Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) Paper: 08-02

Practical use of *FLAC3D* in tunneling

Kurt Mair am Tinkhof & Nedim Radončić
Amberg Engineering AG., Innsbruck, Austria

1 INTRODUCTION

Amberg Engineering is working in the field of tunneling for more than 50 years. We have been developing solutions in the fields of underground railway, road and metro tunnels, caverns and infrastructure galleries. In the last years the development goes always more in the direction of BIM (Building Information Modeling)-oriented design of underground structures. The numerical modeling software *FLAC3D* (Itasca 2012) from Itasca in conjunction with all its *FISH* abilities and the meshing tool *Griddle* (Itasca 2017) is used to calculate the stability and the support measures for complex underground structures. The following paper gives a short overview about the work of Amberg Engineering with the Itasca Software *FLAC3D* and the experience of Amberg Engineering employees with *FLAC3D* in the past.

2 DIMENSIONING OF A SHIELD TBM DRIVE (BRENNER BASE TUNNEL)

The Brenner Base Tunnel (BBT) runs for 64 km between Austria and Italy, making it the longest underground railway tunnel in the world. The BBT consists of two single track tubes, connecting cross passages every 333 m and an exploratory tunnel – which lies between 10 and12 m below the main tunnels (Fig. 1).

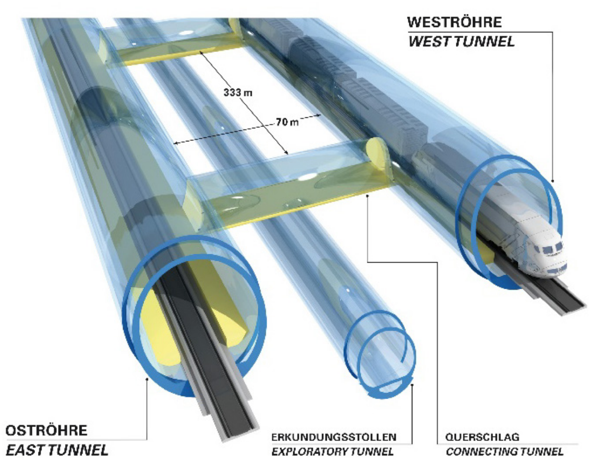

Figure 1. Brenner Base Tunnel System with two Main Tunnels and the Exploratory Tunnel (BBT SE 2019).

On the Austrian side of the BBT the access tunnels and parts of the main and exploratory tunnels have already been built or are currently under construction. Two final main tunnel lots (one of those is already under construction) will complete the tunnel works. The tunnels run through very complex and heterogeneous geological and geotechnical conditions. In the course of designing the mechanized drives of the main tunnels on the Austrian side of the Brenner Base Tunnel with hard rock shield TBMs with diameters of ca. 10m, a detailed tunneling concept was created, which deals with the project-specific features and boundary conditions.

The observations from the exploratory tunnel have been systematically used to optimize the design and correctly assess the hazards. Based on the location and the orientation of the fault zones, the measurement data from the laser scans and the machine data (thrust force) in the exploratory tunnel it was possible to back calculate the geotechnical parameter of significant fault zones with numerical calculations in *FLAC3D*, taking into account that this heading is done with an open gripper TBM. These results are used in a next step in “forward calculations” to verify the feasibility of a Shield TBM drive in the main tunnels by checking the max. thrust forces (Fig. 2). In a next step the design of the precast concrete segments is based on the results of those calculations (lining thickness, annular gap size). With this information and results the geological-geotechnical risk for this tunnel section could be reduced to nearly zero (Rehbock-Sander et al. 2018, Mair am Tinkhof et al. 2018) – the defined capacity of the TBM and the designed capacity of the pre-cast concrete segments are custom tailored for the observed in-situ conditions.

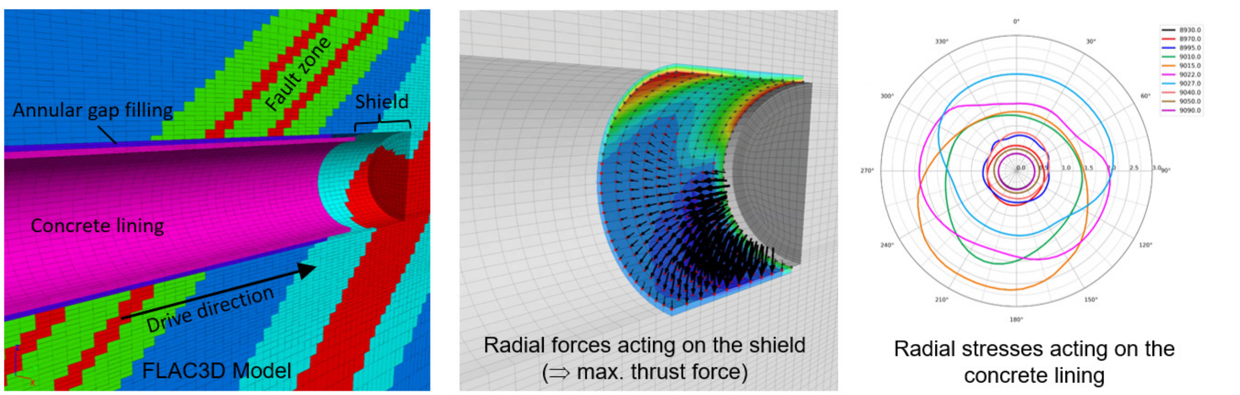

Figure 2. a) *FLAC3D* model of a “forward calculation” through a fault system with a TBM-S; b) Radial forces acting on the shield to determine the required thrust force; c) Radial stresses acting on the concrete lining (Rehbock-Sander et al. 2018).

3 COMPLEX 3D MODELS FOR UNDERGROUND SYSTEM (TUNNELBANA STOCKHOLM)

The underground system of Stockholm will be significantly extended in the next years. Besides the expansion of the existing metro lines the design of a new “yellow line” of Stockholm’s subway network is progressing steadily since 2013. The geological conditions are very good compared to many other cities of the world with hard granite and gneiss formations, paired with high horizontal primary stresses. Several weakness zones are present; however, they are composed of strongly jointed rock and do not contain strongly cataclastic rocks. On the other hand, there are different challenges caused by the imperative of using minimum amount of support measures, local areas with very low rock cover, close distance to the existing underground structures and possible influence of the blasting of hard rock in the midst of a modern city environment.

Due to these boundary conditions and the ever-increasing need for complex excavation geometry, the application of a comprehensive 3D design has proven to be an effective instrument. The stations were analyzed with a *FLAC3D* numerical analysis, as those areas have a complex geometry with big spans, several weakness zones and occasionally, low overburden. The Rhino Plugin (McNeel 2018), *Griddle*, developed by the Itasca group, allowed us to perform seamless geometry transfer from the underlying BIM model into Rhino and finally into *FLAC3D* (Fig. 3). In *FLAC3D* a routine was generated to show the influence of the weakness zones within the analysis. The routine conducted two separate numerical analysis runs. One contains no weakness zones and is used as a reference case, and the other one is modelled with them, allowing quantification of the influence. The quantification is performed by checking the difference in the absolute displacement magnitude and by examining the ratio of the displacements in both cases (Fig. 4).

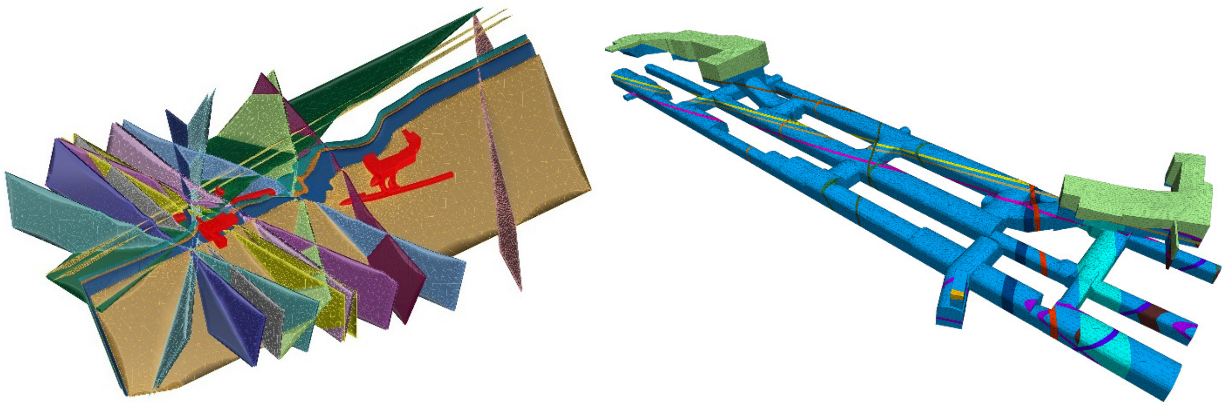

Figure 3. a) Rhino model of the complex geometry of the excavation of an underground station including several weakness zones b) *FLAC3D* model of the excavation geometry with the weakness zones.

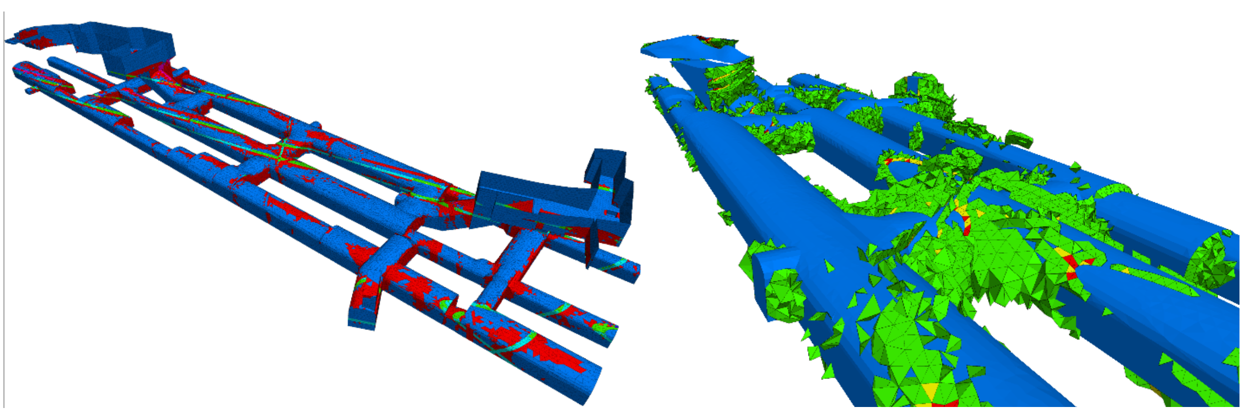

Figure 4. a) Plastic zones on the excavation surface, b) Zones with maximum principal strain exceeding 50 µstrains.

4 DESIGN OF SHAFT HEAD CAVERNS WITH LARGE SPANS (SEMMERING BASE TUNNEL)

The Semmering Base Tunnel is located approximately 80 km south of the Austrian capital Vienna. The railway tunnel consists of two 27.3 km long single-track tunnels, cross passages and a complex underground emergency station. Temporary shafts are required to provide access to the underground construction. The two shafts are excavated, starting underground via a 1.0 km long temporary access tunnel, located around 250 m above the main tunnel alignment. Cavern systems at the heads of the subsurface shafts and at the bases of the shafts accommodate installations and logistics for construction purposes (Proprenter & Wagner 2019).

Figure 5 shows the *FLAC3D* model of a temporary cavern system at the heads of the subsurface shafts with cavern spans up to 20 meters. In the area of the shaft head cavern, Permo-Mesozoic carbonate rocks were forecast, characterized mainly by largely competent, isotropic Rauhwacke (leached limestone) with frequent transitions to calcareous breccia and dolomite breccia and isolated breccia layers. The geological layers were integrated in the model. In the model, the construction sequences and the installation of support measures (shotcrete and rock bolts) were simulated in detail. This was done with *FISH* Routines that allowed the exact simulation of the excavation sequences with automatic installation of shotcrete with different thicknesses and of rock bolts with different lengths and spacings. Based on the results of the numerical calculation, the structural verifications of the support measures were performed (Fig. 6).

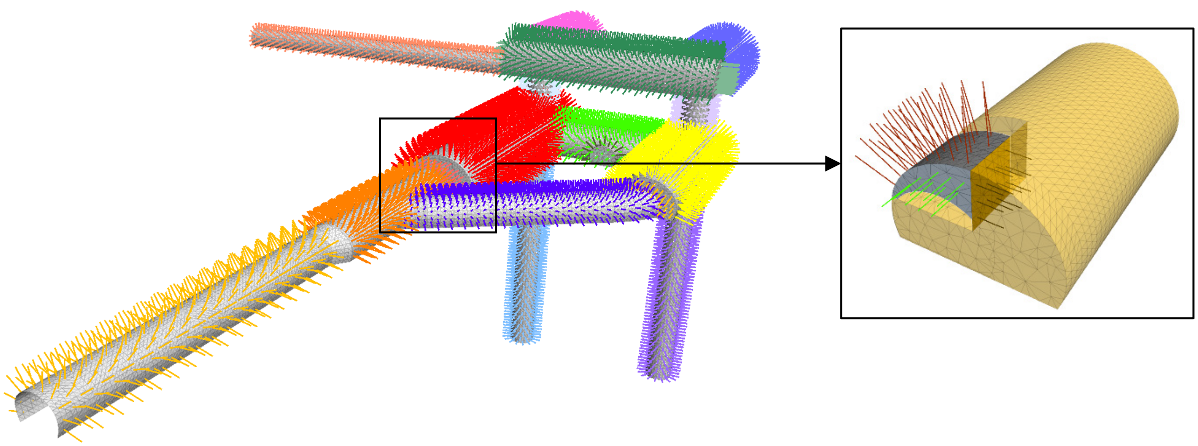

Figure 5. a) *FLAC3D* model showing the excavation surface and the rock bolts of the shaft head caverns, b) detailed excavation sequences and installation of support measures.

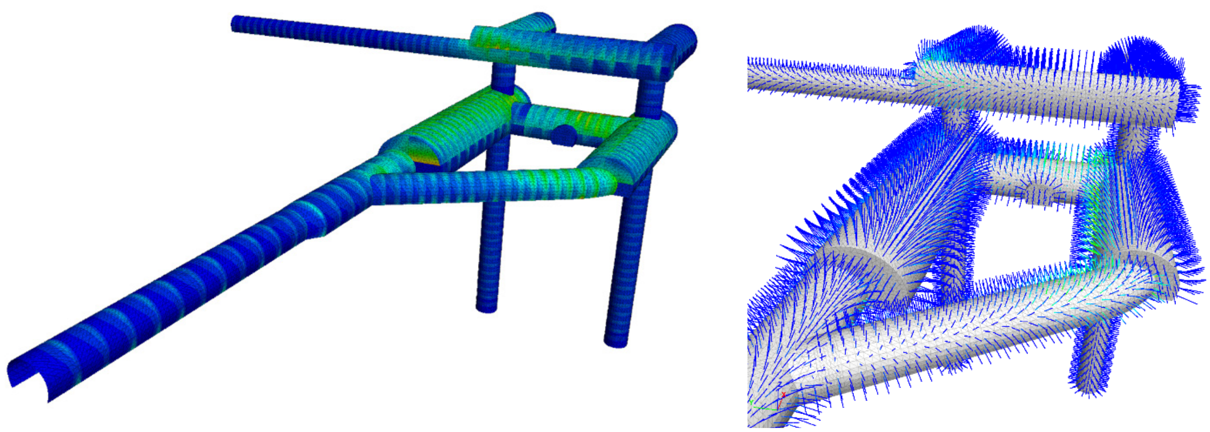

Figure 6. a) *FLAC3D* model showing the displacements of the excavation surface and b) the loads in the rock bolts.

5 CONSTITUTIVE MODELLING OF SHOTCRETE

The influence of the yielding element load-displacement line on the displacement development and utilization of shotcrete has been examined systematically (Radončić 2011). In the first step, a fish runtime procedure (fishcall) has been developed, allowing dynamic determination of shotcrete creep parameters based on shotcrete age and present deviatoric stress in the shotcrete. The routine has been tested rigorously against test data and validated as sufficiently accurate and stable (Fig. 7).

The rock mass has been modelled with a strain softening law, where the strain softening parameters have been obtained by explicitly modelling the direct shear test on intact rock specimen and additional check whether or not the predicted behavior fits with the densely available absolute displacement monitoring data. The development of the shear band between the shotcrete and the rock mass has been thus captured by applying a strain softening law, allowing proper yielding element mobilization (Fig. 8).

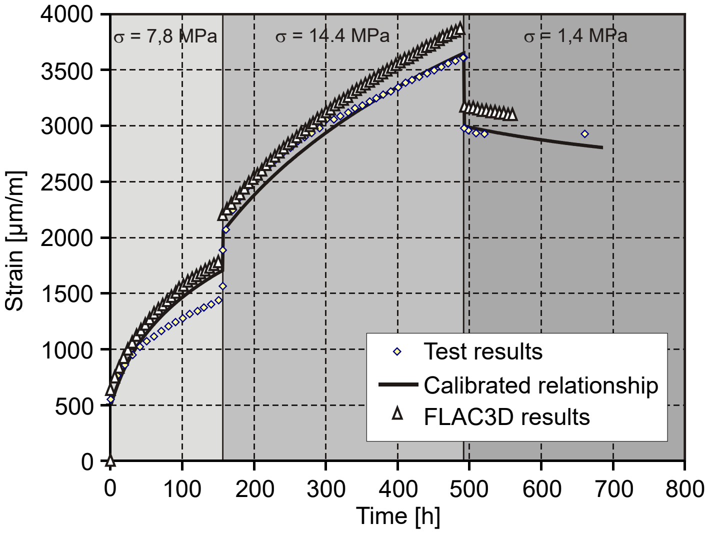

Figure 7. Comparison between test results from a multi-stage load test on young shotcrete, empirical relationship (Schubert 1987) for creep calibrated on the test results, and *FLAC3D* implementation of the relationship.

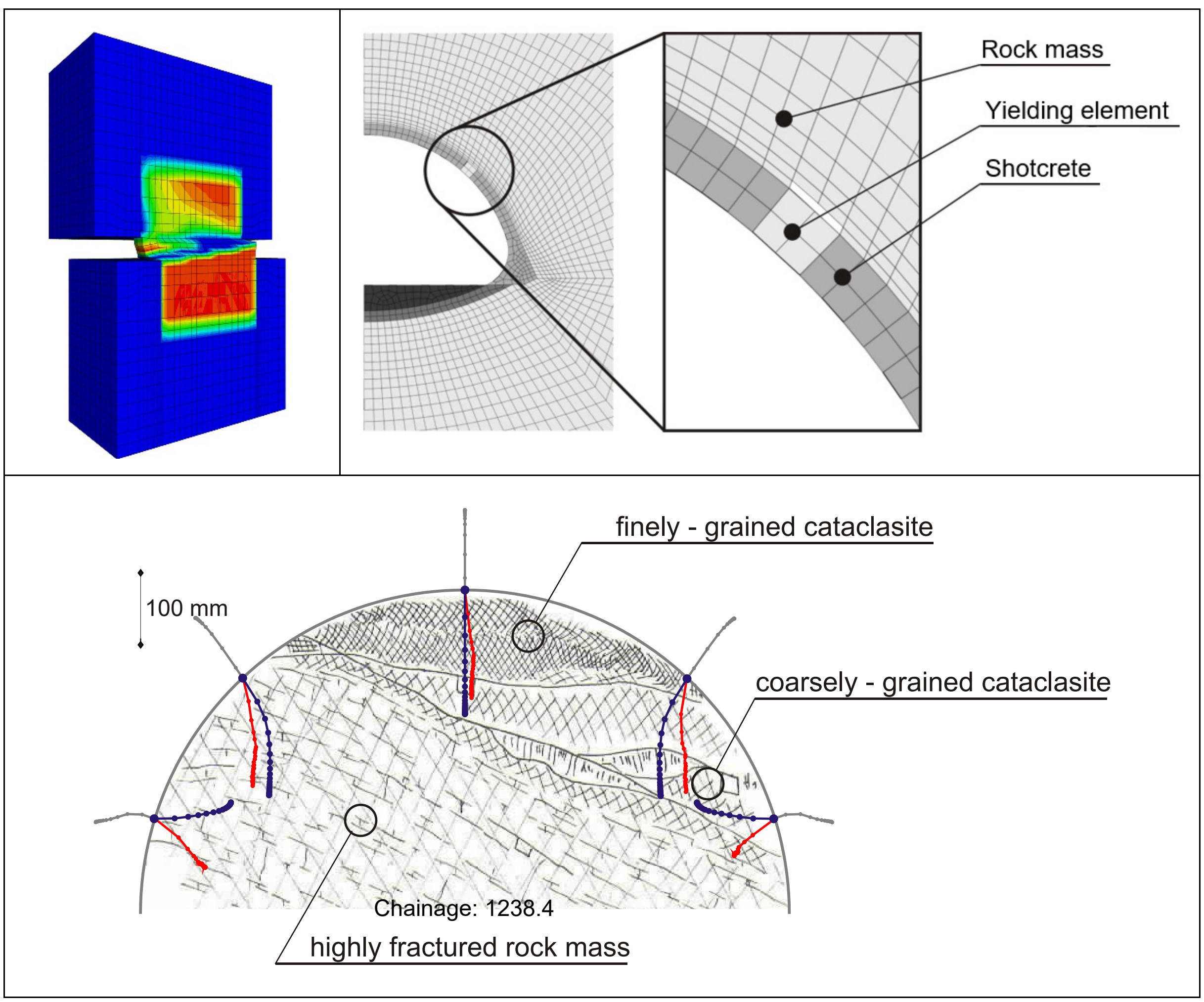

Figure 8. Top Left: Mobilized cohesion in an intact rock direct shear test. Top Right: Cross section and discretization of the used numerical model. Bottom: Comparison between absolute displacement data and analysis results, along with the respective geological mapping.

The thus validated model has been used to predict the displacement development and shotcrete mobilization in case other yielding element types are used and finely tune the required characteristic for future construction (Fig. 9).

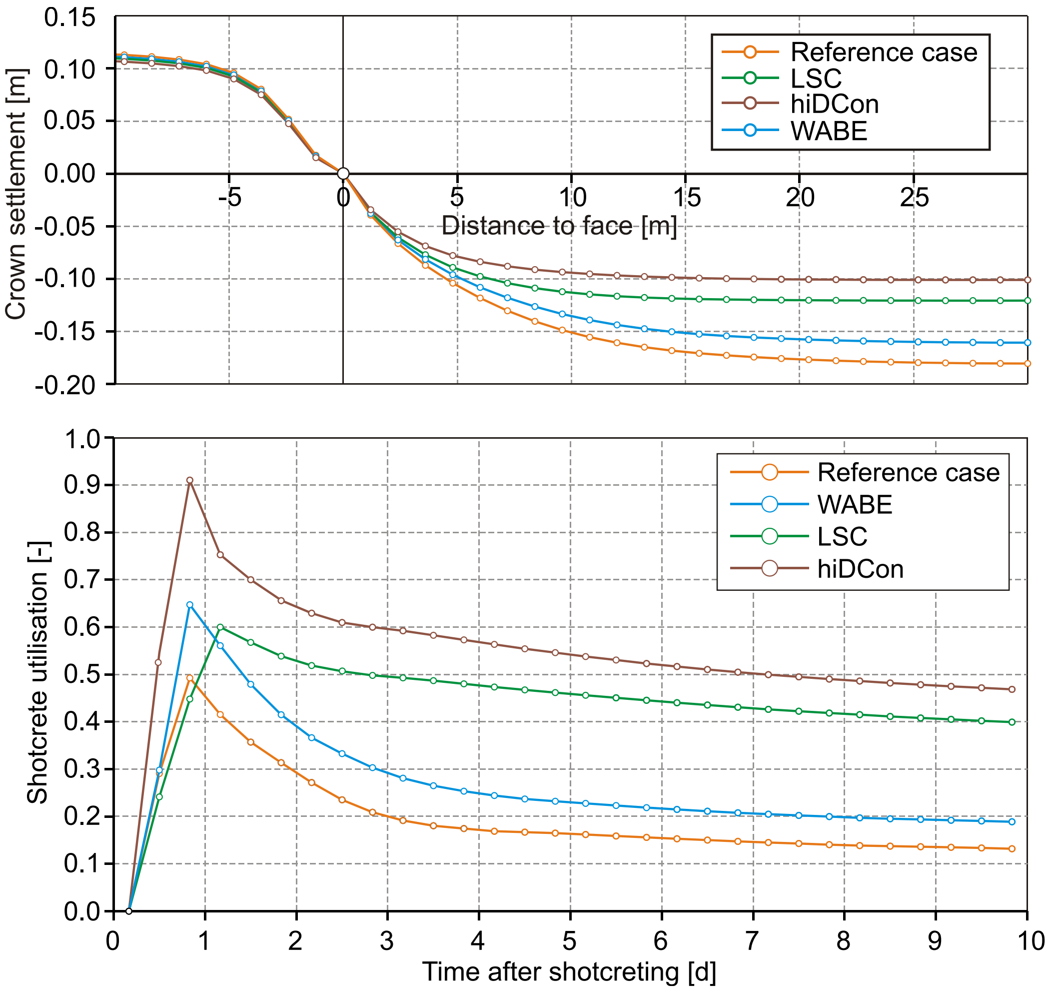

Figure 9. Top: Influence of yielding element choice of on the displacement development. Bottom: Shotcrete utilization over time.

6 CONCLUSIONS

FLAC3D, especially with the recent additions of the hardening soil model and *Griddle*, represents an excellent tool for numerical analysis of different geotechnical problems. The fact that the input is still entirely based on input files is regarded as exceptionally favorable, since it uses a much more direct control of the analysis parameters, copy/paste operations are used in case of similar models and simple parameter studies. Even a fully working coupling between *FLAC3D* and an external optimization routine has been managed, allowing automatic back analysis of a simpler problem with *FLAC3D* (Radončić et al. 2008). The ability of *FISH* to manipulate basically all aspects of the model grants extreme flexibility and renders *FLAC3D* an unparalleled product – from our point of view – on the market.

Since the need for complex 3D analysis is rising, due to ever increasing complexity of underground projects, Amberg Engineering's main focus is currently on the consolidation of the currently present knowledge and development of standard *FISH* libraries for model setup, analysis and post-processing. Once this is present, our productiveness with *FLAC3D* will be substantially increased.

REFERENCES

BBT SE. 2019. https://www.bbt-se.com/en/information/media-corner/.

Itasca Consulting Group, Inc. 2012. *FLAC3D – Fast Lagrangian Analysis of Continua in 3 Dimensions, Ver. 5*.0. Minneapolis: Itasca.

Itasca Consulting Group, Inc. 2016. *Griddle, Ver. 1.0.* Minneapolis: Itasca.

Mair am Tinkhof, K., Radončić, N., Reinhold, C., Insam, R. & Rehbock-Sander, M. 2018. From the geological prognosis to the TBM drive: Planning the main construction lots of the Brenner Base Tunnel. *Geomechanics and Tunnelling* 11, No. 5, S. 519-529.

McNeel. 2018, Rhinoceros, Version 6.

Proprenter, M. & Wagner, O.K. 2017. Semmering Base Tunnel – Large Caverns in Challenging Conditions. *Proceedings of the World Tunnel Congress 2017 – Large Caverns – Underground solutions*. Bergen, Norway.

Radončić, N. 2011. *Tunnel design and prediction of system behavior in weak ground*. PhD Thesis, Institute for Rock Mechanics and Tunnelling, Graz University of Technology.

Radončić, N., Gresovnik I., Grossauer, K., Gober, H. & Schubert, W. 2008. Back-Analysis of Elastic Properties of the Ground Using Data from a Largescale Plate Load Test. *42nd US Rock Mechanics Symposium and 2nd US-Canada Rock Mechanics Symposium,* San Francisco, California, USA.

Rehbock-Sander, M., Insam, R., Reinhold, C. & Mair am Tinkhof, K. 2018. The Brenner Base Tunnel, Overview and TBM Specification for the 2 tunnel lots at the Austrian Side. *Proceedings WTC 2018*, Dubai.

Schubert, P. 1987. Beitrag zum rheologischen Verhalten vom Spritzbeton. *Felsbau* 6 (3), 150–153.

Wieland, G., Prall, K., Lenz, G., Schachinger, T. & Gobiet, G. 2018. Semmering Base Tunnel – design and construction of the shaft head caverns under difficult conditions. *Geomechanics and Tunnelling* 11, No. 5, S. 462-470.