# Evaluation of trends in tunnel lining utilization with regard to the moment of ring closure

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ABSTRACT: At sequenced tunnel drives, next to the rock mass conditions, the advance rates of the single excavation stages and the moment of ring closure determine the performance of shotcrete linings. Especially in heterogeneous rock masses, the investigation of the optimum ring closure moment resulting in no damage of the lining challenges the engineers. If the ring closure is too early, the lining may experience compressive failure because the building up of ground loads is too large. A late ring closure may allow for too much tunnel displacement. To investigate the effects of various ring closure moments on the utilization of the tunnel lining and the tunnel crown convergences, this study performs 3D finite element simulations. The results at a specific measuring cross section and for the assumed ground conditions suggest that a delayed ring closure can lead to higher utilizations compared to an early ring closure.

*Keywords: ring closure, 3D finite element simulation, lining utilization, sequential excavation.*

## 1 INTRODUCTION

Sequential tunnel excavations are based upon the concept that the ground in the vicinity of the tunnel is not only a load element but also acts as a load bearing element. The excavation and support activities are adjusted in real time to suit the ground conditions considering the design requirements (Galler et al. 2009). A balance must be maintained between the construction speed and the need to expose a minimal area of ground at a time to ensure reduced deformation in the unsupported zone (Clayton et al. 2000). To stabilize the tunnel structure and the surrounding ground, a closed ring of tunnel lining is introduced. The chosen construction speed and construction sequences, determining the moment of ring closure, influence the utilization of the tunnel lining as shown by Stärk & Zachow (2015). To maintain a balance between the need for a cost intensive strong support and low safety margins for lighter support structures, the closure length should generally be less than one diameter as concluded by the studies of Awaji et al. (2016).

In this paper, trends for tunnel crown convergences and lining utilizations in dependency of various ring closure moments are evaluated. To achieve this task, 3D finite element models are established, and two design parameters are varied: first, the advance rate of the excavation and second, the length of excavation stretches in top heading and bench. A limitation regarding the simulation of the shotcrete behavior is made upon the phenomena of creep, shrinkage and softening which are not included in the models.

In section 2, the methodology followed within the finite element simulations is described. Section 3 presents the results for a cross section in the center of the considered tunnel stretch. Finally, in section 4, a conclusive summary is elaborated and the effects of advance rate and excavation length on the tunnel crown convergences and lining utilizations are discussed.

## 2 METHODOLOGY

### *2.1 General model considerations*

A deep tunnel with high overburden is considered for the simulations. The rock mass is modelled by an elastic-perfectly plastic Mohr-Coulomb constitutive model. A hydrostatic initial stress field with a magnitude of 10 MPa is generated using the $K_0$-procedure in PLAXIS 3D. Therefore, the unit weight of the rock is assumed with 0 kN/m³ to prevent any initial stress gradients. Standard deformation boundary conditions are applied to the model with roller boundaries on the vertical sides. Only one half of the tunnel is included in the model as symmetrical conditions are assumed. The shotcrete support is modelled with linear elastic volume elements with properties as described in section 2.3. Each excavation step is simulated by deactivating single volumes, installing the shotcrete, and stiffening the shotcrete with time at the respective locations. Two different tunnel advance speeds are simulated with excavation rates of 3 m/day and 6 m/day. Further, the length of the excavation stretches in the top heading and bench is varied with values of 9, 15 and 21 m.

### *2.2 Model geometry and sequencing*

Only a part of the rock mass surrounding the deep tunnel is modelled. The remaining overburden is simulated with a high-density layer of rock placed on top of the model. The model dimensions are 40 m x 80 m x 25 m referring to the *xyz*-coordinate system as shown in Figure 1b.

A horseshoe shaped tunnel (Figure 1a) with a regular cross section and a width and height (inner dimensions) of 10.98 m and 9.65 m is considered. A 0.25 m thick shotcrete lining is accounted for. The tunnel is excavated in round lengths of 1 m. The simulation sequence considers the excavation of the top heading slices in a first step until the defined length for the top heading stretch is reached. It further proceeds with the excavation of the bench slices until the closure length of 6 m from the heading face is achieved. Subsequently, this process is repeated (see Figure 2) until a steady-state tunnel behavior without any influence of the model boundaries can be observed. The different colors for the tunnel lining in Figure 2 indicate various considered stiffnesses of the shotcrete with regard to its age from the moment of installation (modified after Pöttler 1985). Darker colors correspond to higher stiffnesses of the shotcrete volumes.

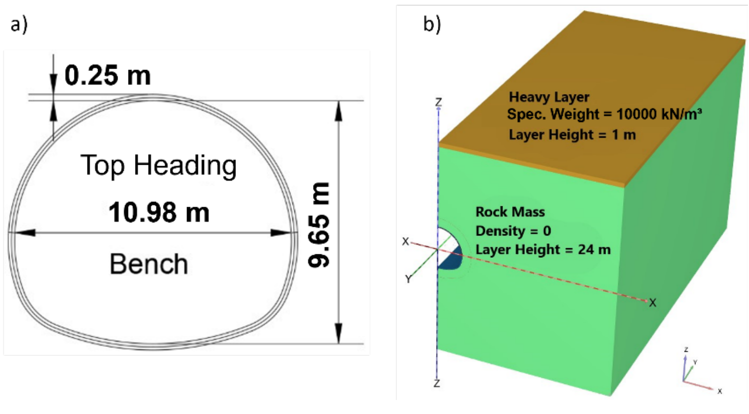


Figure 1. a) Dimensions of the tunnel cross section and b) 3-D model overview.

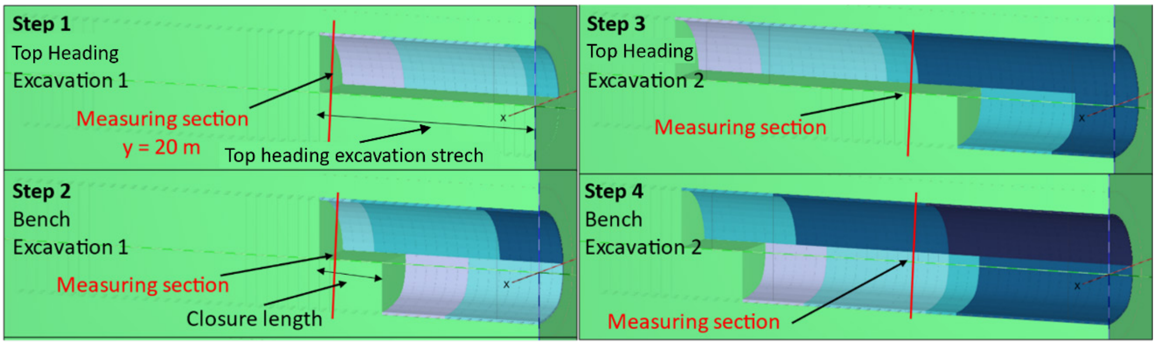


Figure 2. Sequential excavation procedure as considered within the simulation of the tunnel excavation exemplarily shown for a chosen excavation stretch length of 21 m. The red line indicates the location of the measuring cross section considered for the result evaluation.

## *2.3 Material properties*

The properties for the high-density overburden layer, the rock mass in the vicinity of the tunnel and the shotcrete for different ages are given in Table 1 and Table 2. A rigid connection between the lining and the rock mass is assumed. A weightless elastic dummy plate, as can be seen in Figure 3, is introduced along the neutral axis of the shotcrete lining aiding in the result extraction. The virtual thickness of the dummy plate is chosen with the same value as for the shotcrete lining. However, the plate stiffness is selected by a factor $10^4$ times smaller than for the actual shotcrete, not to influence the simulated shotcrete behavior (Papavasileiou 2020).

Table 1. Material properties for the overburden layer and the rock mass.

| Parameter | | Overburden layer | Rock mass |
|---|---|---|---|
| Material model | [-] | Linear Elastic | Mohr-Coulomb |
| Specific weight | [kN/m$^3$] | 10000 | 0 |
| Young's modulus | [MPa] | 7500 | 7500 |
| Poisson's ratio | [-] | 0.3 | 0.3 |
| Cohesion | [MPa] | - | 1 |
| Friction angle | [°] | - | 25 |
| Lateral pressure coefficient | [-] | 1 | 1 |

Table 2. Time-dependent shotcrete properties, modified after Pöttler (1985).

| Parameter | | Fresh shotcrete | 1 day | 3 days | 5 days | 10 days |
|---|---|---|---|---|---|---|
| Material model | [-] | Linear Elastic | Linear Elastic | Linear Elastic | Linear Elastic | Linear Elastic |
| Specific weight | [kN/m$^3$] | 24 | 24 | 24 | 24 | 24 |
| Young's modulus | [MPa] | 3000 | 5000 | 7500 | 12500 | 15000 |
| Poisson's ratio | [-] | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |

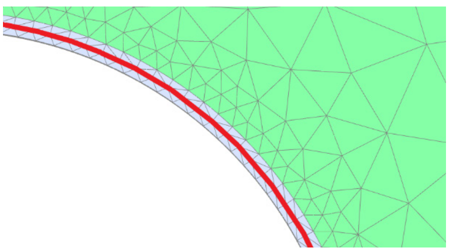

Figure 3. Cross section through the shotcrete lining (purple) with the dummy plate (red) placed at the neutral axis of the shotcrete support.

### 2.4 Result evaluation

#### 2.4.1 Crown convergence

Besides the rock mass conditions, the tunnel displacements will also be affected by the moment of ring closure in dependency of the advance rate and heading/bench excavation lengths. To make these influences visible, crown convergences for the models with varying inputs for these two parameters are observed. The crown convergences are evaluated at the specific measuring cross section as displayed in Figure 2.

#### 2.4.2 Utilization of the shotcrete lining

The ratio of the maximum compressive stress in the lining to the time-dependent shotcrete strength is termed as utilization (Stärk & Zachow 2015).

In this study the progressive lining utilization is evaluated at the measuring cross section according to Figure 2 right after the installation of the lining at this section. The maximum lining compressive stress at this location is evaluated as stated in Eqn. (1) from the observed structural forces within the dummy plates upscaled by the previously considered stiffness reduction factor (section 2.3). In this equation, *M* denotes the bending moment; *N* denotes the hoop force; and *b* (= 1 m acc. to round length) and *t* (= 0.25 m) are lining width and thickness respectively. For calculating the utilization value, the ratio between maximum compressive stress in the lining and the time-dependent shotcrete strength acc. to Neuner et al. 2017 is considered.

$$\sigma_{max} = \max\left[\frac{6 \cdot M}{(\mathrm{b} \cdot \mathrm{t}^2)} + \frac{\mathrm{N}}{(b \cdot t)}\right] \quad (1)$$

Because the lining is modelled as elastic, compressive stresses higher than the time-dependent shotcrete strength are possible to occur in the simulations. Therefore, utilizations higher than 100 % are visible in section 3.

## 3 RESULTS

### 3.1 Crown convergence plots

The crown displacements at the measuring cross section as observed for all simulation models are plotted against the excavation phase number in Figure 4. All graphs indicate a higher displacement of the crown following a higher advance rate of excavation. This is connected with the overall lower stiffness of the shotcrete at younger ages. It is also noted that the final phase displacements among the models with different excavation lengths are approximately the same. Hence, the excavation length is not impacting the final crown convergences for the investigated situation. Most of the displacements occurring in the crown happen during the top heading excavation of the tunnel. The bench excavation has a minor effect on the crown displacements.

### 3.2 Utilization plots

The comparatively lower values for the lining utilization at the measuring cross section (Figure 5) for the models with 21 m of excavation length signify the start of the bench excavation shortly after the shotcrete was installed in the heading at the measuring section. The low utilization is a result of the minor effects of the trailing bench excavation on the buildup of lining forces and the time-dependent strength increase of the shotcrete at the measuring section. For models with excavation lengths of 9 and 15 m the excavation sequence foresaw an immediate continuation of the heading excavation after passing through the measuring section. Hence, the structural forces continued to increase and did not show a steep decline in the utilization initially. It can generally be observed that the utilization at the measuring section reaches a more critical state with the highest value of excavation length. It is also noted that a higher utilization is observed for a slower advance rate. Hence, for the investigated ground conditions and the assumption made for the lining to be elastic, a too slow advance rate might be associated with potential damages of the lining.

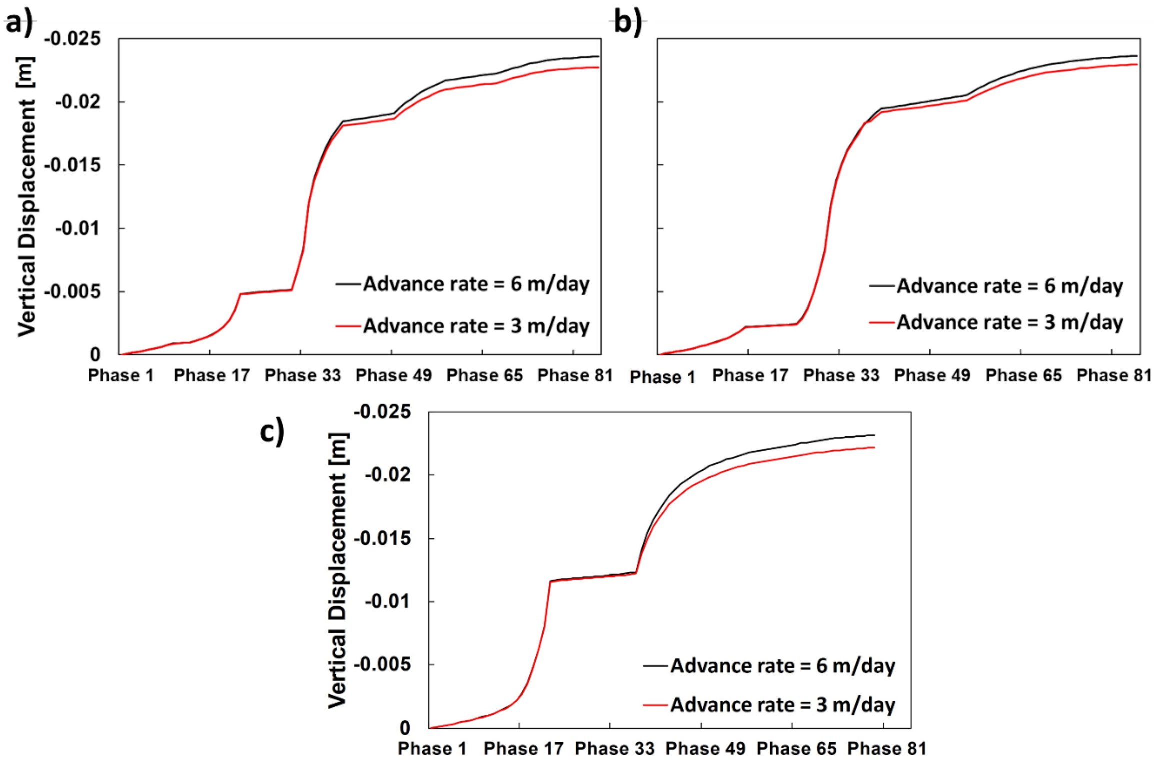


Figure 4. Crown displacement at the center of tunnel for a) excavation length 9 m, b) excavation length 15 m, c) excavation length 21 m.

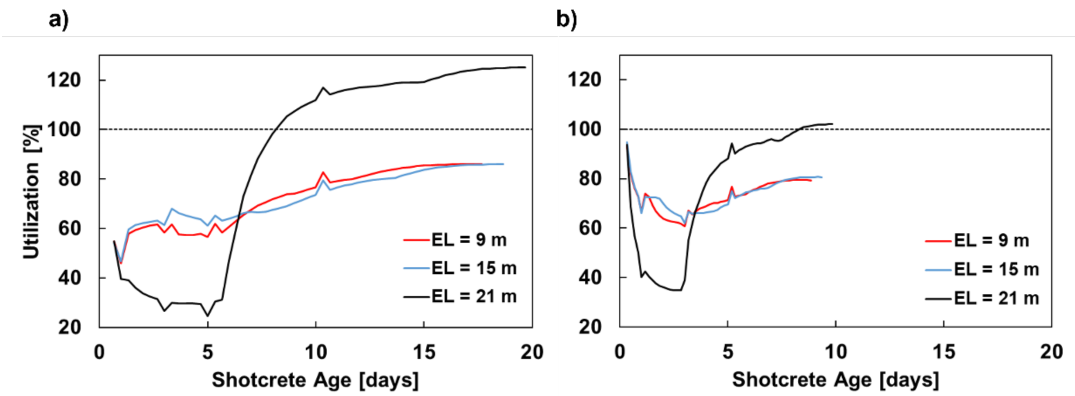


Figure 5. Utilization of the lining at the measuring cross section for models with an a) advance rate of 3 m/day, b) advance rate of 6 m/day. EL is short for excavation length.

## 4 CONCLUSIONS

A numerical study on the evaluation of the influence of the tunneling advance rate and three different lengths of top heading/bench excavation stretches on the crown convergences and lining utilizations at a specific measuring cross section in the tunnel was presented. As further aspects of the general boundary value problem, such as the material properties and the initial stress states, where considered as fixed in this study, the conclusions made are limited to the respective case and to the chosen measuring cross section only.

A higher advance rate of excavation has been observed to result in slightly higher values for the vertical crown displacements as compared to the lower advance rate. However, using a lower advance rate has eventually developed a higher ultimate utilization in the shotcrete lining, which at a first glance is unexpected. The high levels of utilization in this case have been found to be associated with the specific location of the soft-to-stiff shotcrete intersections which for the most critical model combination was located close to the measuring section. Typically, stiffer shotcrete parts tend to attract a higher amount of stress. Thus, a high stiffness contrast of consecutive lining segments is counterproductive on the utilization. Despite the increase in shotcrete strength over time, the factor in stress-increase due to higher stiffness attracting more stresses outweighed the factor for the strength-increase in our specific case. Possible stand-still times, amplifying the stiffness contrast between consecutive lining segments, might have an additional unfavorable effect on the lining strength utilization factors. A better trend could be established if the evaluation is carried out along the entire simulated tunnel alignment. Further research on the effect of the moment of ring closure in tunneling is required and more realistic and comprehensive simulations in various ground types including advanced material models for the shotcrete need to be performed.

## REFERENCES


Awaji, D., Isago, N., Kusaka, A., & Kawata, K. 2016. Performance requirement of immediate ring closure method for difficult ground conditions in conventional tunneling. In: *Proceedings of the ITA-AITES World Tunnel Congress 2016 (WTC 2016),* Vol. 1, 22-28 April, San Francisco, USA, pp. 640-649.

Clayton, C., Hope, V., Heymann, G., Van der Berg, J., & Bica, A. 2000. Instrumentation for monitoring sprayed concrete lined soft ground tunnels. In: *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 143(3), pp. 119-130. DOI: https://doi.org/10.1680/geng.2000.143.3.119

Galler, R., Schneider, E., Bonapace, P., Moritz, B. & Eder, M. 2009. The New Guideline NATM – The Austrian Practice of Conventional Tunnelling. *BHM Berg- und Huettenmännische Monatshefte*, Vol. 154, pp. 441–449. DOI: https://doi.org/10.1007/s00501-009-0503-9

Neuner, M., Cordes, T., Drexel, M., & Hofstetter, G. 2017. Time-Dependent Material Properties of Shotcrete: Experimental and Numerical Study. *Materials*, 10(9), 1067, pp. 1-17. DOI: https://doi.org/10.3390/ma10091067

Oreste, P., Spagnoli, G., Luna Ramos, C.A. & Hedayat, A. 2019. Assessment of the Safety Factor Evolution of the Shotcrete Lining for Different Curing Ages. *Geotechnical and Geological Engineering*, Vol. 37, pp. 5555–5563 (2019). DOI: https://doi.org/10.1007/s10706-019-00990-2

Papavasileiou, S. 2020. *Dummy plate properties in PLAXIS 3D*. Bentley Communities. Available online: https://communities.bentley.com/products/geotech-analysis/f/forum/197815/dummy-plate-properties-in-plaxis-3d (accessed on May 19, 2022)

PLAXIS Scientific Manual: 3D-Connect Edition V21. 2021. Available online: https://communities.bentley.com/cfs-file/__key/communityserver-wikis-components-files/00-00-00-05-58/PLAXIS3DCE_2D00_V21.00_2D00_02_2D00_Reference_2D00_3D.pdf (accessed on February 11, 2023)

Pöttler, R. 1985. Evaluating the stresses acting on the shotcrete in rock cavity constructions with the Hypothetical Modulus of Elasticity. *Felsbau*, Vol. 3(3), pp. 136-139.

Stärk, A., & Zachow, R. 2015. Real time determination of the utilisation of a sprayed concrete lining during tunnelling. Crossrail Learning Legacy. Retrieved February 1, 2023, from https://learninglegacy.crossrail.co.uk/documents/real-time-determination-utilisation-sprayed-concrete-lining-tunnelling/