Volkmann, G.M., & W. Schubert. 2006. Optimization of excavation and support in pipe roof supported tunnel sections.
In Proceedings of the 32nd ITA-AITES World Tunneling Congress, Seoul, 2006, in press. 404 ff.

Optimization of Excavation and Support in Pipe Roof Supported Tunnel Sections

Volkmann Günther[1], Schubert Wulf[1]

[1] Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria

ABSTRACT

This paper presents results obtained from chain inclinometer measurement campaigns during tunnel construction. The applied system allows monitoring of settlements ahead of the face at the depth of the tunnel. These data supplement state-of-the-art 3D geodetic monitoring data to better understand the ground – support interaction. The evaluation of the data enables the optimization of the used support system, maintaining project relevant limitations as well as determining changes in the rock mass quality ahead of the face. Furthermore, the presented observations highlight relevant results for the design of pipe roof supported tunnels.

1. INTRODUCTION

The construction of infrastructure tunnels in cities normally pass below structures founded in soil. At such buildings limitations of the settlement and/or differential settlements due to the construction dominate the design of excavation and support. Changes in the ground conditions and the uncertainties inherent in the ground model require a continuous monitoring program. The results from this monitoring system can detect critical developments in time allowing the excavation and support method to be adjusted.

This continuous process of adjusting the construction not only increases safety, but is also very economical when the data are continuously analyzed. Normally observing the system behaviour is done with geodetic methods in the tunnel as well as on the surface. Inclinometers and extensometers installed from the surface can be used to compliment the geodetic measurements, but their locations are often limited by access or pre-existing structures. Using geodetic systems, deformations can only be measured in the excavated and supported area at the tunnel level. Deformations before the "zero" reading can only be estimated.

In weaker ground a significant part of the deformations occurs ahead of the face; before the "zero" reading is taken. Thus in some cases additional measurement methods have to be applied to obtain a full picture of the processes associated with tunnel excavation. By using a chain inclinometer system, the settlements ahead of the face can be measured and changes in the ground as well as the ground-support interaction determined. These additional data lead to a detailed assessment of the ground support interaction in relation to the actual ground conditions and allow the project limitations to be maintained.

2. STATE OF THE ART & CHAIN INCLINOMETER MEASUREMENTS

Observations and measurements already have a long tradition in tunnelling (Rabcewicz 1944). The measurement data are used to evaluate the excavation induced displacements (Rabcewicz 1963, Steindorfer et al. 1997). Today, geodetic three dimensional observations are state of the art for the collection of displacement data.

The geodetic survey is performed both in the supported tunnel section and on the surface. The measurement frequency is commonly once per day, in special cases readings are taken more frequently. With this system it is not possible to measure the total settlement path at the tunnel level but by using specialized display methods it is possible to observe the spatial and temporal influence of the construction process on the displacements behind the face (Schubert et al. 2002). The information is used to better understand mechanisms and rock mechanical processes in the ground (Steindorfer 1997, Golser et al. 2000, Button et al. 2003, Schubert 2004). Considering the different distances and times in between the face and the "zero" reading it is possible to estimate the displacements between the face and the measuring location. That makes the collected data behind the face more comparable and improves the quality of the geotechnical evaluation. Additionally, special software can predict the development of displacements after a few readings only, considering the influence of time, advance and various support options (Sellner 2000, Sellner et al. 2002).

Especially in shallow tunnels with strong support the geodetical observation does have limitations. Therefore an additional measurement system can supplement the data for a better understanding of the rock mass – support interaction. An in-place chain inclinometer system installed parallel to the pipe roof system meets this demand. The applied system consisted of 10 inclinometer links with a length of 2 m. This system allows the settlements ahead of and immediately behind the tunnel face to be measured, with the data collected in pre-defined time intervals.

3. BENEFITS OF THE INCLINOMETER MEASUREMENT SYSTEM

3.1 Additional information during excavation

In figure 1 the settlement characteristics over time induced by one excavation step starting at 03:00 on the 17th of August is exemplarily displayed. By collecting data every minute it is possible to observe in great detail the development of the settlements. After starting the excavation of phase 1 it can be seen that the settlements start increasing very slowly. In this time the excavator broke the shotcrete temporarily supporting the face. After this the settlements increase rapidly indicating the time when the rock mass was excavated. The stresses stored in this material have to be transferred to the remaining ground. This stress transfer induces the development of the displacements. After each excavation phase the unsupported span and the unsupported areas of the new face are supported with shotcrete. In this time the increase of the settlement values slows down indicating a time dependent stabilization process around the heading. As can be seen in figure 1 this process is interrupted by the next excavation phase. Similar characteristics can be observed in every excavation phase.

The deflection curve in figure 2 demonstrates the influence of the excavation step from chainage 254.21 to 254.88 on the settlements in the longitudinal direction of the tunnel. It can be seen that the

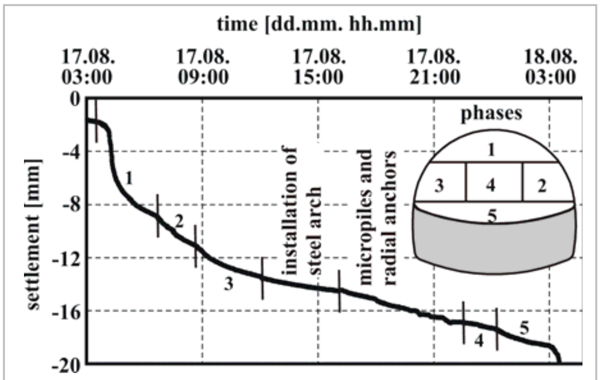

Figure 1. Time settlement line monitored by chain inclinometers

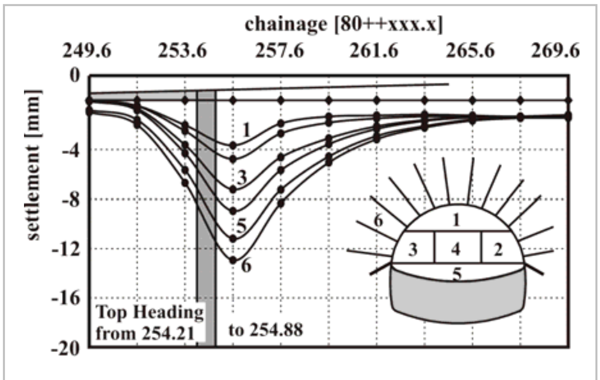

Figure 2. Single deflection curves diagram - settlements in the longitudinal direction

main area influenced by the excavation starts 4 m behind the face and ends 9 m ahead of the face. The maximum value could be measured approximately 1 m ahead of the face. Due to the relatively stiff lining used in the Trojanetunnel (Slovenia) (Likar et al. 2004), the settlements induced by the excavation process behind the face are rather low. This behaviour showed to be characteristic on this particular site. With geodetic monitoring alone, only a minor part of the total displacements can be recorded (Volkmann et al. 2003), possibly leading to wrong conclusions about the system behaviour.

3.2 Additional information during installation of support

Due to the fact that conventional monitoring systems do not continuously record displacements, the influence of different activities in the tunnel cannot be evaluated in detail. After the excavation of the first three phases the installation of the support consisting of wire mesh, steel girders and shotcrete took place. In this time the stabilization process continues (figure 1).

The following installation of the radial rock bolts and micro piles at the top heading footing causes additional settlements with a maximum around 2 mm. The characteristic of this settlement increase is nearly linear over time (figure 1) and the longitudinal extension is comparable with that one of an excavation phase (figure 2). In contrast to this; face bolts, spiles or pipe roof installations cause settlements primarily ahead of the face (figure 4 & 5).

The results of the measurements made till now demonstrate that all drilled supports such as radial bolts, face bolts, spiles and pipe roof systems do have the potential to increase the settlements during their installation depending on the strength and stiffness of the ground.

4. IDENTIFICATION OF CHANGES IN THE ROCK MASS QUALITY

Changes in the displacement vector orientation can be used for a short term prediction of the rock mass quality ahead of the face (Schubert et al. 1995). In cases of a rather stiff lining this method is limited because the deformation in the supported area is damped. Using a chain inclinometer monitoring system changes in the rock mass quality can be identified directly by changes in the measured settlement characteristics.

The chain inclinometer extends up to 20 m ahead of the face. Therefore a normal settlement characteristic ahead of and behind the face can be specified by the earlier observations. Changes in the settlement behaviour can be monitored and evaluated. The differences can be changes in the measured values as well as changes of the distribution in the longitudinal direction (figure 3).

A change in the rock mass quality not only changes the settlement values but also the rock mass – support interaction. Therefore, the observations made when an excavation approaches a weaker zone will be explained. The deflection curve diagram shown in figure 4 indicates normal settlement behaviour till the excavation reaches approximately chainage 254.0. Only the more detailed evaluation of single excavation phases denoted at this time that there may be a change in the rock mass quality. In the following two excavation steps the outstanding change, displayed by the trend lines, is the area in between the face and 3.2 m ahead of the face. Ahead of 257.5 the settlement values relatively decreased whereas the values in between this chainage and the face relatively increased with the same amount. A slightly stiffer material around 258.0 caused this change in the stress transfer. During the following two excavation steps the trend at the face did not change but all trend lines ahead of the face denote a weaker zone indicated by increasing displacement values. With the excavation of the stiffer block the displacements ahead of the face

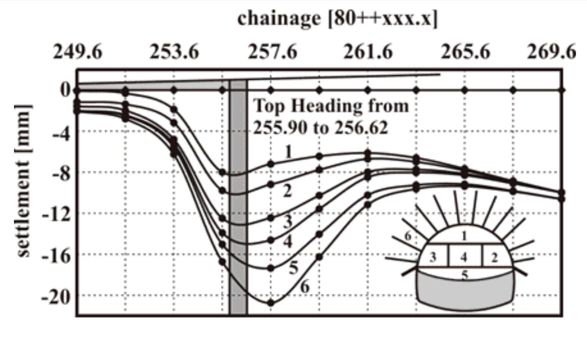

Figure 3. Single deflection curve – non normal settlement characteristic caused by a weaker zone ahead of the face

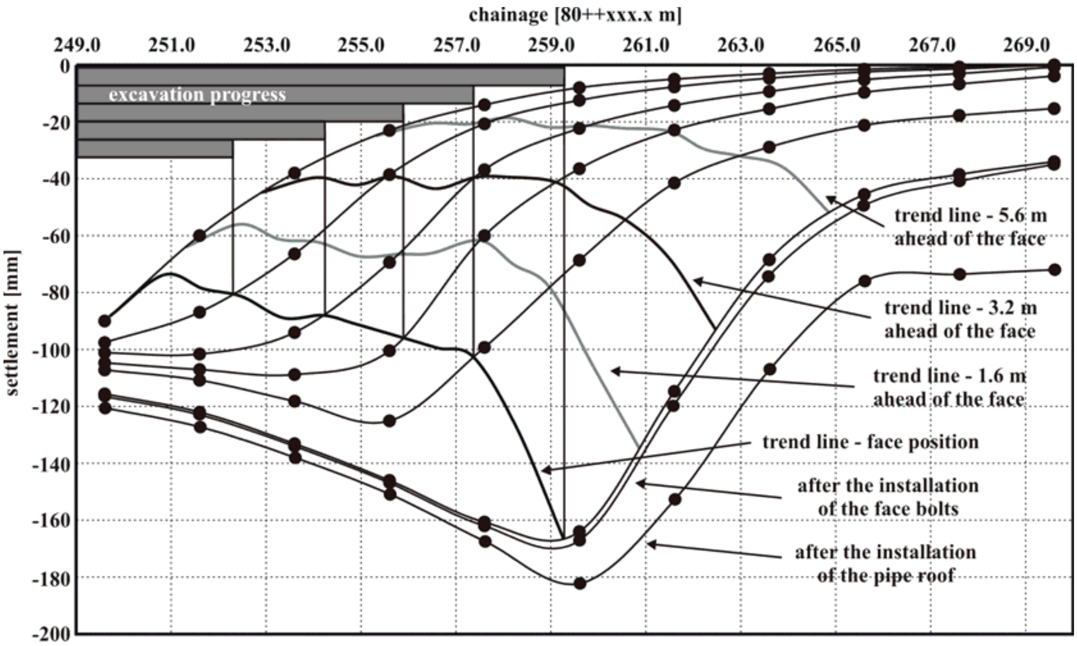

Figure 4. Deflection curves diagram – settlements measured during the construction of the pipe roof supported Trojanetunnel (Volkmann 2005)

increase significantly although the actual face is in relatively stiff material. This change of the ground – support interaction by weakening the bedding ahead of the face resulted in an adaptation of the support. By an immediate installation of a new pipe roof the overlapping length was increased. The old pipe roof pipes acted more like a cantilever founded at the shotcrete arch from the new installation while the new pipes were bedded ahead of and behind the face. With this adaptation of the support the weak zone could be passed without any further problem or major changes in the surface settlement trends.

5. CHOICES FOR THE PIPE ROOF INSTALLATION SYSTEM

There are two different systems for the installation of the pipe roof support. One is the cased-drilling and the other is the pre-drilling system. The characteristic of a cased-drilling system is that the pipe follows directly behind the drilling bit and the backflow of the flushing during the drilling process primarily happens in the pipe. Compared to this; the pre-drilling system means that the holes for the installation of the pipes are drilled first, with backflow occurring in the open hole, and in a second step the pipes are installed in the pre-drilled holes. Figure 5 shows a comparison of the settlements during pipe roof installation of the Birgltunnel (cased drilling system) and the Trojanetunnel (pre-drilling

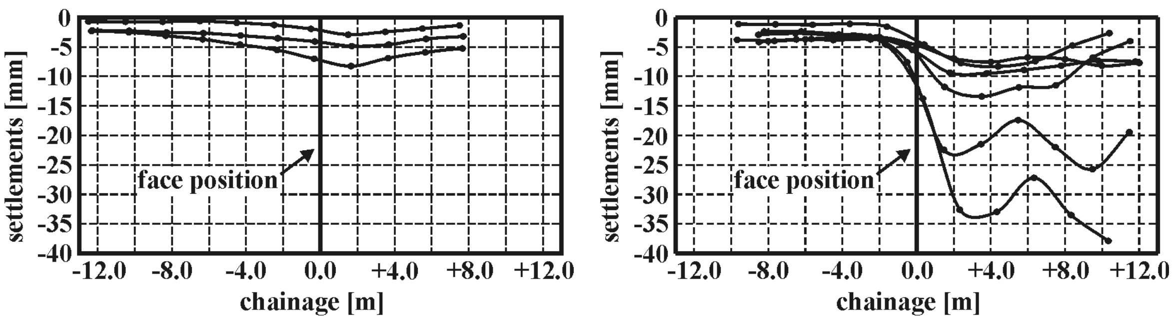

Figure 5. Settlements measured in the time of the installation of the cased – drilling (left) and the pre – drilling (right) pipe roof system (Volkmann 2004)

system). It can be clearly seen that the cased drilling system results in smaller displacements. Both measurement campaigns displayed nearly the same total settlements due to the excavation. This makes the conditions of both projects comparable.

The reasons for this difference in the settlement amounts can be explained by two effects. The first one is the immediate support for the hole when using the cased-drilling system. This limits the possibility for closing the annular gab between the drilling bit and the outer pipe diameter. In a pre-drilled hole the deformations are generated directly behind the drilling bit due to new kinematic freedoms. As seen on site the deformations occur so fast that the backward movement of the drilling bit reshapes the drilled hole. The second reason for the higher settlement amounts is the erosion at the walls of the hole by the flushing. This enlarges the diameter resulting in bigger deformations.

At some projects the amount of subsidence is not relevant for the design. For such cases it should be mentioned that the closing of the holes may make it impossible to completely install the pipes, decreasing the safety for the following construction steps (figure 6).

As figure 7 displays, a simple numerical 2D study can help in choosing the correct installation system. The comparison of the calculated results shows that the unsupported hole closes whereas the pipe supports the surrounding walls of the hole.

Both, the measurements on site and the numerical simulation showed that especially in weak ground a cased-drilling system is less susceptible to settlements than a pre-drilling system (Volkmann 2004). The pre-drilling system should therefore only be applied when the stability of the pre-drilled hole can be guaranteed and the deformations of the unsupported hole are negligible.

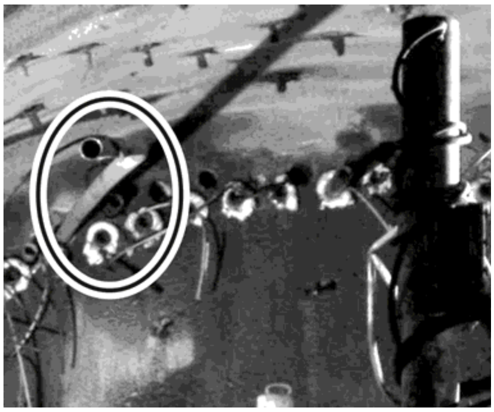

Figure 6. Broken pipe due to the closing of the pre-drilled hole

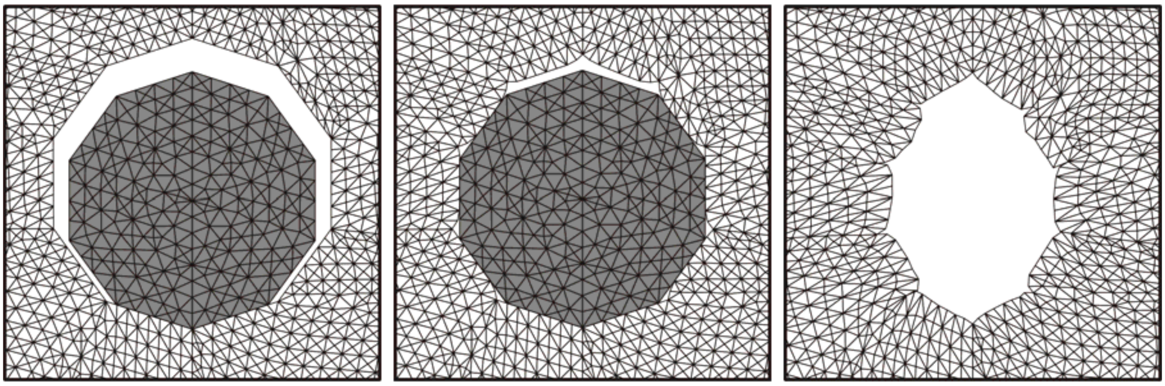

Figure 7. Comparison of numerical investigations on the closing of cased-drilled and pre-drilled holes, each plot is 30 cm x 30 cm and the displayed deformations are scaled to absolute values

6. OPTIONS FOR SUPPORT OPTIMIZATION

Optimizing the support or excavation methods can have different goals. In some projects limitations preventing damages to surface structures dominate the construction decisions. Other projects only require a safe construction where a minimization of support reduces the costs. By using the accurate evaluation results of a chain inclinometer monitoring, the excavation and support can be controlled and adjusted depending on the aims of the project. The possibility to “look ahead” of the tunnel face also provides preparation time for any required changes and allows the engineer to react appropriately to the actual ground conditions.

7. CONCLUSION

Observations and measurements already have a long tradition in tunnelling to evaluate the excavation induced displacements. Nowadays geodetic three dimensional observations are state-of-the-art for collecting displacement data. Especially in weak ground the construction of shallow tunnels can be controlled more efficiently by additional measurements performed with chain inclinometers. The collected data provide information about the ground – support interaction as well as the conditions of the rock mass ahead of the face. This enables the optimization of the support system concerning the project limitations. The continuous optimization not only increases safety, but also leads to a very economical construction process.

REFERENCES

Button, E. A., Schubert, W., Riedmüller, G. 2003. "The Use of Monitoring Data and Geological Documentation as a Basis for Defining Rock Mass Behaviour Types." Proc. of the 6th International Geotechnical Conference, Bratislava, 89-98.

Golser, H., Steindorfer, A. 2000. "Displacement Vector Orientation in Tunnelling – What Do They Tell?" Felsbau 18, Nr. 2, 16-21.

Likar, J., Volkmann, G., Button, E. 2004. " New Evaluation Methods in Pipe Roof Supported Tunnels and its Influence on Design during Construction." Proc. of the 53rd Geomechanics Colloquy and EUROCK 2004, Salzburg, Austria, 277-282.

Rabcewicz, L. 1944. "Gebirgsdruck und Tunnelbau." Vienna: Springer Verlag

Rabcewicz, L. 1963. "Bemessung von Hohlraumbauten. Die Neue Österreichische Bauweise und ihr Einfluss auf Gebirgsdruckwirkungen und Dimensionierung. " Felsmechanik und Ingenieurgeologie, Sonderabdruck aus Vol. I/3-4, 224-244. Vienna: Springer Verlag

Schubert, W., Budil, A., 1995. "The Importance of Longitudinal Deformation in Tunnel Excavation." T. Fujii (ed.), International Congress on Rock Mechanics; Proc. intern. symp., Tokyo: 1411-1414. Rotterdam: Balkema.

Schubert, W., Steindorfer, A., Button, E. A. 2002. "Displacement Monitoring in Tunnels – An Overview." Felsbau 20, Nr. 2, 7-15.

Schubert, W. 2004. "Tunnelling in Alpine Fault Zones – Excavation and Support Strategies." Proc. of the 5th International Conference on Case Histories in Geotechnical Engineering, New York.

Sellner, P. 2000. "Prediction of Displacements in Tunnelling." PhD Thesis, Graz University of Technology, Institute for Rock Mechanics and Tunnelling.

Sellner, P., Grossauer, K., Schubert, W. 2002. "Advanced Analysis and Prediction of Displacements and System Behaviour in Tunnelling." Proc. of ISRM International Symposium on Rock Engineering for Mountainous Regions, EUROCK 2002, Funchal, Madeira, Portugal, 539-546.

Steindorfer, A. 1997. "Short Term Prediction of Rock Mass Behaviour in Tunnelling by Advanced Analysis of Displacement Monitoring." PhD Thesis, Graz University of Technology, Institute for Rock Mechanics and Tunnelling.

Steindorfer, A., Schubert, W. 1997. "Application of new Methods of Monitoring Data Analysis for Short Term Prediction in Tunnelling." Proc. of the 23rd General Assembly of the International Tunnelling Association, Vienna, 65-69.

Volkmann, G., Button, E. A., Schubert, W. 2003. "Influence of Zero Reading Time and Position on Geotedetical Measurements." International Symposium on GeoTechnical Measurements and Modelling. Karlsruhe, Germany, 101-104.

Volkmann, G. 2003. "Rock Mass – Pipe Roof Support Interaction Measured by Chain Inclinometers at the Birgltunnel." International Symposium on GeoTechnical Measurements and Modelling. Karlsruhe, Germany, 105-109.

Volkmann, G. 2004. "A Contribution to the Effect and Behaviour of Pipe Roof Supports." Proc. of the 53rd Geomechanics Colloquy and EUROCK 2004, Salzburg, Austria, 161-166.

Volkmann, G. 2005. "The Use of Horizontal Inclinometers for the Optimization of the Rock Mass – Support Interaction." Proc. of the 31st ITA-AITES World Tunnelling Congress, Istanbul, Turkey.