Geotechnical Online Support for Tunnels in difficult Ground

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ABSTRACT: Tunnel construction in difficult geological conditions requires special attention in order to satisfy safety demands and economical requirements. In particular in heterogeneous ground the prediction of the behavior of the rock mass is essential to be able to adjust excavation and support in time. Very rarely is the required know-how to cope with geotechnical problems available on site. The Internet allows a nearly real time site assistance by experts located somewhere in the world. Relevant data are transferred via Internet, and the data analyzed with special tools by experts. The behavior of the tunnel is analyzed on its "normality", predictions of the future development of displacements and the geotechnical situation ahead of the face (short term prediction) are made. The result of the analyses and recommendations are communicated by Internet or via phone in urgent cases within a few minutes to a few hours. The intervals of data transmission and duration of involvement of the expert(s) is adjusted to the needs of the site. The paper demonstrates the possibilities of this type of online expertise with the help of selected case histories.

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 complex geological conditions. Thus considerable effort and expertise is required to continuously update the ground model, predict ground conditions ahead of the face, identify possible failure modes, determine excavation and support, and predict and verify the system behavior.

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 dispatch an experienced geotechnical engineer to the respective site and allocate appropriate experts for the problems expected, which support him from their offices in case needed. Data exchange and information is done via Internet.

2 REQUIREMENTS

2.1 *Acquisition of experts*

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

2.2 *Identification of required data and organization of data transfer*

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 lack a bit a "feeling" for the ground conditions, and cannot acquire a personal impression, 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, to which the expert(s) have access at any time.

2.3 *Co-ordination with geologist and geotechnical engineer on site*

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 criteria as appropriate.

3 HARD- AND SOFTWARE

3.1 *Geological on-site mapping*

Traditionally this is done by sketches of the tunnel face, accompanied by the measurement of the orientation of some features, like joints or foliation, and occasionally some photographs. Experience shows that due to the unfavorable working conditions such data often are biased, inaccurate, and incomplete. Another disadvantage of this method of data collection is the requirement to digitize the sketches and measurement data prior to transmission, a process which usually does not improve the quality of the data.

To obtain complete, accurate and unbiased structural data, stereo photographic systems have recently been developed (Gaich et al. 2003). With the evaluation software it is possible to measure the orientations of discontinuities, areas, distances, etc. directly in the 3D image. The software also includes statistical routines for clustering of joint sets.

The processing of the images and the 3D reconstruction can be either done on site or in off-site offices. The latter option in the moment is preferable, as still considerable computer power is required for the processing. Within a few hours after the images were taken, the evaluation can be back on the site.

The advantage of such a system is that the evaluation can go into as many details as needed, as all features are recorded. In contrast to that a conventional face map contains only what the geologist did see or recognize. Any feature overlooked during the mapping hence is lost.

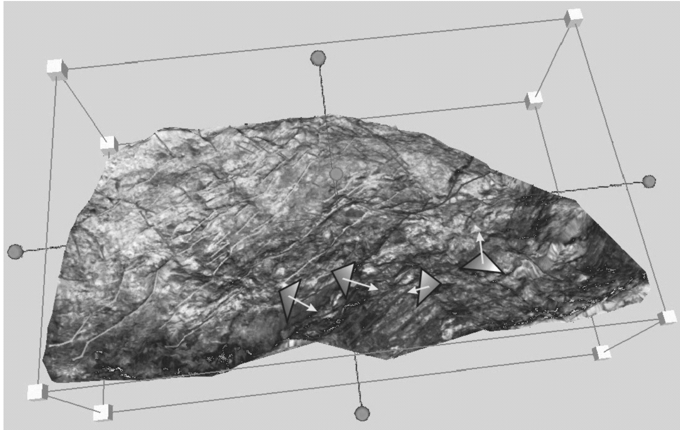

Figure 1. Evaluation of joint traces and measurement of discontinuity orientations from a 3D image

The off-site service not necessarily is limited to the 3D reconstruction, but can include also updating of the geological model and prediction of the geological conditions in the volume of interest ahead and around the tunnel. Also the preparation of reports (daily, weekly, monthly, or final) can be outsourced to off site facilities. This allows the on-site staff to concentrate on the daily duties, not being distracted from routine drawing work, which can be done much more efficiently in well equipped offices with experienced staff.

3.2 *Software for the evaluation of displacement monitoring data*

Over the last decade a number of programs have been developed for the evaluation and display of displacement monitoring data. On site an easy to use and flexible tool should be used to be able to quickly view results. The software should allow plotting displacement histories, deflection lines, and displacement vector plots in the cross section as a minimum. It should be also possible to calculate the pre-displacements to compensate different zero reading times in different measuring sections.

It is important that the data format of the software on site is compatible with that of the users off site. The most advanced product presently is the evaluation software Tunnel:Monitor (Tunnelmonitor, 2004) because of its flexibility, open data format (XML), and the various display options.

For more advanced analyses and prediction of displacements we use the software GeoFit (Sellner, 2000, 3G). This tool allows predicting the development of displacements under consideration of non-steady advance, sequential excavation and various support options. The actual displacements can be continuously compared to the predicted ones, and thus any deviations from the "normal" behavior identified immediately. In addition the tool allows predicting also the ground quality outside of the visible area, e.g. ahead of the face. This allows a timely adjustment of excavation and support. For an optimal result expert knowledge is required for interpretation and reliable conclusions.

4 APPLICATION

4.1 *Shallow tunnel in a tectonic mélange, Case 1*

Extremely heterogeneous ground conditions characterized this tunnel site. Frequently changing deformation characteristics made the adjustment of excavation and support and the prediction of the system behavior very difficult. The owner sought for expert assistance after considerable difficulties were encountered during excavation. The geotechnical engineer on site had standard evaluation software, while in the expert's office GeoFit was used. To save costs, data were transferred only when the geotechnical engineer thought he needed some assistance. Unfortunately the Internet connection of the site was rather poor, making the data transfer unreliable. In addition the discontinuous delivery reduced the efficiency of the expert advice, as time consuming familiarization with the conditions was required each time data arrived. Even with this less than perfect procedure valuable advice could be given in several critical situations, without the necessity to go to the site frequently.

An example shall show the advantage of using advanced software for the evaluation of displacement monitoring data (Sellner et al, 2002). The tunnel was excavated in a top heading – bench – invert sequence, with a temporary top heading invert, where required.

The development of the displacements was predicted with GeoFit. Figure 2 shows a crown settlements of a measuring section which was installed immediately before the Christmas break. It can be seen that the observed displacements were pretty close to the predicted ones for a long period of time.

When the excavation met exceptionally weak material displacements even 30 m back from the face increased considerable, deviating from the predicted "normal" behavior (figure 2).

Two scenarios were considered. One option was that the temporary invert failed the other one that there was also a failure in the rock mass itself. In the first case, the displacements after the sudden increase should stabilize again and follow the predicted displacements for a support without temporary invert (dashed line in figure 2). In the second case, displacements would exceed the values predicted for the support without temporary invert.

As can be seen from figure 3 the assumption of the failure of the top heading invert was correct, as the further displacements followed those predicted for the case without temporary top heading invert. The pause during the Christmas break allowed the shotcrete to cure, increasing its stiffness, and thus make it more sensible to additional displacement caused by the further advance of the face than would be the case with a continuous advance.

As the trend of the displacements was not indicating any stability problem, but only a slight increase in total displacements it was decided to accept the additional displacements. No strengthening of the support or other mitigation measure was required. The fact that shotcrete linings suffer damage after the restart of the excavation after a longer break is well known. In this special case this effect was superimposed by additional displacements due to the weak material at the face.

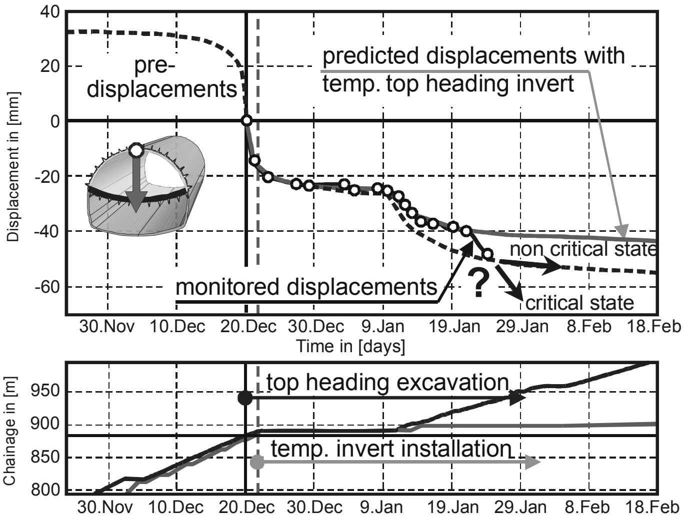

Figure 2. Predicted displacements without temporary invert (dashed line) and with temporary invert (solid line). Deviation of the observed displacements from the predicted ones.

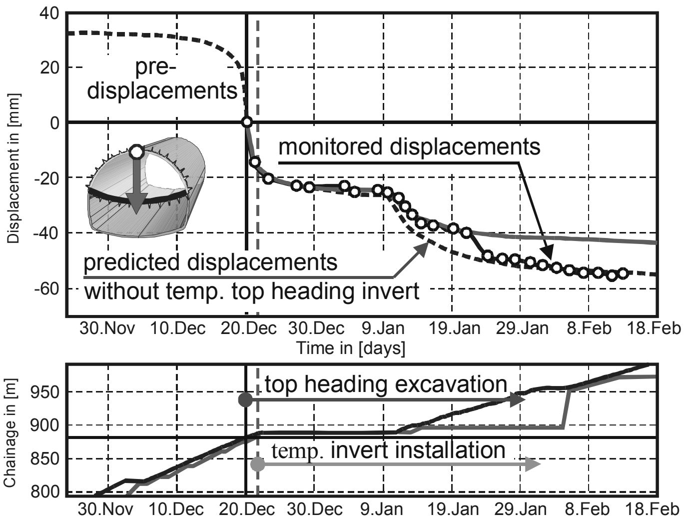

Figure 3. Displacements stabilizing at the level of those predicted without top heading invert after its failure.

4.2 *Shallow tunnel in a tectonic mélange, Case 2*

This tunnel is located basically in the same formation as that described above. The excavation of this tunnel started later than that described above. The assistance of the on-site geotechnical engineer was planned right from the beginning. The transfer of the displacement monitoring data was done on a nearly daily basis, allowing a continuous follow up of the project from the off-site offices. On demand also face maps and data sheets were transferred. Besides a continuous evaluation of the stability, the focus of the assistance in this project was put on the short term prediction of the conditions ahead of the face to allow for a timely adjustment of excavation and support to the frequently changing ground conditions.

For the evaluation of the displacement monitoring data on site standard software was available (ARGUS), while in the experts' offices GeoFit was used. In the course of the project the geotechnical engineer on site was trained in the use of GeoFit, and the software installed on site as well. This showed to be very efficient, as the same graphs could be displayed in both offices, easing the communication.

The trend of displacement vector orientation proved to be a good parameter to predict changes in the rock mass quality ahead of the face in the past in tunnels with high overburden (Steindorfer, 1998). At this project it could be shown that this is also applicable for tunnels with shallow overburden provided the quality of the measurement data is excellent.

Figure 4 shows the transition from a larger block to a block-in-matrix structure. It shows that the displacement vector orientation changes already when the face is well ahead of the transition, while the radial displacements still remain at a pretty low level (Moritz et al. 2004).

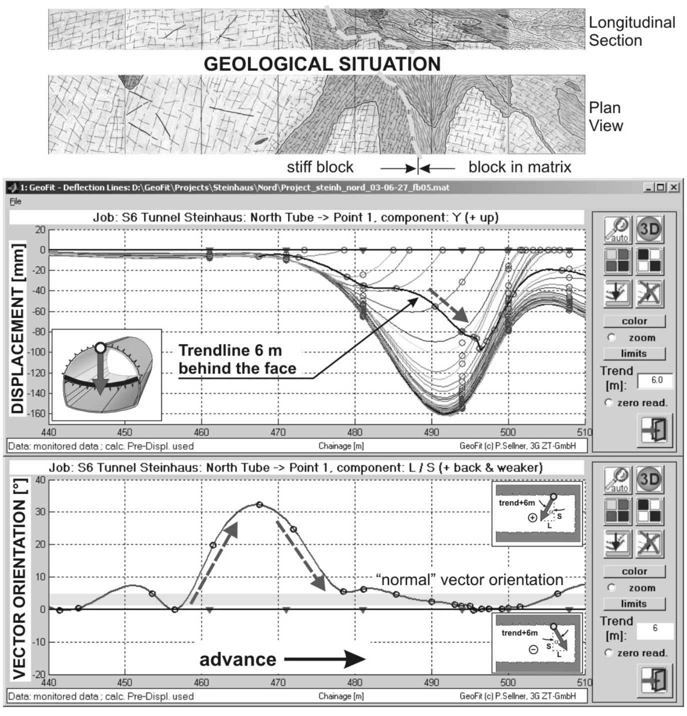

Figure 4. Geological map of a transition from a block to a block-in-matrix structure (top); deflection curves of the crown settlement (center), and trend line of the displacement vector orientation (bottom)

Although such findings have been published since quite some time (Schubert & Budil 1995, Steindorfer 1998, Golser & Steindorfer 2000, Schubert et al. 2002) not many engineers on site are familiar in using these techniques.

4.3 *Tunnel in foliated rock with high overburden*

This case deals with an Alpine tunnel in foliated rocks with an overburden of up to 600m. The orientation of the tunnel axis is nearly parallel to the foliation, which is dipping steeply. Here the off-site advice was done for the contractor, who wanted to optimize excavation and support to achieve good advance rates.

An analysis of the displacement patterns observed was followed by an identification of basic behaviors for different rock mass structures. Figure 5 shows a typical displacement vector plot in the cross section within this material. It can be seen that the displacements are rather unsymmetrical. The numerical simulation clearly shows that shearing along foliation and discontinuities is responsible for this behavior.

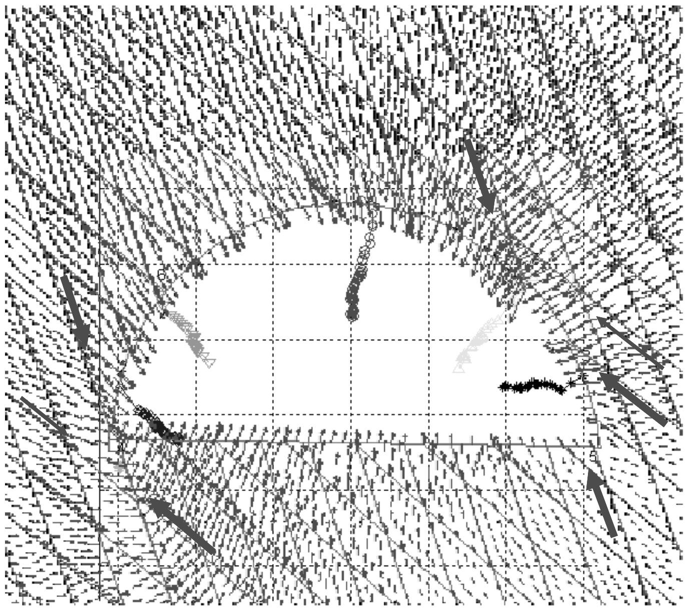

Figure 5. Analysis of displacements and mechanisms; comparison with monitored displacements

Evaluation of monitoring data and numerical analyses showed that the largest displacements usually are at the shoulder situated below the foliation, obviously due to a pronounced dilation more or less perpendicular to the foliation. Displacements on this side in average were 1.5 to 1.7 times the displacements of the opposite side, where the tunnel is above the foliation (Button 2004). With the numerical simulations typical behavior patterns could be recognized, which again allow understanding the rock mass response and thus enable to appropriately adapt the support.

By adding typical smaller shear zones to the basic model, good agreement could be achieved with the measured displacement patterns (Figure 6). Analyses like the ones shown here are not at all common on site due to lack of time and resources, but can provide valuable input for the selection of excavation and support.

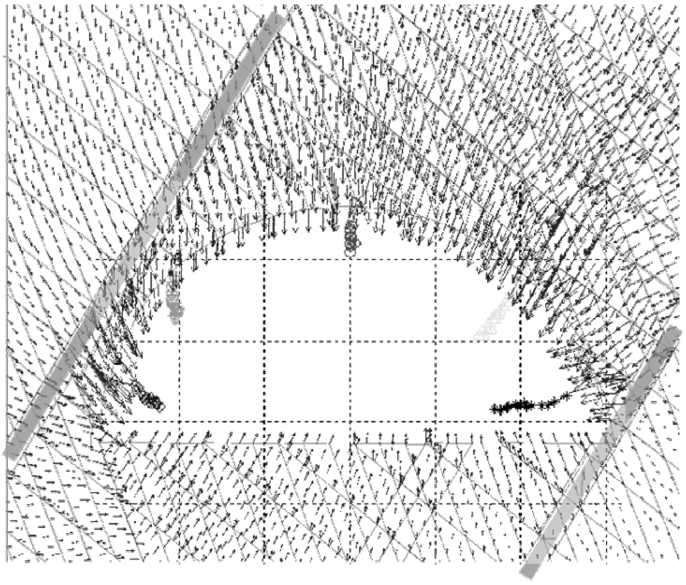

Figure 6. Analysis of mechanisms by a numerical analysis and comparison to the measured displacements

Although the models used were rather simple, the basic phenomena could be shown and the understanding of the rock mass response enhanced. This put the on-site team in a position to quicker react to changes in the system behavior. This is especially important in squeezing ground, where the amount of overexcavation to allow for expected displacements has to be continuously adjusted.

In a section with an overburden of more than 600m a pronounced deviation of the measured displacements from the predicted ones was observed (Figure 7).

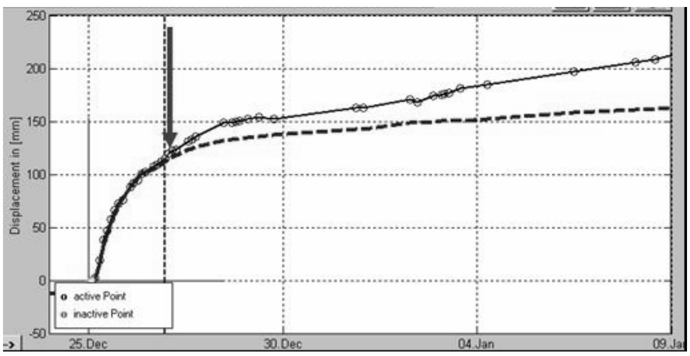

Figure 7. Predicted horizontal displacements for the left sidewall (dashed line), and observed displacements (solid line), showing a deviation approximately 20 days after excavation.

One might be tempted to interpret the long lasting displacements as a creeping process, which is higher than originally expected. Using the displacement vector plot in the cross section, one can see that at a certain time the mechanism must have changed (marked with circles at the sidewall vectors in figure 8). It was found that a wedge in the top heading invert had been squeezed upwards, leading to a relaxation in the bench area, which again caused the increased displacement in the top heading.

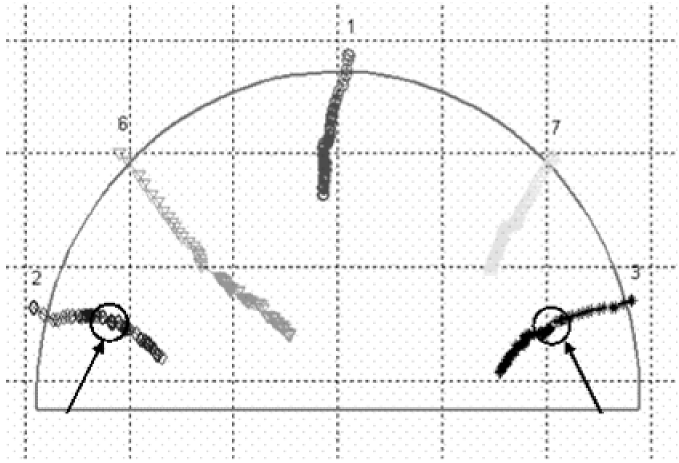

Figure 8. The onset of the invert heaving can be seen from the change in displacement vector orientation (marked with circles).

5 CONCLUSION AND OUTLOOK

Off-site expert support can considerably help in on-site decisions at relatively low costs. The quick and easy transmission of even large data volumes via Internet allows the off-site expert to keep track of the ground conditions and system behavior. The accumulated experience of many cases can thus be utilized for the benefit of a site. Up to now, fixed rules for the evaluation and interpretation of monitoring data are rare. Thus an individual judgment of specific situations is required by an experienced expert. As the experience of on-site engineers not always is adequate to cope with non-standard situations, unbiased external support can be helpful in preparing and making the required decisions. The involvement of the expert depends on the complexity of the ground conditions, on the available experience on site, as well as the boundary conditions of the project. The support can be asked for, when there is a real demand on site and reduced in sections with less difficulty. Thus a very economical use of the resources is possible, avoiding maintaining high-level expertise all the time on site, which is difficult to acquire anyway.

To solve difficult questions, sometimes the use of special software for data evaluation and simulations is required. It would be rather uneconomical to provide all the tools for an on-site application, especially as the on-site staff would require extensive training to be able to use them appropriately.

The easy access to the data from anywhere in the world also does not require the expert being at his office, increasing his availability.

As the services of the off-site expert can be ordered as required and reduced to a minimum involvement in sections with less difficulty, this model is very cost efficient.

An efficient support however is only possible when the data made available by the site are of excellent quality. With incomplete and poor quality data even a most experienced expert will have difficulties to draw correct conclusions.

The quick and easy data transfer via Internet also allows outsourcing other services from the site, like evaluation of stereo photographic face maps, geological short term prediction, or preparation of geological and geotechnical final reports. In most cases the external offices will be better equipped with software and trained personnel than the site itself. This allows the on-site staff to concentrate on their key tasks. An additional advantage is that the off-site personnel in general are less biased and less strained by contractual boundary conditions, allowing concentrating on the technical matters. The value of an independent second opinion should not be underestimated.

In Austria for sites with difficult geotechnical conditions it is common to appoint an independent expert right from the beginning of construction, supporting the site in all geotechnical and stability issues, as well as serving as an arbitrator in case of technical disagreement between contractor and client.

With the further development of telecommunication online communication with the engineers on site directly at the face will be possible. With the help of a video camera carried by the on-site engineer it is possible that the off-site expert sees the same as the on site engineer and gets a better “feeling” for the conditions on site.

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