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YET ANOTHER WAY OF CALCULATING STRESSES IN A SHOTCRETE LINING

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Yet Another Way of Calculating Stresses in a Shotcrete Lining

Ein neuer Weg zur Ermittlung von Spannungen in einer Spritzbetonschale

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Abstract

A complex rheological model has been used recently at several Austrian tunnel job sites to determine stresses in a shotcrete lining. The raw data are from displacements measurements at the lining contour.
The analysis uses a material model based on a thermo-chemo-mechanical approach. This paper gives a short review of the theoretical background and two case studies. The first one considers a tunnel with top heading/bench and invert excavation and the second one a tunnel with a more complex structure with side galleries and core excavation.

Key Words: hybrid analysis method, lining stress, NATM

Introduction

Geotechnical measurements are an integral element of the New Austrian Tunnelling Method (NATM). Today 3D trigonometric measurements are considered as state of the art. Monitoring sections are installed in a regular distance of approximately ten metres. Each section consists of five to seven reading points or more depending on the complexity of the tunnel. Thus a grid of measurement points develops. The main purpose of daily measurements is to continuously validate the dimensions and types of the chosen support. Finding a method to determine the strains and stresses in the lining was just a question of time (1). Another approach evolved from the Austrian SITU research project. A new material model for shotcrete was developed at the Institute for Strength of Materials, TU Vienna. The constitutive model is based on the theory of the thermodynamics in reactive porous media (2, 3). Applying these results lead to the introduction of the so-called hybrid analysis method for the calculation of stresses in a shotcrete lining (3,4). Because the measurements are taken only at discrete measurement points, all analysis techniques require additional assumptions concerning boundary conditions and the displacement field.
The main result is the level of loading defined as the ratio between the stress and the ultimate strength of shotcrete at a given time instance.

A high load level means that at least one of the two main elements of the composite structure ground / support is stressed. It may not necessarily mean a very high risk, for example in deep tunnels, where the rock mass takes higher displacements to develop yield zones. However, in shallow tunnels, particularly in soft ground, where the shotcrete lining is the predominant support a high load level certainly does mean risk.

Within the last couple of years important first-hand experience could be gained in this field. In the following two case studies from an NATM tunnel in Austria are highlighted after a short theoretical review.

Calculation of strains

Displacements are usually determined with a precision of +/- 1mm. As a first step we calculate the strains from an interpolated displacement field in all layers through the thickness of the lining. Therefore a network of splines with constraints in the transition between different construction steps is set up (Figure 1). The change of conditions between two regions with different shotcrete age and a discontinuous displacement field is a critical point in the estimation of the strains. The displacements are extrapolated to the footing of the top heading, because it is impossible to install targets in this region. In a next step the strains are smoothed all over the structure.

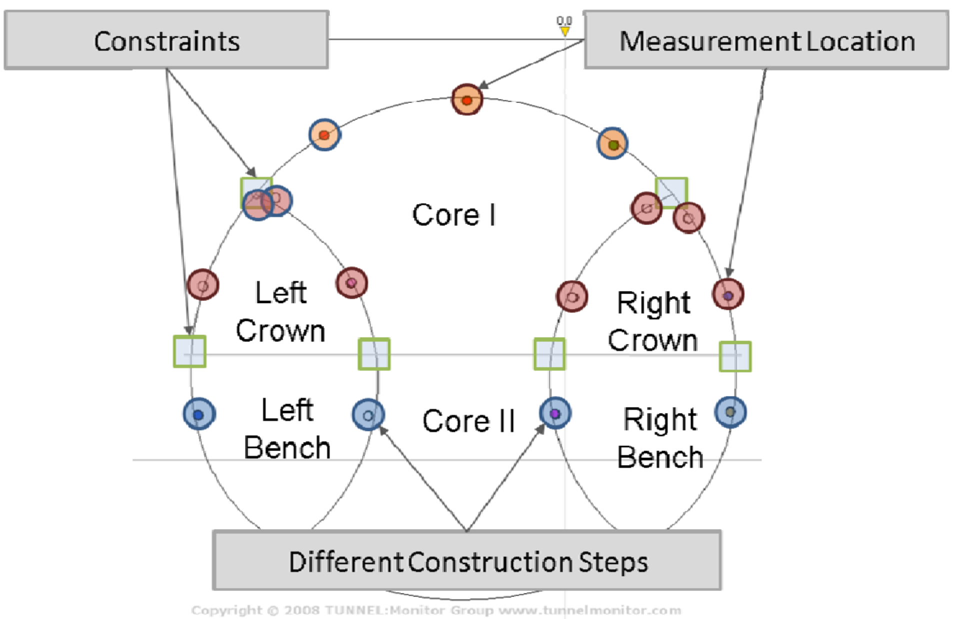

Figure 1: Interpolation network of constrained splines for strain calculation

The material model

Shotcrete as a construction material is interesting on two counts. First, the material is loaded during the formation of hydrates and, second, the properties of the material change during the ongoing chemical reaction. The applied material model takes both aspects into account. The behaviour of the shotcrete is modelled within the framework of thermodynamics. The basic parameter, the chemical affinity, which fully characterizes the macroscopic hydration kinetics, is obtained from a quasi adiabatic laboratory test. Using state equations the whole problem can be divided into three parts:

- The chemo-thermal coupling, which leads to the thermal distribution and the evolution of the degree of hydration as results
- The thermo-mechanical coupling, which considers the strain due to the temperature distribution in the cross section (thermal dilatation)
- The chemo-mechanical coupling, which takes the change of material properties dependent on the degree of hydration into account

A Drucker-Prager yield criterion with Rankine planes in the tension regime is chosen to describe the nonlinear material behaviour of the shotcrete (Figure 2). The yield surface is dependent on the stress and the hardening forces of the concrete. The lining thickness is assumed to remain constant. Taking only circumferential and longitudinal strains into account reduces the complexity.

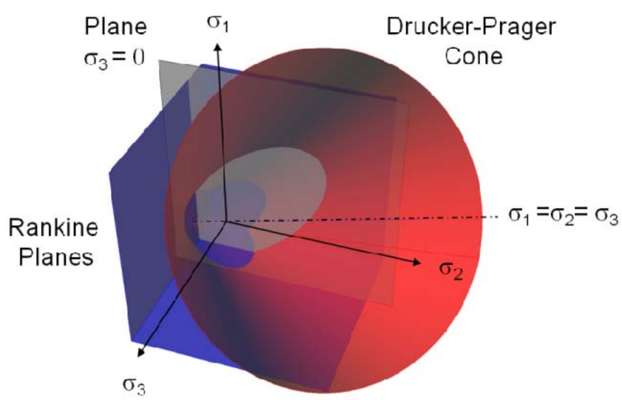

Figure 2: Material Model for Shotcrete – Multisurface Plasticity Model in the Haigh-Westergard stress space

Thermo-chemical analysis

The first step for the thermo-chemical analysis is to identify the normalized chemical affinity of the cement and concrete additives. This parameter, obtained from a quasi adiabatic laboratory test, fully characterizes the macroscopic hydration kinetics. The analysis is done then for a certain shell dimension, where the result is the distribution of the temperature and the degree of hydration over time and shell thickness. Hence the material properties are determined at any time in any fibre of the shell. The procedure is necessary only once for a given shotcrete mixture and shell thickness. The six intrinsic material functions, depending on the degree of hydration, are depicted in the following figure (Figure 3).

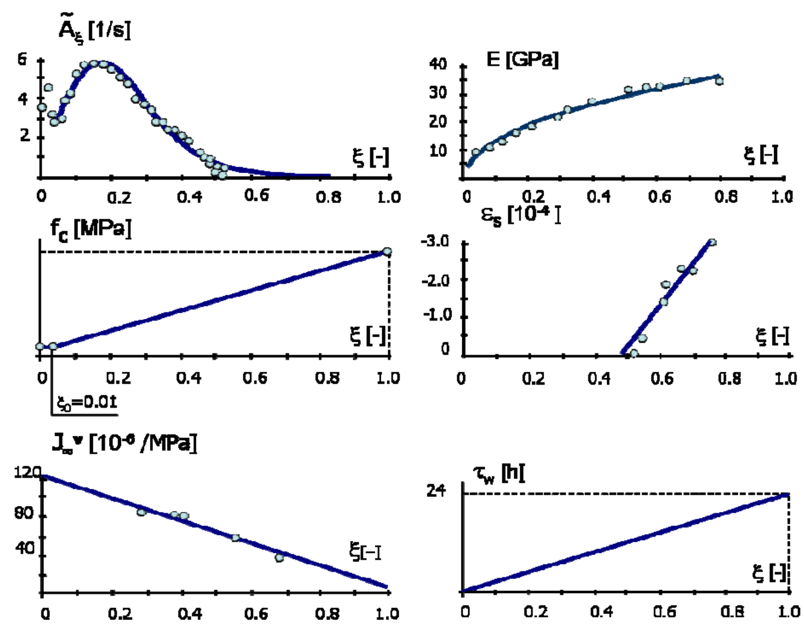

Figure 3: Intrinsic material functions depending on the degree of hydration (from the top left, to the bottom right), normalized chemical affinity, aging elasticity, strength growth, shrinkage, final viscous compliance, characteristic time for short term creep

Chemo-mechanical analysis

Based on the material law, the stresses are calculated from the interpolated strains. Apart from the aforesaid increase of the concrete strength depending on the degree of hydration, creep effects and thermal dilatation are considered as well. This kind of problem is solved using a hardening law in conjunction with a smart return mapping algorithm. The load level, as a result, is defined by the ratio of two distances in the stress space - the distance from the actual stress state to the origin divided by the distance of the point on the yield surface to the stress origin (s. Figure 4).

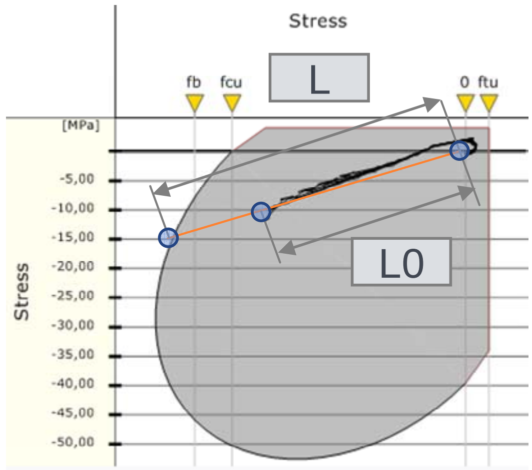

Figure 4: The level of loading is specified by distance of the actual stress state from the yield surface

It is worth noting that the stresses are calculated in incremental time steps, therefore interpolation is done within each time increment.

Experiences with the hybrid method

In recent years the hybrid method has been applied successfully by a number of tunnel projects in Austria (5, 6, 7).

The major task of a geotechnical engineer is to observe the actual system behaviour in terms of ground-support interaction and to compare this with the predicted system behaviour. Any deviation from the predicted system behaviour, both favourable and unfavourable, is analyzed and documented in detail.

In the last two decades methods for the evaluation of 3D displacement monitoring data and early diagnosis of the actual system behaviour have been considerably improved and extended (8, 9).

The level of loading of the shotcrete lining is another valuable indicator for the geotechnical engineer for deciding whether a situation becomes critical or not.

The following two case studies are from a tunnel with shallow overburden in urban environments. The first refers to a tunnel with top heading / bench and invert excavation and the second a more complex construction sequence with side galleries and core excavation.

Case study 1

The first case history considers a tunnel with a diameter of approx. 13m (11) excavated in heterogeneous ground (flysh rocks). The geological conditions in the 100m section selected for the case history are characterised by sheared clay stones and bimrocks (=block in matrix rocks) where blocks are embedded in a soft matrix of sheared clay stones.

The overburden above the crown is around 45m. The design thickness of the shotcrete lining is 35cm.

Due to a residential area above the tunnel surface settlements had to be kept to a minimum.

Monitoring sections were installed in a regular distance of approx. 10m corresponding to a grid of surface targets along the tunnel axis. Each monitoring section consists of five targets in the top heading and two in the bench (Figure 5).

Figure 6 shows the time – dependent development of the level of loading with time in monitoring sections MS 1054 and MS 1090 at the crown. As can be seen the level of loading decreases immediately after a peak of approx. 45% due to creep effects of the young shotcrete. Another peak occurs during the excavation of the bench, the increase at the end of the period is caused by the continuation of excavation after Christmas break.

Figure 5 shows the spatial distribution of the stress in the top heading and bench lining from chainage 1017 to 1117 for a certain time period. The daily analysis of the level of loading in general showed low to medium stress, thus confirming the stability of the structure. The evaluation gives a quick overview about the load - bearing behaviour of the shotcrete lining during sequential tunnelling and enables immediate further analysis and reaction in case of high stress (e. g. increase support).

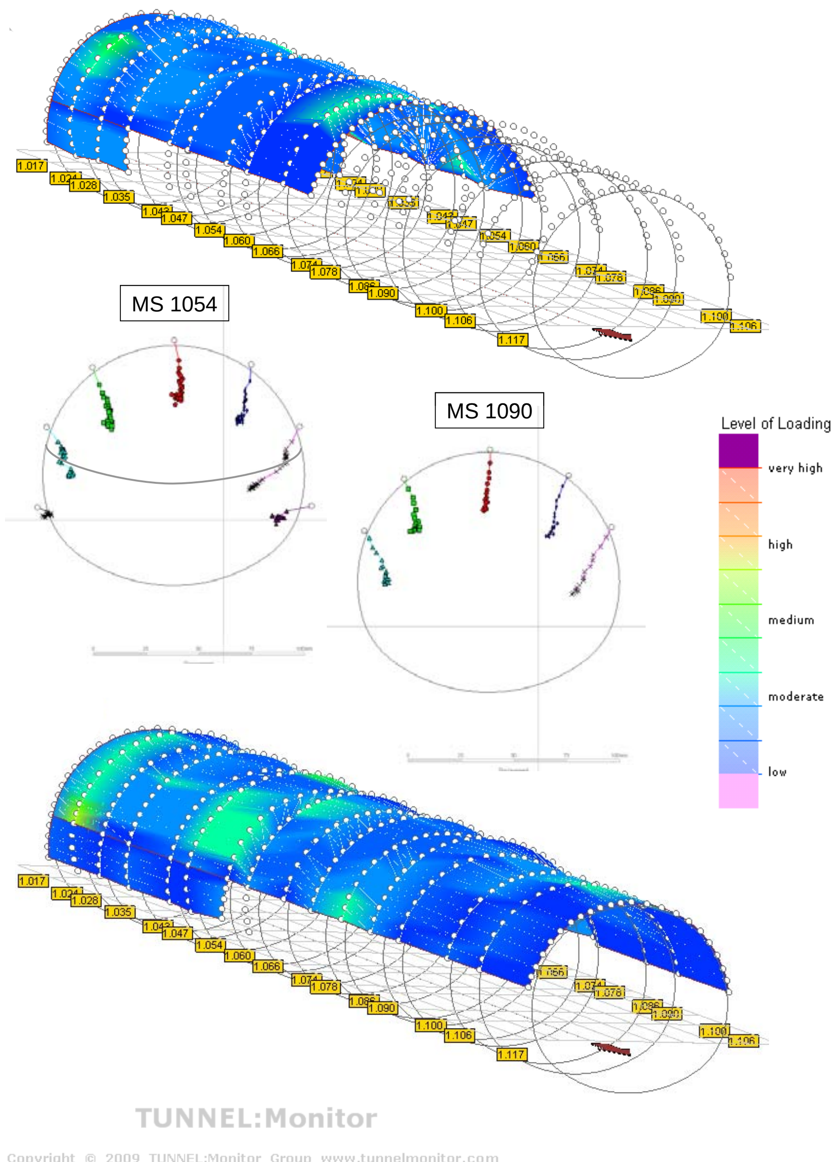

Figure 5: Spatial distribution and development of stress in a shotcrete lining (10) in the top heading followed by bench and invert (top and bottom); Position of targets and deformation pattern indicated by displacement vectors in two selected monitoring sections.

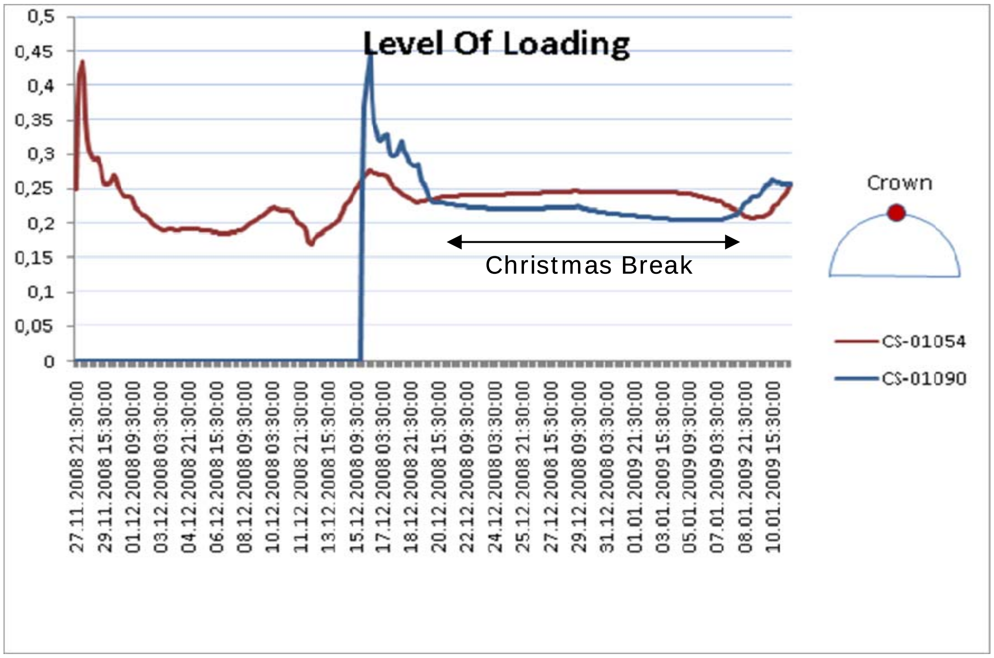

Figure 6: Development of the level of loading for point 01 (crown) in monitoring section MS 1054 and MS 1090 with time (10)

Case study 2

The case history illustrates the system behaviour with the development of the level of loading for a tunnel driven with side-wall galleries and core sections (7,11).

The tunnel with a diameter of approx. 13m is excavated in tertiary sediments. The geological conditions in the considered section are characterised by silt/clay and sand; multiple, steeply dipping faults at right-angles to the tunnel axis displaced the strata by up to several metres.

The overburden above the crown is around 25m.

Considerable sections of the alignment have to underpass residential areas.

The design thickness of the shotcrete for the outer sidewall and core is 35cm, for the inner sidewall 30cm.

Both side-galleries and the core were excavated in top heading, bench and invert sequence.

Monitoring sections were installed in a regular distance of approx. 10m corresponding to a grid of surface targets along the tunnel axis. Each monitoring section consists of 15 targets (6 targets in the side galleries, 3 targets in the core, s. Figure 7).

Figure 7: Tunnel excavated with sidewall galleries followed by core excavation (7,11); photograph showing construction works in the invert and the position of the targets.

Figure 8 shows four typical construction steps and how these phases influence the development of the level of loading in the shotcrete shell. The first step represents the excavation of the side-galleries (phase 1). During this step the stress in the top heading is concentrated at the roof. An ongoing stress reduction takes place due to creep effects.

The next peak occurs when the core of the remaining section is excavated (phase 2).
During this excavation step a movement of the inner sidewalls toward the core occurred. This deformation is caused by the loss of bedding of the inner sidewalls.

Typically, horizontal cracks corresponding to the calculated very high level of loading appeared at the shotcrete lining on the inner walls in the following positions:

- In the galleries in the area of the bench and in the roof
- In the upper core

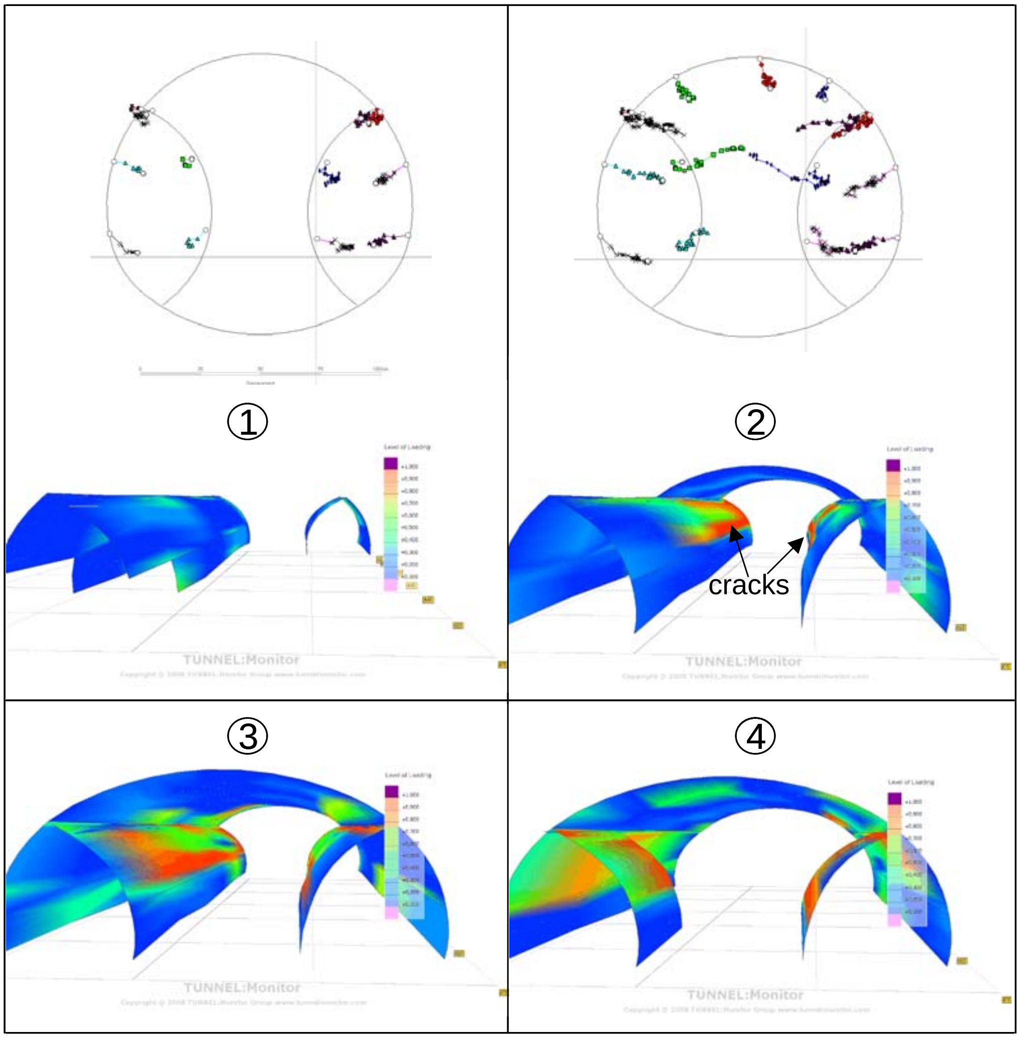

Figure 8: Construction Steps (1-4) and development of the level of loading (10) during and after excavation of the side-galleries and the core.

After the installation of the crown arch in the upper core, loads are transferred into the outer sidewalls inducing a stress increase in this area (phase 3). After removing the inner walls and during excavation of the invert with ring closure in the lower core it takes a while until the stresses are levelled again (phase 4); this is caused by the ongoing creep of the shotcrete lining.

Conclusions

A new method has been used recently at several Austrian tunnel sites to continuously evaluate the strains and stresses in a shotcrete lining based on monitored displacements of a tunnel wall.

The applied material law is based on a thermo-chemo-mechanical approach which turned out to be suitable for this type of calculation.

The level of stress is a useful additional information for the geotechnical engineer to determine whether a situation becomes critical or not, and to determine additional measures (adjustment of excavation and support) in due time.

The quality of the results strongly depends on the accuracy of the measurements. The shotcrete with an early age ‘forgives’ inaccurate measurements or wrong assumption concerning the gradient of the displacements.

The older the sprayed concrete is, the more any inaccuracy in the measured displacements leads to wrong results of the load level and may lead to misinterpretations concerning the geotechnical situation.

Although this approach is very successful, it should be kept in mind that the determination of stresses from measured displacements remains an approximation with uncertainties.

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