Tunnelling methods for squeezing ground

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Summary

The paper addresses problems associated with tunnelling in poor ground under high overburden. Prediction of amount of convergence, estimation of creeping effects, and selection of appropriate support are extremely challenging tasks for the tunnelling engineer. While conventional excavation methods offer a certain flexibility to cope with heterogeneous conditions, TBM´s still have to be improved to successfully master fault zones in Alpine tunnels. Emphasis in this paper is put to recent developments in short term prediction of rock mass behaviour, prediction of tunnel closure, and ductile supports.

1. Introduction

When tunnelling in squeezing rock a number of problems have to be dealt with. The main problems are: instability at the face, failing of supports due to high loads, underprofiles caused by excessive deformation, extreme heterogeneity in the rock mass itself, ground water, and long term creeping processes and swelling.

Due to the geological complexity of fault zones different failure modes of the rock mass have to be expected at different locations. Thus an universally applicable tunnelling method suitable for all types of squeezing rock cannot exist. Methods applied have to be adjusted to the local geological situation and stress field.

Due to the higher flexibility up to now conventional tunnelling methods are still preferred to TBM operation in squeezing ground conditions.

2. Conventional tunnelling methods

2.1. *Full face versus sequential excavation*

With conventional tunnelling (drill & blast, roadheader, excavator) full face and sequential excavation methods are used. Strong regional preferences for one or the other of the methods can be observed. While for example in Italy full face excavation is preferred, in Austria and many other countries sequential excavation methods are applied for bigger tunnels. A number of problems is associated with the full face approach. Namely the stability of the face and the walls requires considerable effort in reinforcement of the face and pretreatment of the rock mass. One of the advantages of the method is the possibility of using bigger equipment. Another one is the early closure of the lining, providing a high support resistance close to the face.

When applying sequential excavation methods, the volume excavated at once is considerably smaller, easing the control of the tunnel stability. In general, displacements until final closure of the lining are higher, leading to lower loads in the lining, but higher stresses in the rock mass. Disadvantages of this approach are the higher deformations, which may lead to a deterioration of the rock mass quality, and require more overexcavation to satisfy clearance requirements.

Technically seen, both options have their merits. Economically it seems, that sequential excavations lead to lower costs, due to the fact, that less ground pre-treatment is required, which is not only costly, but also time consuming.

2.2. *Supports*

Regional preferences can be observed also for the use of the type of support. In Austria in general a combination of light steel arches, shotcrete and rockbolting is used, supplemented by forepoling and face bolting if required. The dense rockbolting contributes to an increase in rock mass strength and ductility of the rock mass. To increase flexibility of the lining previously gaps in the shotcrete lining have been left [Rabcewicz, 1975; Schubert, 1993]. More recently ductile steel elements with defined resistance are installed in the gaps to better utilize the capacity of the lining [Schubert, 1996; Moritz 1999]. Shown in Fig. 1 is a so called Lining Stress Controller (LSC), consisting of a set of steel tubes. Under axial load the central tube buckles, in this way limiting the stresses in the lining. Inner and outer steel tubes are used to control the buckling process, thus smoothening the otherwise heavily oscillating load line. By using different steel tube dimensions and numbers of LSC´s per unit length, the capacity of the system is adjusted to the lining capacity. Fig. 2 shows the use of the lining stress controllers at an Austrian railway tunnel.

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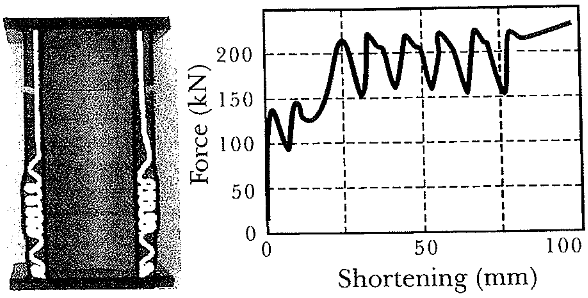


Fig. 1 – LSC after laboratory testing (left) and corresponding load displacement curve (right).
Fig. 1 – LSC (Elementi di attenuazione dello sforzo nel rivestimento) dopo prova di laboratorio (sinistra) e corrispondente curva carico-spostamento (destra).

Some work has also been done on the optimization of rockbolts for squeezing conditions [Blümel, 1996]. Slight modifications of the rib geometry led to a considerable increase in bond strength, and thus an increase in efficiency of the bolts. Tests showed that bolts with a small rib distance have a much lower pull out strength, in case of relative movement of bolt, grout, and rock during the setting of the grout than bolts with bigger rib distance (see Fig. 3). It appears that with a small rib distance, the grout between the ribs is easily sheared off, resulting in a smooth rod with the space between the ribs filled with grout. By increasing the rib distance, the stress situation is much more favorable, leading to a better bond even at high relative displacements.

In many countries, heavy steel sets and thick liners are preferred, obviously due to difficulties in rock bolt installation. The disadvantage of those systems is the relatively brittle behaviour of the support, which under unfavorable circumstances may lead to sudden collapses, while a densely rockbolted rock mass behaves more ductile.

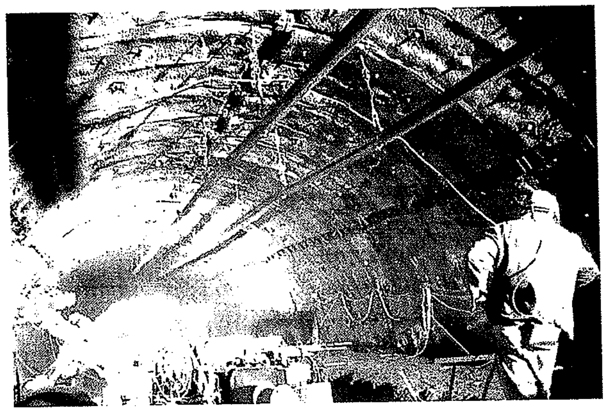


Fig. 2 – Shotcrete lining with LSCs installed in deformation gaps at the Semmering Basis tunnel.
Fig. 2 – Rivestimento in calcestruzzo proiettato con LSC posti nei tagli longitudinali. Galleria di Base, Semmering.

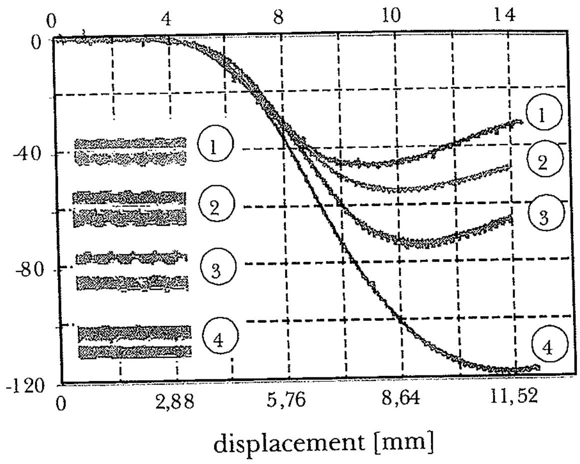


Fig. 3 – Load development of 4 different rock bolt types with a constant displacement rate of 0.72 mm / h.
Fig. 3 – Incremento del carico per 4 diversi tipi di bullone da roccia e velocità di spostamento costante 0,72 mm/h.

The choice of supports should be governed by geological conditions, the local stress field, as well as the size of the tunnel. Different combinations of support elements may lead to comparable results in terms of displacements, and costs. For reasons of stability, and reserves against unforeseen conditions, a combination of steel arches, shotcrete with integrated yielding elements, and systematic rock bolting is recommended.

3. TBM excavation

3.1. General problems

For gripper type machines, the poor ground may lead to problems with the thrust due to reduced gripper reaction. Shield machines, also double shielded machines may be immobilized due to large forces on the shield caused by tunnel closure. This especially applies, when the excavation speed drops below a critical value [Vigl & Jäger, 1997]. High displacements require a flexibility in cutting diameter. Besides the accurate enough prediction of required overcutting, mechanical limits will be a problem with all machines in the near future. Another problem in soft ground or heterogeneous ground is the difficulty to control the direction of the machine. Soil type rock may tend to flow through any opening and into the gap between shield and rock.

3.2. Machine types available

For the time being, a number of machine types is considered adequate for slightly squeezing conditions [Robbins, 1997; Einstein & Bobet, 1997; Vigl & Jäger, 1997].

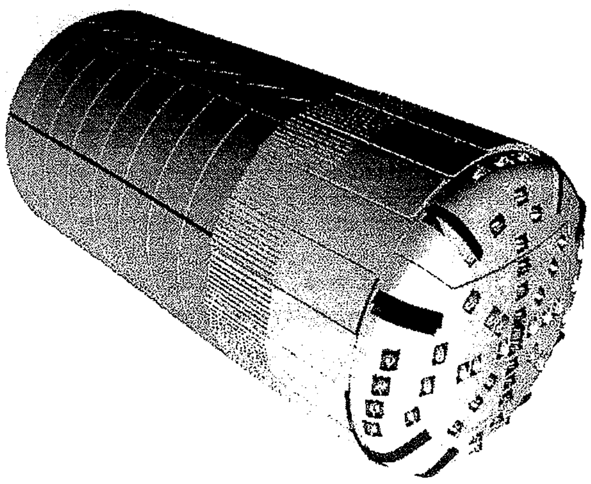


Fig. 4 – Concept of a Walking Blade Shield [ROBBINS, 1997].

Fig. 4 – Concetto di scudo a pettini mobili [ROBBINS, 1997].

Those are:

- Double shielded machines
- Continuous tunnel boring machines
- Open top machines
- Walking blade shields (Fig. 4)
- Low pressure walking canopy

Each of the concepts has its merits, but also its limitations. In contrast to conventional tunnelling, very few successful applications of TBM´s in squeezing rock have been reported so far. Further development is required to make TBM´s fit for heterogeneous fault zones.

3.3. Supports

According to the type of machine used, either prefabricated segments, extruded linings, shotcrete and rockbolts, or steel arches can be used. For squeezing ground, support is required right at the face, either by a flexible shield system, pushed against the rock, or by support installed immediately behind the cutter head (open top machine). In case of high squeezing potential, linings need to be of the yielding type in order to prevent failure. This can be achieved by using frangible backfillings, yielding elements integrated into the lining, or a combination of those methods. Several concepts have been developed [ROBBINS, 1988; BRUNAR & POWONDRA, 1985; SCHUBERT & MORITZ, 1998].

4. Monitoring & short term prediction

4.1. General

In poor and heterogeneous ground during design an accurate prediction of the rock mass behaviour is difficult. Hence the short term prediction on site is of imminent importance for the success of tunnelling.

4.2. Monitoring methods

With conventional tunnelling methods monitoring of displacements of the tunnel perimeter is quite common. Increasingly absolute displacement monitoring systems are applied, providing information on the movement in space.

The limited access to the tunnel perimeter with TBM operation does not allow a comparable displacement monitoring. In general, displacements can be monitored only quite a distance behind the face, a fact which reduces the predictive component. For the purpose of predicting fault zones ahead of the face of TBM's, geophysical methods have been developed [DICKMANN & AMBERG, 1998].

4.3. Prediction of rock mass behaviour

Recent research [SCHUBERT & STEINDORFER, 1997; STEINDORFER, 1998] has shown, that variations in displacement vector orientation can be used to predict rock mass quality ahead of the face. In combination with geological documentation, preferably supplemented by a data base system [LIU *et al.*, 1997;1999] a reasonably reliable prediction of the rock mass structure two to three diameters ahead of the face can be achieved. Shown in Fig. 5 is the trend of the displacement vector orientation a few meters behind the face. When tunnelling in more or less homogeneous material, around 10° to the vertical were identified as "normal" vector orientation. The increase of the angle against the vertical around station 1550 indicates a fault, crossing the tunnel at around station 1570. When the face enters the fault, the vector orientation again goes back to "normal" for a short stretch. The following decrease of the angle indicates the better rock mass, met with the face at around station 1600.

When properly interpreting the spatial vector orientation, surprises during tunnelling in heterogeneous ground can be considerably reduced. As mentioned earlier, the benefit of predicting rock mass behaviour from 3-D displacement data is limited to conventional tunnelling methods and TBM's without shields.

The geophysical methods developed for short term prediction in combination with TBM operation are still in a testing phase, but seem to be promising. For routine application, the collection of all data accessible (geological conditions as far as possible, torque, thrust, wear, etc.) and their interpretation may contribute to a prediction of rock mass quality.

4.4. *Prediction of tunnel closure*

Tunnel convergence in highly stressed rock will always be an important issue. It determines the amount of required overexcavation, influences machine and equipment selection, as well as the support concept. When underestimating the convergence, extremely costly reshaping is required. When overestimating the amount of displacements, in general the "unused" overprofile has to be filled with concrete, which is comparatively cheap. On the other hand, choosing the overprofile on the too safe side, does increase the displacements and thus the amount of required support.

Because of the importance of the prediction of tunnel closure, it is surprising, that not much research has been done in this direction so far. Using analytical or numerical methods only does not appear to lead to sufficiently accurate results because of the huge number of parameters involved.

A procedure is currently under development [Sellner, 1999], which is based on analytical functions developed by Guenot, Panet and Sulem [Guenot *et al.*, 1985] and the modified functions by Barlow [Barlow, 1986]. To determine function parameters an expert system in combination with Artificial Neural Networks (ANN) can be used. The expert system consists of numerous site data, stored in the data base system DEST [Liu *et al.*, 1997; 1999], numerical simulations, and monitoring data. Numerical simulations are used to determine the influence of support and excavation sequence on displacements, while monitoring data are used to predict rock mass structure ahead of the face [Steindorfer, 1997].

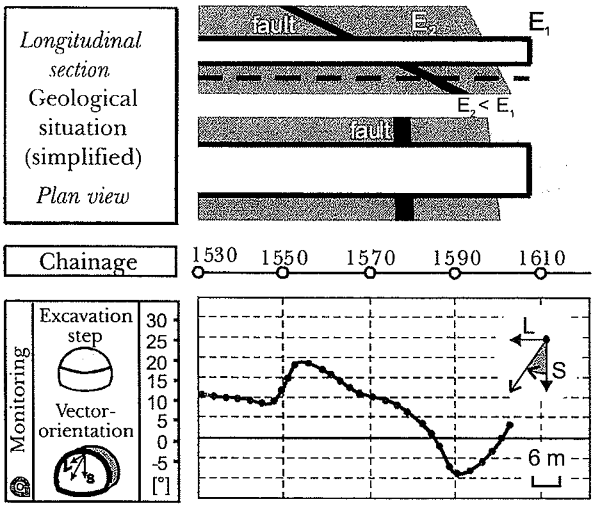


Fig. 5 – Development of vector orientation (longitudinal / settlement displacement) when driving through a fault, and approaching a section of more competent rock at the "Galgenberg" tunnel. Trend of vector orientation 6 m behind the face (geological situation simplified).

Fig. 5 – Variazione del vettore orientazione (spostamento longitudinale/cedimento) durante l'avanzamento attraverso una faglia e via via che ci si avvicina ad una zona di ammasso roccioso a migliore qualità nel tunnel "Galgenberg". Andamento del vettore 6 m a tergo del fronte (situazione geologica semplificata).

MATLAB (The Math Works Inc.) is used for the procedure, including the "Neural Network Toolbox" and the "Optimization Toolbox". The program is prepared to consider several options, such as installation of supports of different quality and quantity at any desired time, simulation of sequential excavation and non steady tunnel advance, or calculation of displacements ahead of the face. The easiest application is the prediction of final displacements after a few days of observation of a monitoring section. This option allows a reliable estimate of the final displacement already a few days after excavation. This early estimate can be used to decide, whether additional support or a change in the excavation procedure is required to meet the clearance or surface settlement requirements.

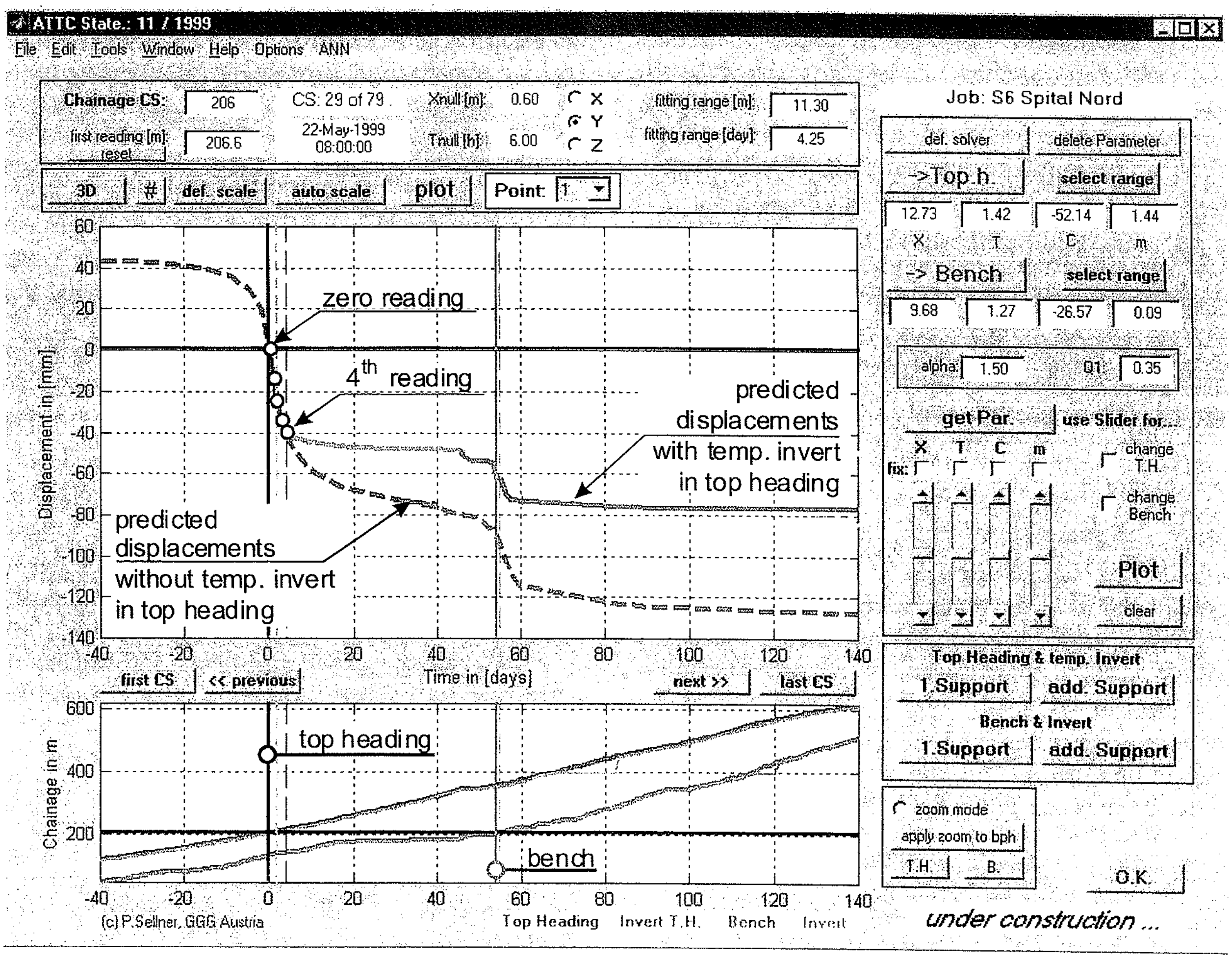
An example of this application for a relatively shallow tunnel in poor rock is shown in Fig. 6. A decision had to be made whether to install a temporary invert in the top heading. Both possibilities were calculated and compared. Here, the rock mass behavior was back calculated by using the four available displacement readings. Support parameters were obtained from case histories of already excavated sections. The final predicted displacement for tunnelling using a temporary invert was 77 mm and 128 mm when no temporary invert was installed. In this case, the temporary invert was constructed and the final displacements of the crown reached a value of 82 mm. The procedure has been tested also for tunnels with high overburden with good result.

With some more case histories implemented we are confident that this program will be a useful tool to support on site decisions.

5. Conclusion

Tunnelling in squeezing rock definitely is one of the most challenging tasks in tunnel engineering. Strong regional preferences for methods to tackle stability and deformation problems can be observed. Prediction of rock mass behaviour is a crucial issue for conventional, but especially for TBM excavation. Due to the relative inflexibility of TBM´s, geological investigation and geotechnical design are extremely important.

Experience with tunnels in squeezing ground in the Alps during the last decades has led to improvements in short term prediction, supports, and monitoring techniques. The increasing share of TBM excavations in poor ground calls for further development in order to prevent disastrous applications.



ATTC State.: 11 / 1999

Chainage CS: 206

first reading [m]: 206.6

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Xnull [m]: 0.60

Tnull [h]: 6.00

○ X ● Y ○ Z

fitting range [m]: 11.30

fitting range [day]: 4.25

Point: 1

Job: S6 Spital Nord

->Top h.: X 12.73, T 1.42, C -52.14, m 1.44

-> Bench: X 9.68, T 1.27, C -26.57, m 0.09

alpha: 1.50

Q1: 0.35

Fig. 6 – Prediction of final displacements of crown for a support system with (solid line) and without (dashed line) temporary invert in top heading.

Fig. 6 – Previsione degli spostamenti di lungo termine in calotta in presenza di prerivestimento con (linea continua) e senza (linea a tratto) arco rovescio provvisorio.

The heterogeneous nature of fault zones requires a continuous updating of the ground model, as well as adaptation of excavation and support to allow safe and economical tunnelling. Even with increasing mechanization, there will remain a good share of geotechnical engineering also during construction in squeezing ground conditions.

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Metodi di costruzione di gallerie in condizioni spingenti

Sommario

La nota discute problemi tipici dello scavo di gallerie in ammassi rocciosi scadenti, in presenza di alte coperture. La previsione dell'entità della convergenza, la stima degli effetti connessi con i fenomeni deformativi a carico costante (creep), e la scelta del metodo di sostegno sono tutti compiti assai ardui per l'ingegnere progettista di gallerie. Mentre i metodi di scavo tradizionali posseggono una certa flessibilità per affrontare condizioni non omogenee, lo scavo meccanizzato con TBM necessita ancora di significativi miglioramenti, in particolare per poter affrontare con successo le zone di faglia nei tunnel alpini. L'enfasi della presente nota è posta sui recenti sviluppi nella previsione del comportamento dell'ammasso roccioso allo scavo, nel breve termine, delle convergenze del cavo, e dell'impiego di sostegni flessibili.