical length of a fault zone. As for fault zones with an extent of less than about three to five tunnel diameters, a certain arching between the more competent rock masses can be observed, also the displacement magnitude within the fault zone is smaller than in a fault zone with a large extension.

Displaying the spatial displacement vector orientation in stereographic projection, the orientation of faults outside the tunnel profile can be determined with some accuracy. Naturally also the virgin stress field and anisotropy of the rock mass influence the displacement vector orientation. Thus for each project the range of “normal” displacement vector orientation will be somewhat different.

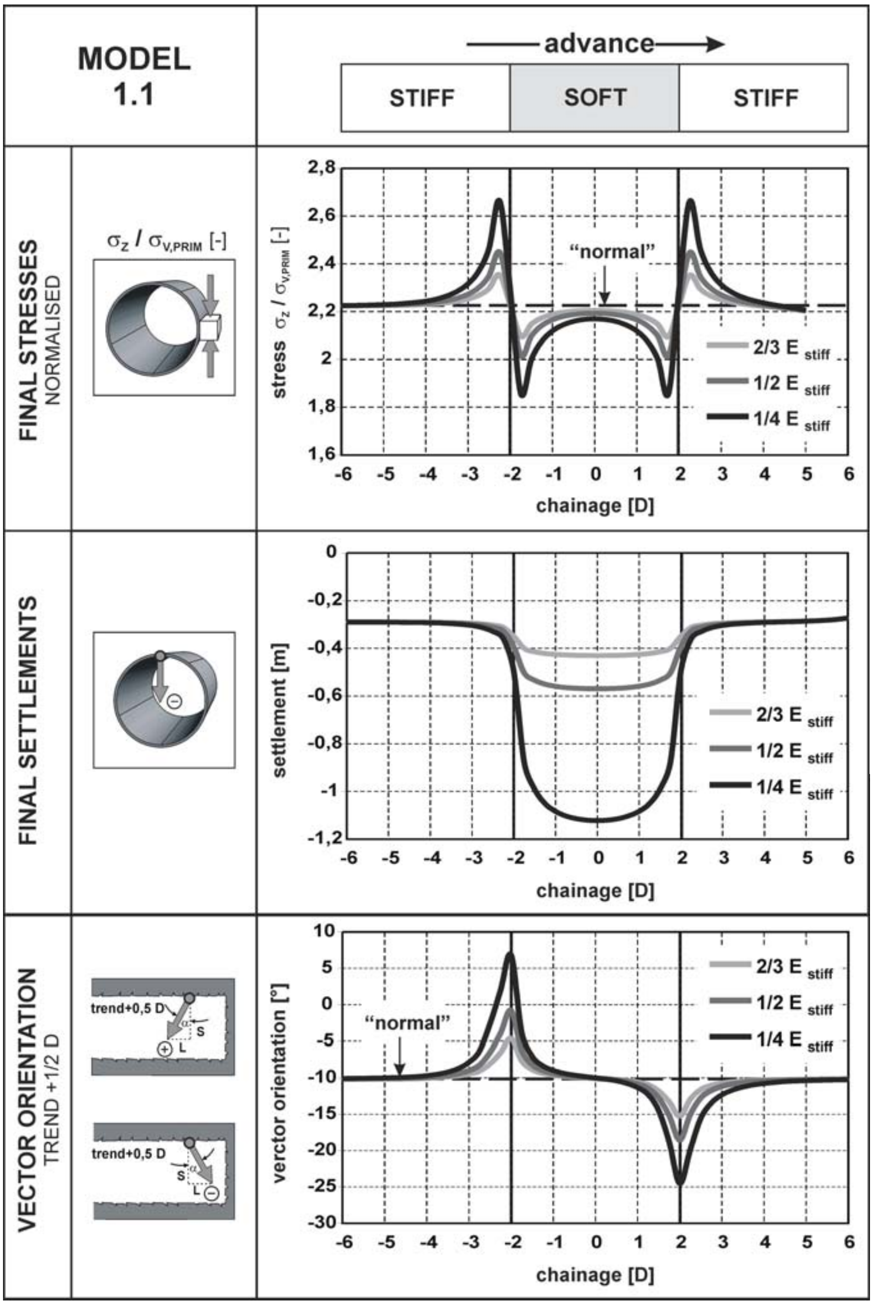


Fig. 2 Distribution of stresses along the sidewall of a tunnel when the tunnel penetrates a weak zone (upper). Development of displacements, when the tunnel penetrates a weak zone (center). Trend of displacement vector orientation (lower) shows a clear deviation from its normal when the heading approaches a zone of different stiffness already a few tunnel diameters ahead of the transition. The different lines show the influence of different stiffness contrasts between soft and stiff rock (Grossauer, 2001)

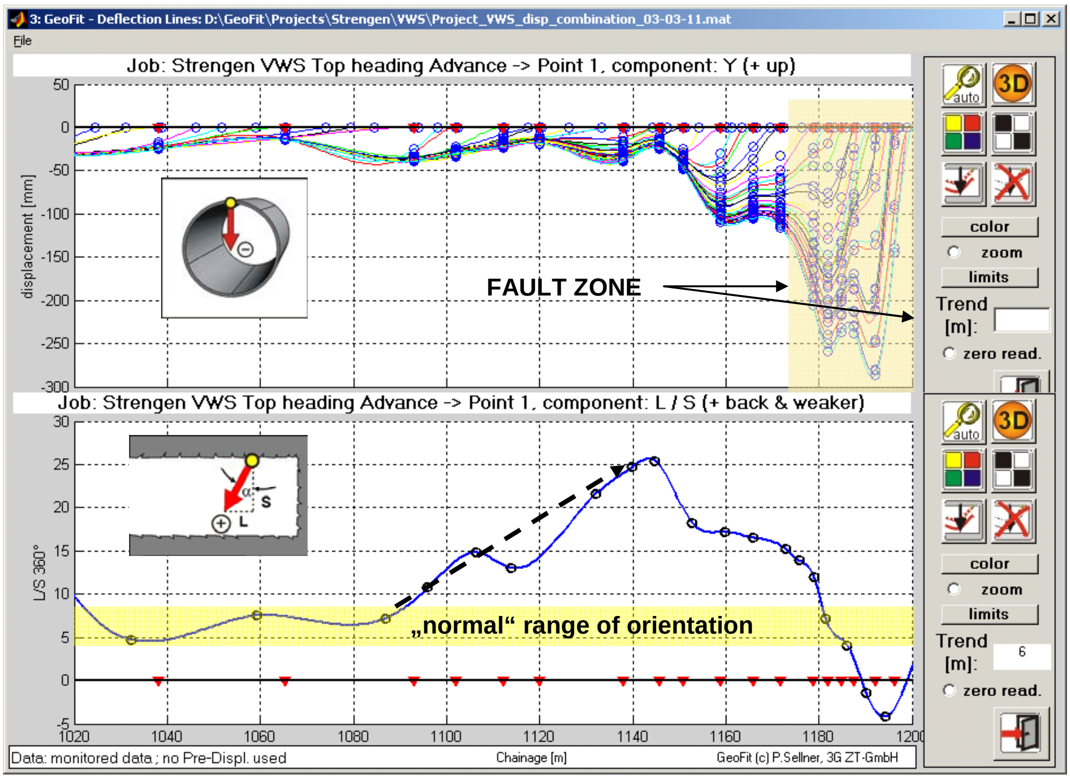
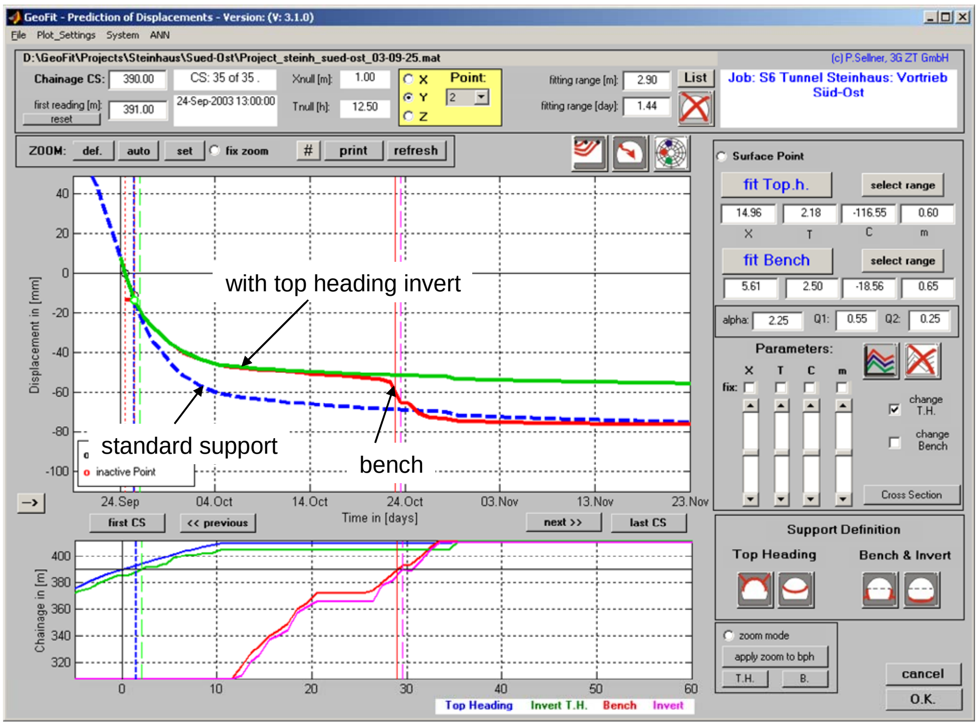


Fig. 3 Deviation of the displacement vector orientation from the “normal” several diameters ahead of a fault zone. When the excavation passes the fault zone the deviation in the opposite direction indicates stiff rock mass ahead again.

3.3. *Prediction of displacements*

Once the geological-geotechnical model for the region ahead of the face has been established, the support and excavation measures can be determined, and the expected displacement development predicted. Sellner (2000), based on research conducted by Sulem et al. (1987) developed software (GeoFit®) allowing the prediction of displacements considering varying excavation sequences, advance rates and different supports. With this tool it is not only possible to predict the development of the displacements and the final displacement magnitude, but also the effect of different supports. Figure 4 shows such a prediction of the displacement development for a shallow tunnel in a tectonic mélange. The excavation was done in a top heading-bench-invert sequence. The shotcrete-rock bolt support is supplemented by a temporary shotcrete invert in the top heading. Based on an assumed construction progress, the development of the displacements for the top heading without temporary invert is predicted (dashed line). Then the temporary invert is added, showing in a decrease of displacements. In a third step the additional displacement caused by the bench and invert excavation are predicted. This approach allows an assessment of the effectiveness of various support types and the influence of the construction sequence on the development of displacements in a very early stage. With some experience, the displacement development can be predicted already a couple of hours after excavation, if readings are taken in a sufficiently short interval. If it for example shows, that displacements would be in an unacceptable range, support can be increased, and the efficiency immediately simulated.



GeoFit - Prediction of Displacements - Version: (V: 3.1.0)

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(c) P.Sellner, 3G ZT GmbH

Job: S6 Tunnel Steinhaus: Vortrieb Süd-Ost

Chainage CS: 390.00

CS: 35 of 35 .

first reading [m]: 391.00

24-Sep-2003 13:00:00

Xnull [m]: 1.00

Tnull [h]: 12.50

Point: ○ X ● Y ○ Z 2

fitting range [m]: 2.90

fitting range [day]: 1.44

○ Surface Point

fit Top.h.: X 14.96, T 2.18, C -116.55, m 0.60

fit Bench: 5.61, 2.50, -18.56, 0.65

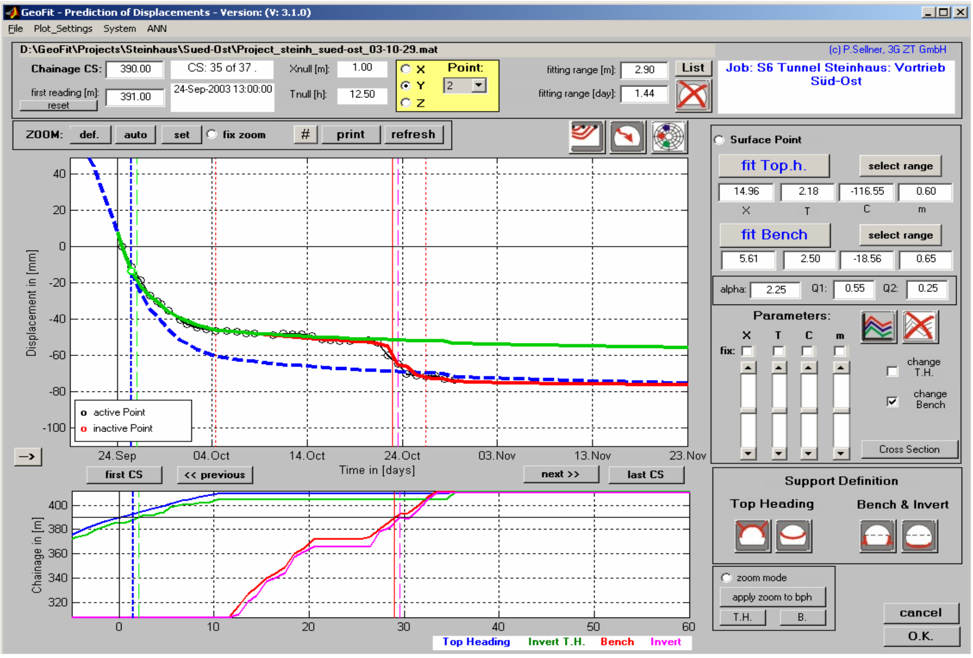
alpha: 2.25 Q1: 0.55 Q2: 0.25

fix: X ☐ T ☐ C ☐ m ☐

☑ change T.H.

☐ change Bench

Fig. 4 Predicted development of the displacements for a top heading bench invert excavation. In the top heading a temporary invert is installed.



GeoFit - Prediction of Displacements - Version: (V: 3.1.0)

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(c) P.Sellner, 3G ZT GmbH

Job: S6 Tunnel Steinhaus: Vortrieb Süd-Ost

Chainage CS: 390.00

CS: 35 of 37 .

first reading [m]: 391.00

24-Sep-2003 13:00:00

Xnull [m]: 1.00

Tnull [h]: 12.50

Point: ○ X ● Y ○ Z 2

fitting range [m]: 2.90

fitting range [day]: 1.44

○ Surface Point

fit Top.h.: X 14.96, T 2.18, C -116.55, m 0.60

fit Bench: 5.61, 2.50, -18.56, 0.65

alpha: 2.25 Q1: 0.55 Q2: 0.25

fix: X ☐ T ☐ C ☐ m ☐

☐ change T.H.

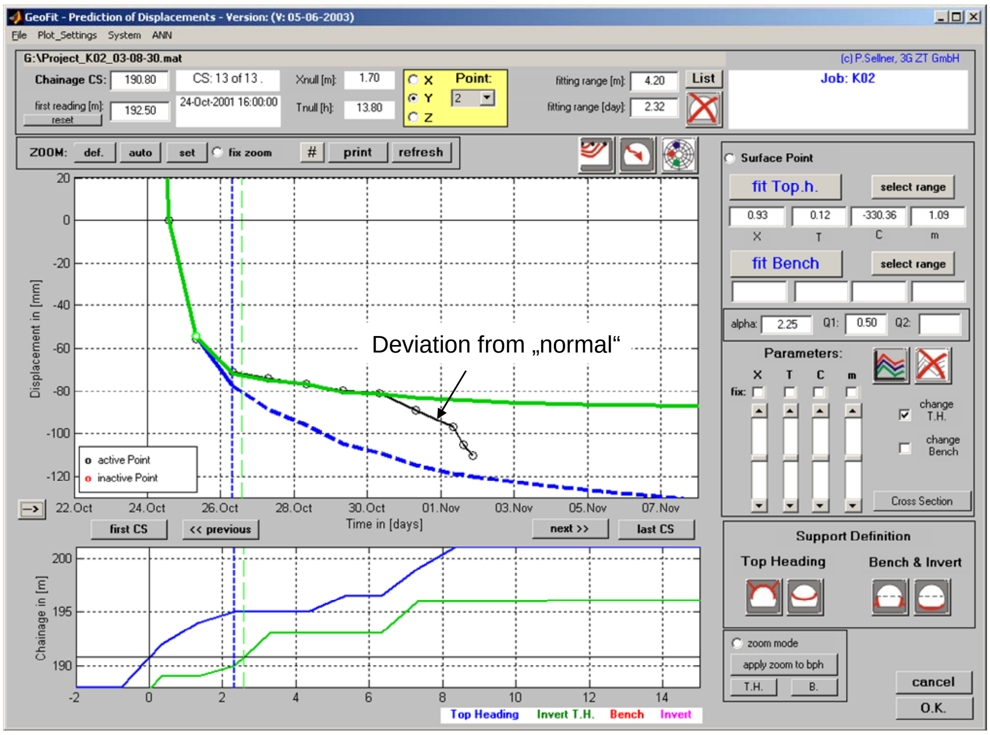
☑ change Bench

Fig. 5 Comparison of the measured displacements (circles) to the predicted ones (full lines)

During excavation, the measured displacements can be compared to the predicted ones (Figure 5). The big advantage of such a tool compared to traditional plots of the displacement history only is the fact that also for unsteady advance a clear assessment of the normality of the system behavior is possible.

It has been shown in many applications that the empirical formulations used in GeoFit® for the prediction of displacements very well reflect the ground reaction. Deviations from the predicted displacement development thus can be attributed to unusual behavior or failure in the ground – lining-system. A reasonable application of the software however needs quite some experience.

The previous example shows an excavation with a very steady advance rate. In such cases the interpretation of displacement history diagrams is pretty simple, as the displacement rate should continuously decrease with increasing distance between face and measuring section. More challenging is the assessment of the normality of the system behavior in case of an unsteady advance. Figure 6 shows an example, where a weak zone in the ground to the left of the tunnel led to overstressing, showing in a pronounced deviation from the predicted displacement development. If the comparison between predicted and measured displacements is done routinely, such deviations can be easily detected, and mitigation measures implemented in time.



GeoFit - Prediction of Displacements - Version: (V: 05-06-2003)

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(c) P.Sellner, 3G ZT GmbH

Job: K02

Chainage CS: 190.80

CS: 13 of 13 .

first reading [m]: 192.50

24-Oct-2001 16:00:00

Xnull [m]: 1.70

Tnull [h]: 13.80

Point: ○ X ● Y ○ Z 2

fitting range [m]: 4.20

fitting range [day]: 2.32

○ Surface Point

fit Top.h.: X 0.93, T 0.12, C -330.36, m 1.09

alpha: 2.25 Q1: 0.50 Q2:

☑ change T.H.

☐ change Bench

○ zoom mode

Fig. 6 Deviation from the predicted “normal” behavior, indicating destabilization of the tunnel.

In addition the prediction is used to determine the required overexcavation to allow for the expected displacement without impairing the clearance after stabilization of the tunnel. This in particular is of importance when tunneling in fault zones, as the final displacement magnitude may vary in a wide range, depending on the rock mass structure and quality, and it is well known, that reshaping is extremely expensive.

3.4. *Check of lining stresses*

For shallow tunnels in urban areas usually a pretty stiff lining is used to minimize ground deformations. As such linings tend to fail in a brittle mode at low levels of deformation the evaluation of the displacements only does not provide a reliable indication of the state of stress. The results of 3D optical monitoring can be used to evaluate the strain development. With an appropriate material model, considering time dependent hardening and strength development, as well as the effects of shrink, temperature and creep, the actual stress level in the lining can be evaluated (Schubert, P. 1988, Aldrian 1999, Rokahr *et a*l. 2002, Hellmich *et al*. 1999, Macht 2002, Tunnel:Monitor, 2006).

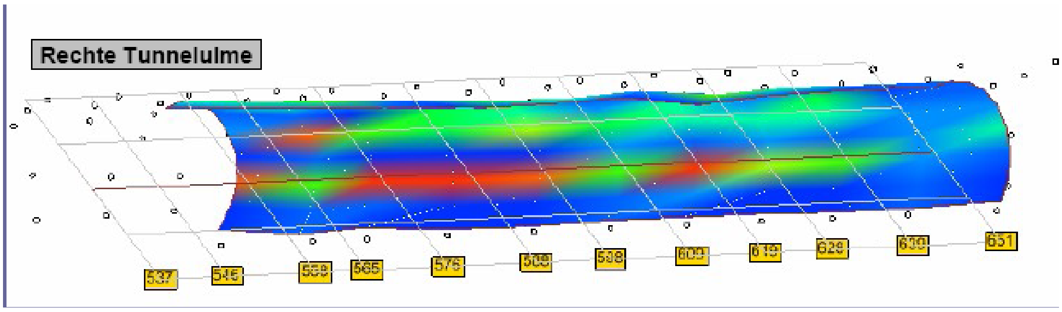

Fig. 7 Evaluated stress level in shotcrete lining with the software Tunnel:Monitor

The evaluation of stresses in the lining not only can be done after monitoring results are available (Figure 7), but can be predicted on the basis of the predicted development of the displacements.

In tunnels with high overburden and weak ground, the deformability of the lining in many cases is not sufficient to cope with the displacements without failure. Checking the expected lining stresses on the basis of the expected development of the displacements can help in making the right decisions for excavation and support. While in some cases, where the expected stresses in the lining only slightly exceed the strength, a reduction in progress rate might give the shotcrete enough time to develop strength, in other cases ductile linings could be required (Moritz, 1999, Button et al. 2003).

Figure 8 shows an example of the evaluation of a shotcrete lining utilization for an expected development of displacements. Due to the low strength of the shotcrete at an early age, the stresses would exceed the strength after one day (upper diagram). Thus either a reduction in excavation rate, or a change to a ductile lining are required. As a reduction in excavation rate will be acceptable only in cases of short sections of weaker ground, the change to ductile supports will be the reasonable measure for longer sections. With the incorporation of ductile support elements into the lining, the stress intensity is re-evaluated. The lower diagram in figure 8 shows the development of the utilization for the ductile lining. The maximum utilization rate is only 50% of the lining capacity.

The combination of comparing predicted to the measured displacements, and the check of the lining utilization considerably contributes to a reduction of “surprises“ during tunneling.

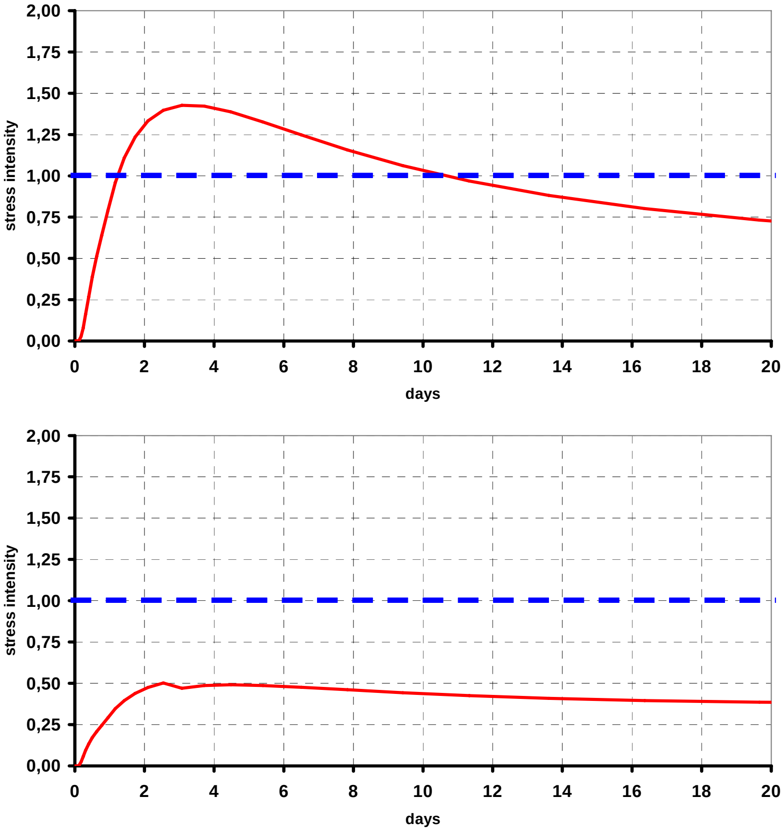

Fig. 8 Development of lining utilization factor for a stiff lining, using predicted displacement development (upper diagram), and lining utilization for a ductile lining (lower diagram)

4. The role of off-site experts

In most cases it is impossible to maintain appropriately experienced staff on site to cope with all expected and unexpected scenarios. For an optimal construction the involvement of experts is required. This involvement may be necessary only for short periods or over the whole construction time, depending on the complexity of the ground conditions, and the expertise available on site. The traditional way of acquiring external expertise is to call in an expert to the site, brief him on the situation, and expect a sound advice within hours. This procedure is not only time consuming and expensive, but also inefficient, as even nowadays nobody carries all the supporting hard- and software around the world. In addition the appropriate expert might be unable to allocate the time to go to a site being far away from his office.

The solution to this problem is to allocate appropriate experts for the problems expected which support the on-site staff from their offices in case needed. Data exchange and information is done via Internet.

4.1. *Requirements*

It is recommendable that already in the pre-construction phase the respective expert(s) are contacted and made familiar with the project, generating some costs, but being good investment, as a familiarization during the construction inevitably leads to delays and/or lower quality advice.

Depending on the problems expected during construction, the type of data, their quality and quantity need to be determined. In general this will be geological data from face mapping and on-site modeling, data on excavation and support, and in particular displacement monitoring results. Photos can supplement the information. As the experts working off site cannot acquire a personal impression and thus lack a bit a “feeling” for the ground conditions, the data collected and transmitted must be objective, complete, and of high quality.

The format of the data has to be agreed upon to allow a processing in the office of the expert(s). Preferably the data are uploaded to a server, which the expert(s) can access at any time.

4.2. *Co-ordination with site staff*

For a successful co-operation between the expert(s) and the on-site geological - geotechnical staff a start up meeting is very useful. In this meeting the site conditions should be discussed, as well as other boundary conditions clarified, like site organization, reporting scheme, etc. As in many cases the external expert(s) will not be involved on a daily basis, but more intensive in times of more critical geotechnical conditions, rules have to be established for the alert of the expert(s). This may be done by fixing warning and alarm criteria as appropriate.

5. Conclusions

The uncertainties associated with underground construction call for continuing design during construction. A continuous adjustment of the excavation and support methods to the actual rock mass conditions contributes to safe and economical tunneling.

A prerequisite for successful application of such an observational approach is an appropriate basic design, which should incorporate means and tools to cope with difficult conditions. Another must is the implementation of an adequate monitoring system, allowing the acquisition of accurate data in due time. The huge amount of data obtained during excavation needs to be processed, evaluated and interpreted. For an efficient decision process the results have to be available practically in „real time“, which requires equipping the site with advanced software for data management and evaluation. Quite some progress was made in this respect over the last decade.

Interpretation of geological, geotechnical, and monitoring data due to the complexity of the ground and the interaction between ground and construction still relies a lot on education and experience. Responsible owners account for this by hiring qualified geotechnical personnel for the site assistance. Not only can qualified staff contribute to reduce accidents and damages, but can also identify opportunities to make the construction smooth and economical by optimally adjusting construction methods to the encountered ground. Hard- and software for the collection, processing and evaluation of monitoring data have enormously improved over the last decade. Last but not least, the contractual setup has to allow the continuous optimization of the construction.

Internet has made it possible to involve also off-site experts at comparatively low cost in real time. All data can be made available on a server, allowing to follow up the construction from any part of the world.

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