

DESIGN AND CONSTRUCTION OF TUNNELS IN POOR AND FAULTED ROCK MASSES

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Abstract

In weak or faulted rock and high overburden considerable displacements occur during excavation of tunnels and galleries. In most cases the behaviour of the ground is not ductile, but governed by different failure modes. In the design stage it is important to identify potential failure modes under the given boundary conditions to be able to select appropriate construction methods. A particular problem under such conditions is that the strains developing often exceed the deformability of standard linings, frequently leading to severe damages and the necessity of costly repairs. To allow for safe and economical tunnel construction, strategies have to be used, which guarantee support characteristics compatible with the strains, and at the same time utilize the supports as much as possible. Recent developments of ductile elements used in combination with shotcrete and rock bolts are shown, and their efficiency reviewed. For the design of such supports the development of the expected displacements must be predicted and the time dependent properties of shotcrete considered.

Special tools to predict displacements and a relatively simple analysis method to design shotcrete linings with integrated yielding elements, based on expected displacements and the transient lining properties are presented.

The methods described in this paper have been successfully used in the European Alps and on other projects around the world.

Keywords: Tunnel, weak rock, ductile supports, time dependent properties of linings.

1. Introduction

The huge number of tunnels constructed during the last decades has led to the accumulation of considerable experience. Due to improved investigation and modelling methods the construction of tunnels under adverse conditions has become safe and efficient. The inherent inaccuracies in the geological and geotechnical models, as well as the simplifications in the analysis tools also play a role in the success of a project.

Experience in tunnel construction in poor and faulted rocks under high overburden still is limited. However, with the construction of long basis tunnels those conditions are met quite frequently. A serious challenge is the heterogeneity of brittle faults, as well as the large, anisotropic and in many cases long lasting deformations [1]. In addition, with high overburden the exact location and properties of fault zones usually are unknown, requiring continuous updating of the ground model during construction, as well as an adjustment of the

construction methods to the actual conditions. Advanced exploration and monitoring methods are required to recognize changes in the ground quality in time, allowing for a timely adjustment of excavation and support.

Special attention has to be paid to an appropriate estimation of displacement magnitudes and its timely development. The size of the excavation has to allow for the expected displacements without impairing the clearance profile. When displacements are underestimated, extremely costly reshaping is required. On the other hand, the timely development of the displacements can play a major role in the utilization of the lining capacity in case shotcrete is used.

Conventional supports often are not able to sustain the large imposed strains. In the past this problem has been addressed by leaving open gaps in shotcrete linings. More recently the integration of ductile elements into linings has become common practice on many projects.

2. Design

Designing tunnels with low cover and uncertain ground properties, one can simply increase the lining thickness or quality to obtain a reasonable factor of safety even under adverse conditions. This is not a viable approach when expecting large displacements under high cover. In such cases, much care has to be taken in the selection of the models and the input parameters.

2.1. Modeling methods

Frequently the concept of the ground reaction curve is used for the pre-design of tunnels. This approach is useful for an estimate of the expected displacements. The combination of the ground reaction curve with supports is questionable, as supports are activated by the displacements, and are no active support loads on the perimeter. The question of pre-relaxation prior to installation of support is discussed below.

To save time, it is still common practice to use 2D numerical models for the design of tunnels. One of the problems with 2D numerical simulations is the selection of proper pre-relaxation or load reduction factors. In many cases, the equivalent support pressure prior to installation of support is chosen with something like 0.7, leading to an overestimation of lining load and effect of the support. It has shown that for poor ground failure occurs already ahead of the face [2], influencing the development of

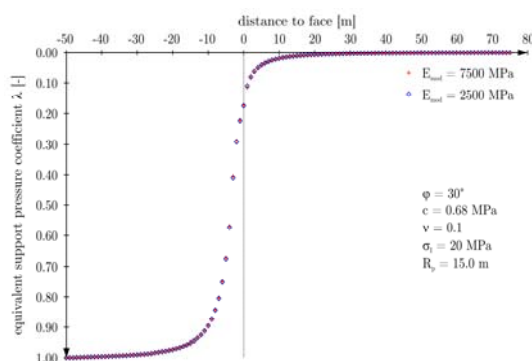


Figure 1. Back calculated equivalent support pressure coefficient for certain conditions [from 3]

displacements. An empirical relationship between ground quality, ground stress, and tunnel size was developed by Pilgerstorfer [3]. He used 3D numerical simulations to determine the development of the displacements, and then back calculated the equivalent support pressure with closed form solutions. It showed that for an unfavorable ratio between stress and ground strength the equivalent support pressure factor at the tunnel face can reach values of 0.2 and less.

The application of those relationships allows realistically evaluating the development of displacements and loading of the lining for rather uniform ground conditions with 2D simulations. In case of a strongly heterogeneous ground, with blocks or stiffer rock mass embedded in a soft matrix, a three dimensional modeling will be unavoidable, as 2D models may provide misleading results.

When deciding whether a 2D or 3D model is required, following effects have to be considered:

- Arching within fault zones can develop up to a certain critical length of a weak zone. This leads to a reduction in displacements within a weak zone, and additional loads in the better ground close to the weak ground [4].
- Stiff blocks or regions embedded in soft matrix may accumulate stresses during and after tunnel excavation. Overloading and subsequent brittle failure of those blocks or zones may be the result.

An important issue is also if a continuous model is appropriate, or joints and other rock mass features have to be modelled explicitly. In all cases, where the behaviour is dominated by shearing along joints or joint opening, discrete models will be required. This typically applies to foliated rock mass, with the strike of the foliation parallel or sub parallel to the tunnel axis. Displacement characteristics and magnitudes with different relative orientations between foliation and tunnel axis can differ considerably [5].

Another issue also rarely addressed in simulations is the time dependent development

of strength and deformability of shotcrete. In most cases linings are simulated as elastic material, with a step wise increase of the elastic properties, usually from 5.000 MPa to 15.000 MPa and more. Simulations under consideration of time dependent shotcrete properties showed that the fictitious E-modulus practically never exceeds 5.000 MPa [6]. Only when ground and lining properties are chosen with care, we can speak of a realistic model.

2.2. Support options

Tunnel supports on the one hand should provide as much resistance against deformation as possible, on the other hand should be able to sustain the large imposed strains. Various methods have been developed over the decades to cope with the difficulties.

A traditional method in mining when experiencing large displacements was to use U-shaped steel sets with sliding couplings in combination with wire mesh or lagging. In particular in cases of anisotropic deformation the steel sets buckle, and costly and dangerous repairs are required. Supports had to be replaced many times until stabilization was reached.

The improvement of the tunneling technique during the nineteen sixties, in particular the increased use of shotcrete and rock bolts, considerably reduced the problems in poor ground. Severe problems with considerable displacements and destruction of the shotcrete lining were experienced in a fault zone at the Tauerntunnel in the Austrian Alps in the early nineteen seventies [7]. To prevent the failure of the shotcrete, open deformation slots were left in the lining, which closed with deformation. In combination with a dense bolting, this concept worked quite well. The same concept was later used at the Arlbergtunnel [8], the Karawankentunnel [9] and Inntaltunnel [10, 11] in western Austria with quite some success.

A serious collapse during the excavation of the Galgenbergtunnel in a very heterogeneous fault zone showed that this type of support is rather vulnerable to rapidly developing loads in

the excavation area. As a consequence of the accident, ductile lining systems were developed with the aim to provide as much support resistance as possible, but on the other hand guaranteeing that the linings are not overstressed. Several systems of yielding elements presently are on the market, some using steel, others using cement based materials. A comparative study recently showed that the LSC (Lining Stress Controller) system is easiest to control and has the highest efficiency [12]. It consists of a set of steel tubes, which are loaded axially. Special provisions allow a rather “soft” initial response, accounting for the low strength of young shotcrete. The system easily can be adjusted to the project specific requirements by combining different numbers and types of tubes. Special software is used for the determination of the layout of the elements, considering expected displacement development, time dependent



Figure 2. Yielding elements of the type LSC integrated in a shotcrete lining at the Tauerntunnel. Photo: Vergeiner

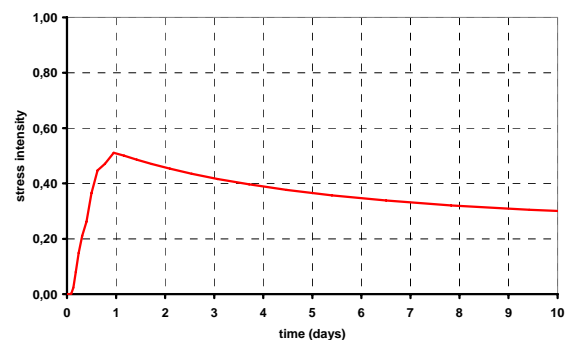


Figure 3. Utilization rate of the lining versus time for a 4-tube LSC element; tunnel diameter 10 m, final radial displacements about 300 mm

shotcrete properties, and advance rate.

In general in Alpine tunnels in poor and faulted ground, the ductile shotcrete support is supplemented by lattice girders, and rock bolting in considerable density. The length of the bolts ranges from 1/2 to 2/3 of the tunnel diameter. The density of the bolts is influenced by the ground structure and the relative orientation between main geological features and the tunnel axis. The density commonly is in a range of 1 to 2 pieces per square meter. As a rule, the strike of foliation parallel or sub parallel to the tunnel axis is more unfavourable, than a strike perpendicular or in an oblique angle to the tunnel axis.

An important factor for the performance of grouted bolts, which are subject to large displacements, is the rib geometry. Investigations showed that with wider rib spacing the efficiency of the bolts considerably increases [13, 14].

Figure 4 shows the results of laboratory tests on bolts with different rib geometries. The bolts were pulled with a constant displacement rate, while the grout was still fresh, as is the case also in nature. It showed that with small rib spacing the grout easily is sheared off, resulting in a low capacity of the bolt. From this example it can be seen that for tunnels under difficult conditions also apparently minor details can have a big impact on the success.

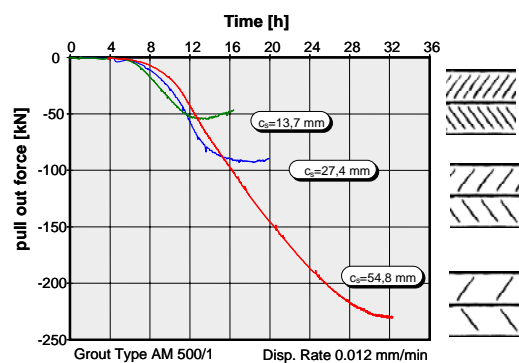


Figure 4: Results of laboratory tests on grouted bolts with different rib spacing; Displacement was imposed on the bolt, while the grout was setting [13]

2.3. Construction sequence

Face stability problems in many cases are associated with poor ground conditions. Basically two approaches exist to cope with this problem. One is a heavy support of the face, frequently with glass fibre bolts in case of full face excavation. The other approach is to make a sequential excavation. As the required face support increases exponentially with the height of the face, in most cases the sequential excavation is more economical and quicker.

3. Detailed design during construction

The uncertainty in the geological models and the variability of the ground quality within a fault zone require a continuous updating of the ground model during construction. With the updated model, the final layout of excavation and support can be done.

3.1. Prediction of ground quality ahead of the face

Prediction of the ground quality ahead of the face is essential for choosing appropriate excavation dimensions and support type and quantity.

Probing ahead by core drillings is costly and time consuming. Thus such methods are used in exceptional cases only. Geophysical investigation ahead of the face definitely has potential, but still is not developed to a state which would allow a reliable prediction.

A very efficient method for predicting ground conditions by evaluating data from 3D displacement monitoring has been developed more than ten years ago [15,16, 17]. The basic idea behind the evaluation method is rather simple. As long as there is no major change in the ground volume affected by the excavation, the displacement characteristics will be similar. As soon as the stress distribution changes due to the influence of zones of different quality, the displacement pattern will change. In case weak material is ahead, the displacement vector will rotate against the direction of excavation. A

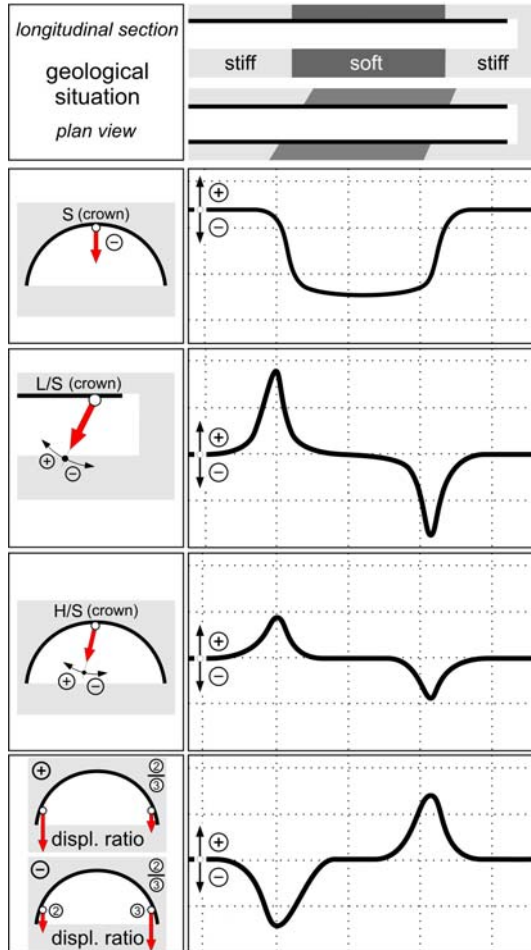


Figure 5. Typical development of displacement trends when tunnelling through heterogeneous ground [18]

change to stronger rock mass ahead shows in a relative rotation of the displacement vector into the direction of excavation.

Recently systematic evaluation of site data and numerical simulations has been used to develop a catalogue of characteristic displacement trends for standard geotechnical conditions [18]. The expert knowledge will be used to develop an automated data evaluation and interpretation tool. Typical displacement trends for an excavation through heterogeneous ground can be seen in Figure 5. Site application showed that this method is relatively reliable.

Besides there are no additional costs, as the measurement data are available in any case. To make at least qualitative predictions only a few additional evaluations need to be made. Figure 6 shows monitoring results from a tunnel in western Austria, where the change in the displacement vector orientation clearly indicated the change in the ground conditions well ahead of the transition.

Naturally, no precise prediction of the extent of a zone of different properties or the exact quality of the ground ahead can be made. The tool in combination with other evaluations and

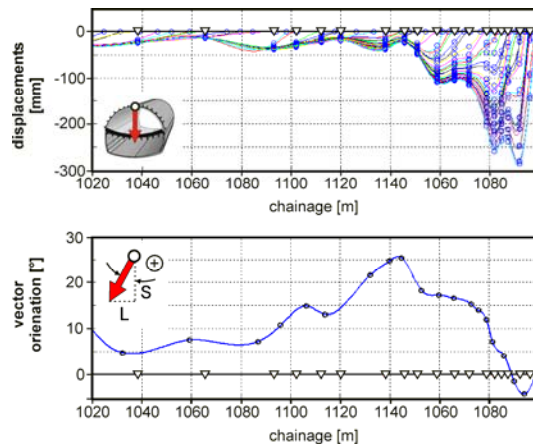


Figure 6. Plot of crown settlements (top), and displacement vector orientation (bottom) along a tunnel section. The change in the displacement vector orientation indicates the change in the ground conditions.

engineering judgment should be used to be prepared for changes in the ground conditions. A timely alert can ease preparations, and thus save a lot of repair works.

3.2. Prediction of displacements during construction

In weak ground not only the final magnitude of the displacements is of importance, but also the development with face advance and time, as this controls the lining load development.

Guenot et al. [19] and Sulem et al. [20] proposed analytical functions that describe

displacements in a plane perpendicular to the tunnel axis as a function of time and the face advance. Barlow [21] and Sellner [22] modified this approach. The displacement behaviour of the rock mass and support basically is represented by four function parameters. Two parameters (T, m) are used to simulate time dependency and the other two parameters (X, C) the face advance effect. With curve fitting the characteristics of the displacements can be determined. Extrapolating the parameter trends, the displacements can be predicted even for sections ahead of the face, using also the information from the evaluation of the monitoring data as described above. Add-ons to the prediction module allow an assessment of the effect of different linings and construction sequences. Sellner has developed a user friendly code for the prediction of displacements (GeoFit® [23]).

The predicted displacements can also be used to estimate the expected utilization of the lining capacity. This for example is very valuable when the decision has to be made if a closed lining is still appropriate or the integration of yielding elements is required. Thus one is in a position to adjust the support to the expected behavior.

3.3. Check of System Behaviour

Once a section has been excavated, the system behaviour has to be monitored to see if it is within acceptable limits. Again here the comparison between predicted with the actually measured displacements using the same procedure is very important [Figure 7]. Deviations from the expected behaviour can be easily detected, also in cases of varying excavation rate. This is particularly important in heterogeneous ground, where deviations from the “ideal” behaviour can indicate changes in the ground conditions, or beginning failures in the ground or support.

Preconditions for a successful use of monitoring data for prediction of displacements and ground conditions ahead of the face, as well as check of the system behaviour are 3D measurements with high quality and consistency. A certain problem

still is the limited availability of geotechnical engineers, trained in the use of those tools.

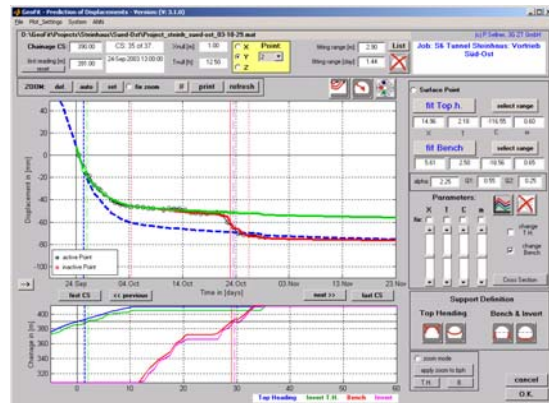


Figure 7. Comparison of predicted and measured displacements on a tunnel with a top heading – bench excavation sequence and a temporary top heading invert with the code GeoFit®

3.4. Site organization and construction quality

It should be stressed that tunnelling in difficult geotechnical conditions requires perfect site organization and construction quality. The site has to be organized in a way that responsibilities are clear, and evaluation and interpretation of the monitoring data is done sufficiently rapid in relation to the possible evolution of the system. Contingency measures and actions shall be planned for cases where the system behaviour exceeds acceptable limits. This contingency plan



Figure 8. Top heading at the second tube of the Tauertunnel with four rows of ductile elements integrated in the shotcrete lining. Photo: Vergeiner

shall continuously be updated, as the experience with the system behaviour increases.

Needless to say that difficult ground conditions besides experienced engineers for design and on site also require experienced miners, who can produce the best possible quality.

4. Conclusion

Tunnelling in poor ground with high overburden is a real engineering challenge. Usual engineering approaches, like increasing the structures` capacity or dimension does not provide satisfactory results. Quite in contrast, the damage and loss are even bigger, when one tries to suppress displacements under such conditions. The means economically available simply are not sufficient to cope with the energy inherent in the system. For an economical and safe tunnelling, the design of excavation and support has to be robust in a way that a wide variation in displacement magnitudes and characteristics can be covered. Ductile elements incorporated in the lining have shown to be effective, if the right system is chosen, and the detailed adjustment is done on site.

The design of tunnels in poor ground and high overburden requires more attention than for project with "average" conditions. Time dependent ground and support properties, heterogeneity of the ground, and large displacements require a thorough and realistic modeling.

Tools have been developed for prediction of displacements and check of the system behavior. The application on a great number of projects has shown the reliability of the tools, as well as the capacity to support the site engineers in their decisions.

Essential for successful tunneling in such conditions also is the availability of qualified site staff, a flexible contract setup and a site organization which enables quick decisions.

Considerable effort was put into the collection and generation of expert knowledge. Appropriately used, this will assist in making

decisions in design and construction of tunnels in poor ground.

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