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The Use of Horizontal Inclinometers for the Optimization of the Rock Mass – Support Interaction

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ABSTRACT: Nowadays a number of tunnels are constructed in urban areas in weak rocks with high or low overburden. In both cases geodetic methods are used to monitor displacements and control stability. In special cases additional other measurement systems are used to supplement the information gained by geodetic methods. This paper deals with the information gained by using a continuously recording horizontal chain inclinometer installed from the tunnel face. The increased information on the rock mass – support interaction can be used to better control the construction process and allows detecting unexpected changes in the rock mass earlier than with traditional measuring methods.

1 INTRODUCTION

The uncertainties inherent in each ground model with respect to geological setup and mechanical parameters require a continuation of the design into the construction phase. The behavior of the ground - support system is continuously monitored and excavation and support adjusted to the real rock mass conditions and requirements.

Urban tunneling is usually associated with limitation of settlements and/or differential settlements. By means of continuous monitoring and prediction of displacements critical developments can be detected in time and excavation and support methods adjusted in time.

This process of optimization the construction not only increases safety, but is also very economical, as an "overdesign" to account for uncertainties is not required.

All these facts call for an intensive observation program of the system behavior. Normally this observation is done using geodetic methods, as well on the surface as in the tunnel. As those methods only measure displacements on surfaces (ground surface and tunnel perimeter), deformations of the rock mass can only be estimated. Thus in some cases additional measuring methods have to be applied to obtain a full picture of the processes associated with tunnel excavation.

2 STATE OF THE ART MEASUREMENTS

Observations and measurements already have a long tradition in tunneling (Rabcewicz, 1944). The measurement data are used to control the excavation induced displacements (Rabcewicz 1963, Pacher 1964, Steindorfer et al 1997). Nowadays geodetic three dimensional observations are state of the art for the collection of displacement data.

2.1 *Geodetical Measurements*

Geodetic survey is performed both in the supported tunnel sections and on the surface. Due to the influence of temperature and air pollution the accuracy of the measurements is around +/- 1 mm.

The displacement observation is normally performed in cross sections with five to nine points in the total excavation area. The distances between those cross sections are rarely shorter than 10 m in the longitudinal direction.

The displacements induced by shallow tunnels are normally also measured on the surface. The layout of the measuring points on the surface frequently is determined by the surface structures, such as roads, and buildings, preventing a systematic and regular grid, which would be preferable for complete information on the subsidence.

The frequency of the measurements commonly is one per day, in some cases readings are taken twice a day.

2.2 *Evaluation*

Various methods of data evaluation and presentation exist and are used to support the control of the system behavior. By using different display methods like development of displacements as a function of time or tunnel advance, deflection curve diagrams, displacement vector diagrams, etc. it is possible to observe the spatial and timely influence of the construction process on the displacements. (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, Schubert 2004; Schubert et al. 2003)

Special software has been developed to 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. 2000, Sellner et al. 2002).

2.3 *Shortcomings*

With the geodetic measurement system it is not possible to measure the total settlement path at the tunnel level. Due to the fact that the measurement targets are installed only behind the face after support installation displacements ahead of the face and between face and monitoring section cannot be measured.

Considering the different distances and times in between the face and the zero reading it is possible to extrapolate the pre-settlements to the face with evaluation programs. That makes the collected data behind the face more comparable and results in a better quality of the geotechnical evaluation. (Sellner 2000)

Due to the commonly long interval between the geodetic measurements

- it is not possible to evaluate single excavation steps or single excavation phases.
- it is not possible to evaluate the influence of the support installation on the displacements.

The measured cross sections are often not correlated to periodically installed support like face anchors or pipe roof systems. Due to the fact that the efficiency of such support systems changes with position to the installation the evaluation of the geodetical data becomes more difficult (Volkmann, 2003).

3 INCLINOMETER MEASUREMENT SYSTEM

The estimation of the system behavior using the geodetic survey is more difficult in weaker ground, where the stiffness contrast between the support and the rock mass is more significant and support ahead of the face is used.

For such conditions a measurement system was developed consisting of horizontal in-place chain inclinometers and a data acquisition system.

3.1 *Positioning*

The measurement system was installed in the crown of the tunnel parallel to the pipe roof (figure 1). One chain consists of ten 2 m long links connected to each other. The data acquisition system situated approximately 20 m behind the actual face collects the data. Thus the measurements did not disturb construction.

3.2 *Differences to the Geodetical Measurements*

The density of the observed points in the longitudinal direction is with 2 m much higher than that one from the geodetically monitored points.

The position of the chain inclinometer is primarily ahead of the face (figure 1). The length ahead of the face ranged between 8 m and 20 m (directly after the installation) depending on the position to the last installation in the applications till now.

Data can be acquired in predetermined intervals. For the applications described in this paper one minute reading intervals were chosen.

Even though the longitudinal and horizontal displacements cannot be measured this system supplements the information obtained from the geodetic measurement system.

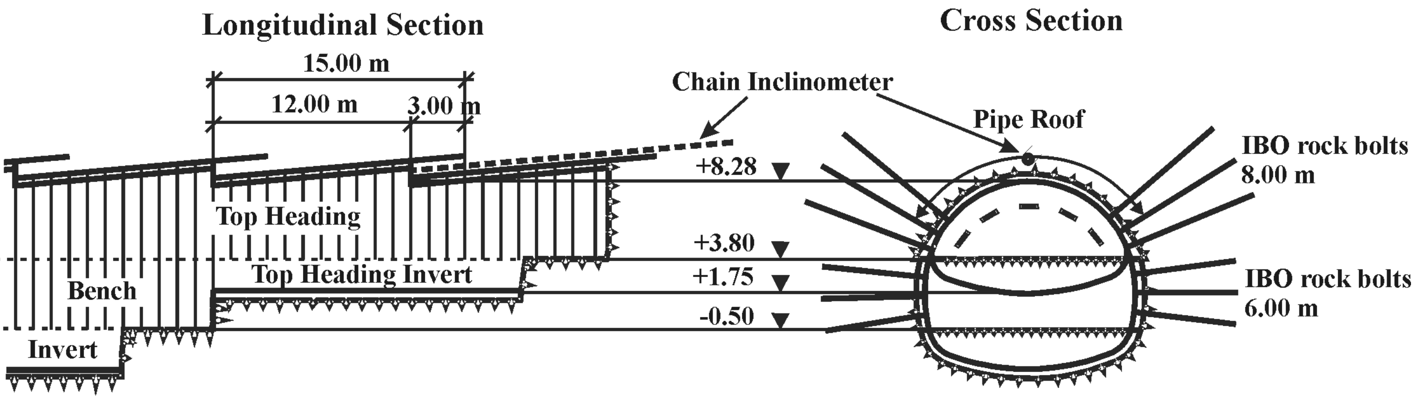

Figure 1. Position of the chain inclinometers (Volkmann et al. 2003)

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4 ADDITIONAL RESULTS

4.1 *Displacements during excavation*

In weak ground frequently sequential excavation is applied. A typical excavation procedure includes excavation of the top heading, followed by the bench and the invert. In case of an instable face the top heading excavation can also be divided into several phases.

Figure 2 shows the development of the settlements during the excavation of a round of 1m length, which was done in two steps. After each step a shotcrete sealing was applied, with the completion of the support, including lattice girders, wire mesh and shotcrete following after step 2.

At the beginning of each excavation phase the displacement rate increases. After completion of the excavation the rate decreases significantly, indicating stabilization.

By using this system an excavation dependent evaluation is possible that can show the influence of each phase on the settlements in the excavation process. The combination of all simultaneously measured inclinometer links creates a deflection curve for an excavation step (figure 3).

Figure 3 shows the settlements induced by the excavation step from Station 254.21 to station 254.88. The top heading was excavated in 3 phases that were followed by the installation of the lining. After that the supporting rock wedge at the face and the top heading invert were excavated and supported. The work in this round was finalized with the installation of radial rock bolts.

A major proportion of the settlements occur in the area from 9 m ahead of the new face to 4 m behind the new face. The maximum settlement value is approximately 1 m ahead of the new face. Due to the pretty stiff lining used in this project, the settlements induced by this excavation phase behind the face are rather low.

This behavior showed to be characteristic on this particular site. With a geodetic monitoring alone, only a minor part of the total displacements could have been recorded (Volkmann et al. 2003), probably leading to wrong conclusions.

A detailed evaluation of the single excavation phases present different stress transfer areas defined by the occurring settlements. Depending on the relative position of the excavation phase the maximum values as well as the area where major displacements occur varies. When excavating the upper portion of the tunnel, the highest settlement values are recorded near to the unsupported area. When excavating the lower parts of the face, the maxima of the settlements are recorded further ahead of the face.

Using the settlement characteristic displayed in figure 3 the expected final settlement amount can be extrapolated. With the assumption of homogeneous ground conditions the area in between zero and the deflection curve defines the final settlement amount due to the excavation of the top heading.

With the detailed information on the spatial and timely deformation process, the excavation layout and timing of support installation can be optimized on site.

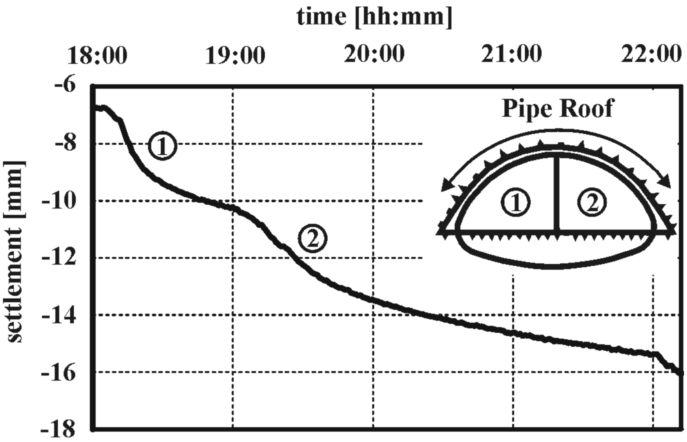

Figure 2. Time settlement line of one top heading excavation

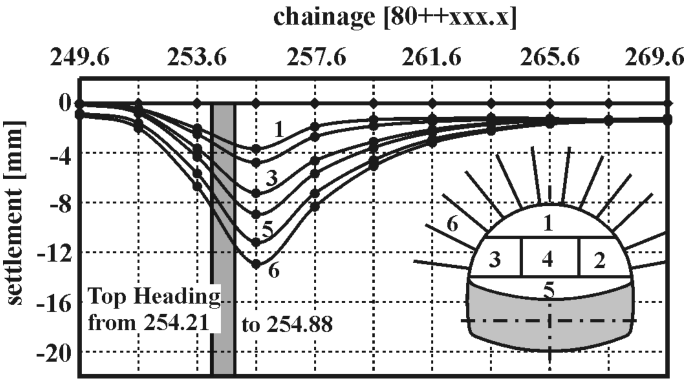

Figure 3. Deflection curve of one excavation step – normal settlement behavior (Volkmann & Button, 2003).

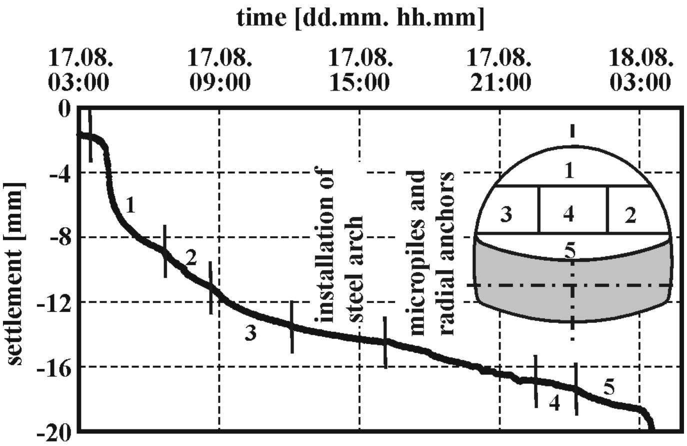

Figure 4. Time settlement line including the installation of radial rock bolts

4.2 *Displacements 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.

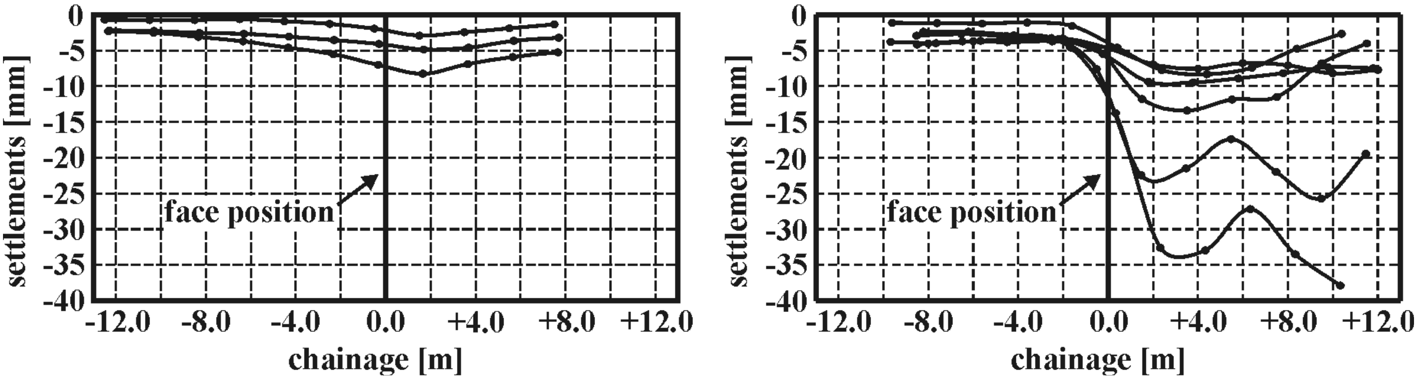

Figure 5. Settlements measured in the time of the installation of the cased - drilling (left) and the pre - drilling (right) pipe roof system (Volkmann, 2004)

Figure 4 shows the development of the settlements during the excavation and support installation process. After the excavation of the first 3 phases a pronounced stabilization process can be observed, which continues through the installation of steel arch and shotcrete. The following installation of radial rock bolts and micro piles at the top heading footing cause additional settlements.

This additional settlement caused by the drilling of bolts and micro piles can be seen also in figure 3. The process causes additional settlements of maximum around 2 mm (difference between the last two lines). The influence can be observed as well ahead, as also behind the face on a couple of meters.

In contrast to this face bolts, spiles or pipe roof installations increase the settlements primarily in sections ahead of the face (figure 5, face position = 0).

The comparison of two different methods of pipe roof installation showed that especially in weak ground a cased-drilling system is less susceptible to settlements than a pre-drilling system (Volkmann, 2004). The reasons for this are the immediate support of the drill hole and the flushing inside the pipe. This way of flushing does not erode the walls of the drill hole. The pre-drilling system should therefore only be chosen when the stability of the pre-drilled holes is guaranteed and the deformations of the unsupported hole are negligible. It has been observed that the installation of the pipes in uncased drill holes was rather difficult due to the convergence between drilling of the hole and installation of the pipe.

The result of the measurements made till now demonstrate that the installation of support like shotcrete with or without wire meshes and all types of arches do not increase the settlements. Supports like radial rock bolts, face bolts or pipe roof systems increase the settlements. The magnitude of this increase is a function of the strength and stiffness of the ground.

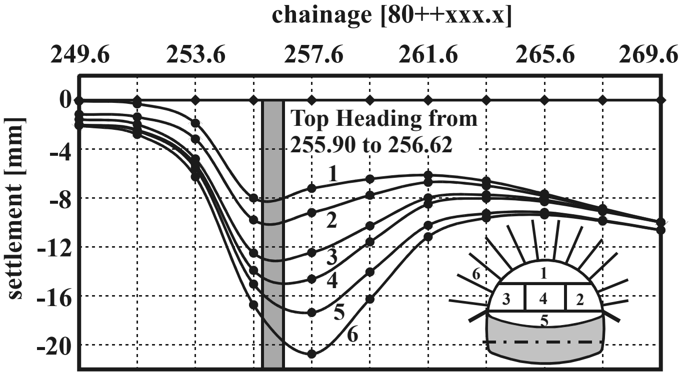

Figure 6. deflection curve of one excavation step– non normal settlement behaviour.

4.3 *Detection of changes in rock mass quality*

Methods have been developed to use the changes in the displacement vector orientation from geodetic monitoring data for the short term prediction of changes of the rock mass quality ahead of the face. In cases of a rather stiff lining however the value of this method of data evaluation is limited. The chain inclinometer on the other hand extends up to 20 m ahead of the face, allowing observing untypical deformations in this section directly.

The measurement of the total deformation path with the inclinometer clearly indicates changes in the rock mass ahead of the face.

The deflection curve shown in figure 6 is a good example how a weaker zone ahead of the face influences the displacements. While influence of the excavation cycle shown in figure 3 can be observed up to about 8m ahead of the face, the cycle shown in figure 6 influenced a much longer section, which extended beyond the end of the inclinometer. This clearly indicates weaker material ahead of the face.

The total settlement path evaluated in a deflection curves diagram (figure 7) can also be used to determine the rock mass quality ahead of the face. When excavating from chainage 252.49 to 253,36 an increase in the displacements between the face and approximately chainage 258 could be observed, with not much influence on the section beyond this station. The next rounds did not cause a significant increase in the displacements, while a considerable increase can be observed again after the face passing chainage 256. The reason for this behavior was a stiffer block embedded in the weak matrix around chainage 258, which "blocked" the progression of the displacements beyond this station. Only when the bedding of the block due to excavation became weaker, the displacements progressed considerably ahead of the face again. At face position 259,3 it was decided to install a new round of pipe roof support, which decreased the displacements during further advance. The weak zone could be passed without further problems (Likar et al. 2004).

4.4 *Further results*

In shallow tunnels the geodetically measured data on the surface generally display higher settlement amounts than in the tunnel. This fact in many cases is explained by consolidation processes of the material. Only when also underground total displacements are measured it can be determined if a consolidation process or relatively high displacements ahead of the face are the reason for high subsidence.

The continuous recording of displacements ahead of the face allows detecting failure mechanisms in the ground practically in real time. This enables to initiate appropriate mitigation measures in time to guarantee stability of the structure.

5 OPTIONS FOR THE OPTIMIZATION

The optimization of support or excavation methods can have different reasons. In some projects the use of support should be minimized to save time and money, while at the same time guarantee stability and safety. In other projects the most important factor is the control of surface settlements or differential settlements to prevent damage to surface structures.

The continuous recording of displacement data with high resolution can help to better understand the complex interaction between rock mass and construction measures. The analysis and interpretation of the geodetic data set can be used for this optimization in normal rock mass conditions.

In environmentally sensible areas with weak ground this system preferably is supplemented by a system as described in this paper to enhance the level of information and to allow for prompt reaction to unusual or unexpected processes.

By using the accurate evaluation results of a chain inclinometer measurement the excavation and support system can be changed depending on the aims of a project. The excavation can be adjusted to the ground conditions. The possibility to "look ahead" of the tunnel face also provides preparation time for any required changes.

The knowledge about the displacements ahead of the face allows optimizing the overlapping length of support systems reinforcing the area ahead the face, like face bolts or pipe roof supports.

By a continuous adaptation of the installed support the system behavior can be fitted to the actual demands. A precondition for a successful adaptation and optimization process is the availability of complete quality data, collected in intervals, which allow for a timely response to any changes in the ground conditions.

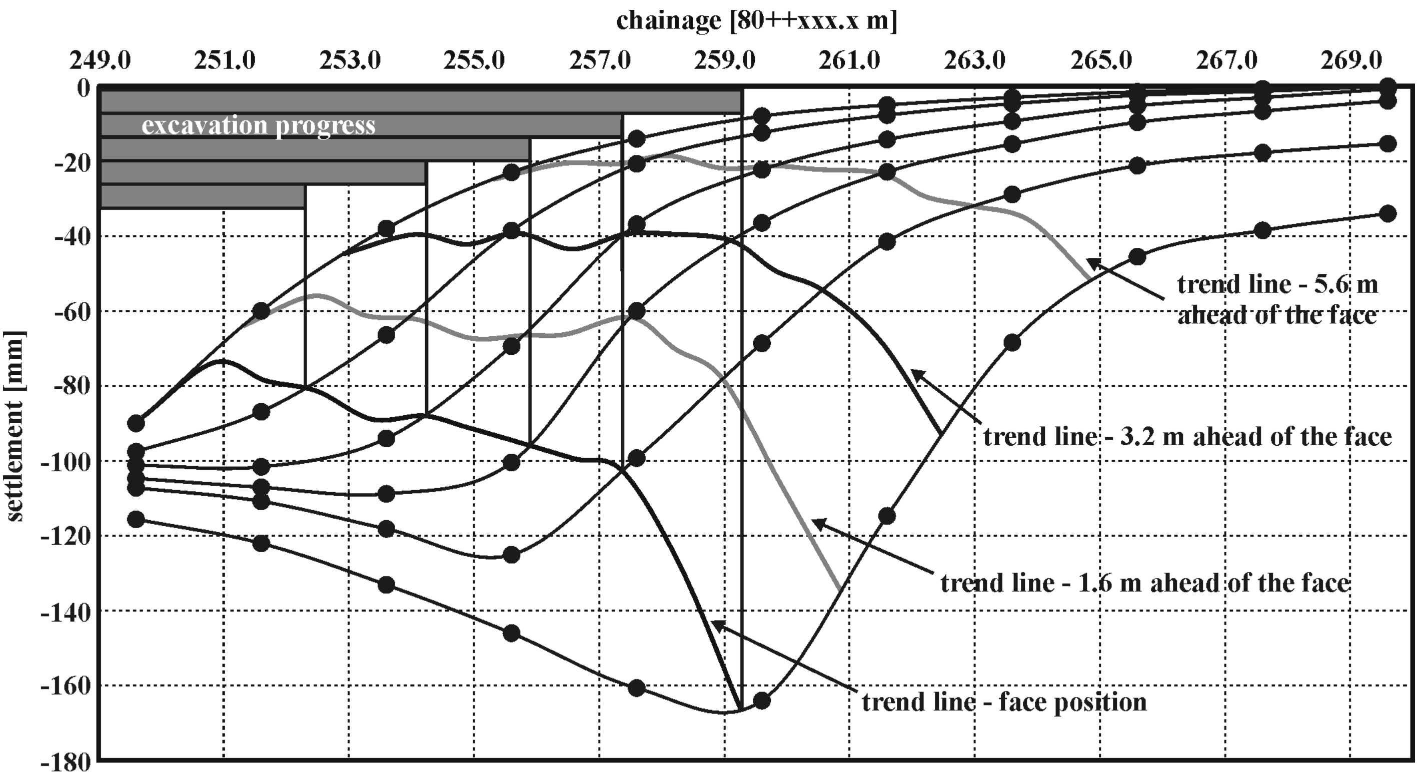

Figure 7. Settlements measured by the chain inclinometer system.

6 CONCLUSION

Tunnels in weak ground and environmentally sensible areas require special attention during design and construction. An extended monitoring program considerably can help in better understanding the complex processes of the interaction between ground and construction, and identify significant influences on the displacements. A continuous recording chain inclinometer system has been successfully applied for a tunnel in faulted rock in a built up area. The complete and in time information on the displacements in the ground allowed an optimization of the construction process, thus minimizing the damages to the surface structures.

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