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Parametric study of displacements on sequential and full-face tunnel excavation

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ABSTRACT: When constructing tunnels with low overburden in built-up areas face stability and in the unsupported span, as well as displacements of ground and subsidence are major issues. Presently two different concepts to deal with such tunnels can be observed. One concept is to subdivide the face into several excavation steps, like top heading bench and invert excavation with a certain distance between the single steps. The other concept is a full-face excavation with a quick ring closure and heavy support of the face to account for the face stability problem. The different concepts have been compared in a parametric study, using the code FLAC3D.

1 INTRODUCTION

According to the Austrian Guideline for Geomechanical Design of Underground Structures, the system behaviour is defined as the behaviour of the compound system resulting from rock mass and selected construction measures (excavation and support method, auxiliary measures). In tunnels with low overburden, the stress redistribution, combined with poor quality of the ground can lead to instability of the face and the crown. Shear failures can develop progressively without significant sign (Schubert & Vavrovsky 1994). This can lead to serious overbreak of the crown or even to a chimney type failure in case of poor ground and low confining stress (Feder 1981). Therefore, deformations should be carefully controlled to minimize the risk and scale of collapses, as well as surface settlements.

The advocates of the full face method claim that the increase of the rigidity of the core ahead of the face is the main medium of controlling pre-convergence and convergence in the cavity (Lunardi 2000). In cases of low face stability extensive face reinforcement is applied, ranging from a number of 50–60 anchors in shallow tunnels, up to 200 in tunnels with higher overburden (100–200 m) or even 400 in extremely poor ground.

Quick final ring closure was also demanded by some protagonists of the NATM (Müller 1978). Over the decades in poor ground, sequential excavation with the installation of a temporary invert in the top heading however has become common practice. In very weak ground, the face usually is supported by shotcrete and a small and adequate amount of anchors.

An unbiased evaluation of the advantages and disadvantages of the different construction methods so far has not been attempted. To allow an objective comparison of the two approaches, a parametric study has been conducted. The emphasis in this work was put on the evaluation of displacements of the tunnel, the ground ahead of the face, and the surface settlement.

2 3D NUMERICAL MODEL

The Flac3D code was used for the simulation of the tunnel excavation.

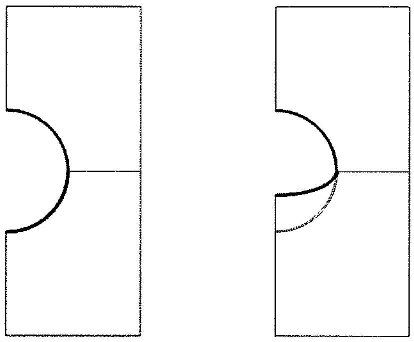
2.1 *Model geometry*

The length of the model was chosen with 150 m and the width with 60 m and 80 m respectively for the weaker ground. The tunnel diameter was chosen with 10 m, while the overburden was 20 m. For the sequential excavation, the top heading height in the model is 5 m with a depth of the temporary invert of 2 m. The thickness of the slices in longitudinal direction was chosen with 2 m. The two construction methods simulated are shown in Figure 1a, b.

2.2 *Material parameters*

The Mohr-Coulomb failure criterion was used for the soil, while the shotcrete was modelled elastically. The parametric study included variations of cohesion, friction and K_0 (Table 1).

The shotcrete was modelled with elastic behaviour, considering the effects of time dependent hardening,



(a) Full-face excavation method.

(b) Sequential excavation method (top heading stage)

Figure 1. Excavation methods.

Table 1. Ground parameters used in the study

Model	Cohesion (kPa)	Friction angle (degrees)	E (MPa)	ν (–)	k_0 (–)
1	10–100	25	40	0.3	1.0
2	20	15–25	40	0.3	1.0
3	30	25	40	0.3	0.5–1.0

Table 2. Development of effective Young's modulus of shotcrete.

Input parameter Ec,eff	1 (MPa)	2 (MPa)	3 (MPa)
	500	1000	2000

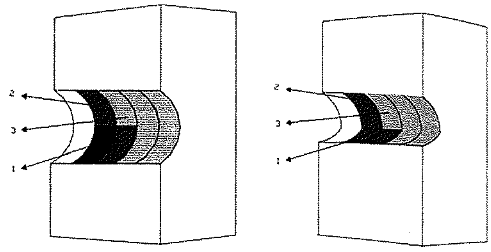
shrink and creep by using an effective Young's modulus with a maximum value of 2000 MPa (Wittke et al. 2003, Schubert 2001, Leitner 2005). Three stages of hardening were considered (see Table 2).

For all simulations a shotcrete thickness of 20 cm was chosen.

2.3 *Sequence of excavation and support installation*

Excavation of 80 m in the longitudinal direction was simulated step by step with round lengths of 2 m. The installation of the support is done 2 m behind the face. The process of installing the support in both construction methods is illustrated in Figure 2a, b. Numbers 1, 2, and 3 in the diagrams correspond to the table 2 values above.

For the top heading – bench excavation sequence it showed, that due to the invert in the top heading and the immediate invert closure after bench and invert excavation only negligible displacements occurred. Hence, the results of the bench excavation are not shown in this paper.



(b) Installation of support for full-face excavation.

(b) Installation of support for top heading excavation.

Figure 2. Installation of support behind the face for both methods.

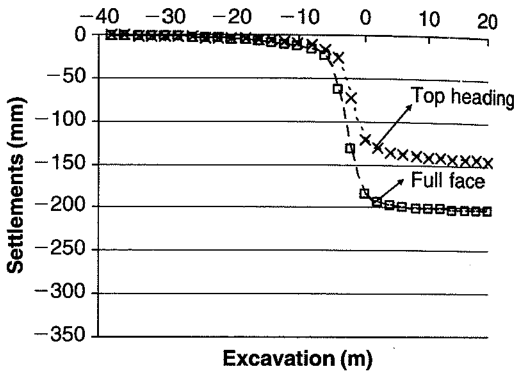


Figure 3. History plot of crown settlements for station 40, $\varphi = 25°$, $K_0 = 1.0$, $c = 10$ kPa.

2.4 *Face support*

The face support was simulated with a uniformly distributed pressure on the face. The influence of the face pressure on the displacements was studied for both excavation methods. The support was simulated in cases, which would not stabilize without it. To evaluate the equivalent number of face bolts, the average load taken by each bolt was chosen at 100 kN. Some authors use the ultimate load of bolts (Peila 1994) to evaluate the equivalent face support pressure. Other studies show, that the load taken by a bolt is in the range of maximally 100 kN, regardless of its strength (Dias 1999, Trompille 2003, Leitner 2005).

3 RESULTS

3.1 *Terminology*

In this study, pre-settlement refers to the settlement, which takes place ahead of the face.

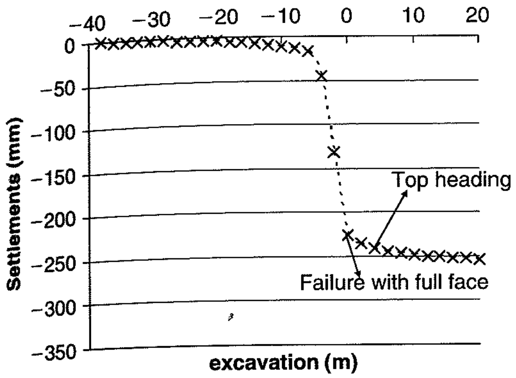


Figure 4. History plot of crown settlements for station 40, $\varphi = 25°$, $K_0 = 1.0$, for c = 15 kPa.

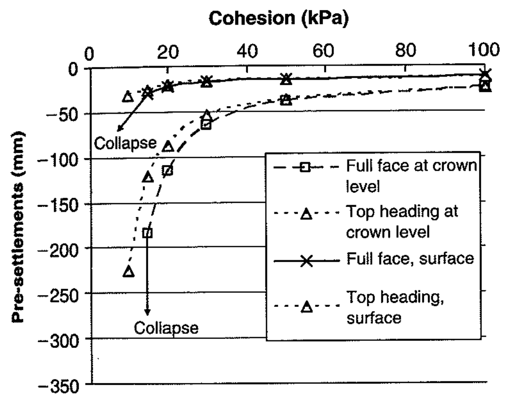


Figure 5. Pre-settlements at crown level and surface, $\varphi = 25°$, $K_0 = 1.0$, cohesion varied.

3.2 *Influence of cohesion*

For a cohesion below 50 kPa, pre-settlements (at the crown as well as at the surface level) caused by sequential excavation are smaller than those with full -face excavation, even if they both increase with decrease of cohesion (See Fig. 5). Disturbance of ground ahead of the face increases with full-face excavation. This soon leads to larger final crown settlements as well as slightly larger surface settlements (Fig. 6). The main difference is that with the full-face excavation the pre-displacements are considerably higher. Face displacements in the case of full-face excavation are much larger (Fig. 7) than those with sequential excavation. Higher displacements of the face increase the hazard for the labour force and lead to the requirement of face support.

A critical cohesion of 30 kPa was detected for which final crown settlements with staged construction are lower than the ones with full-face (Fig. 6).

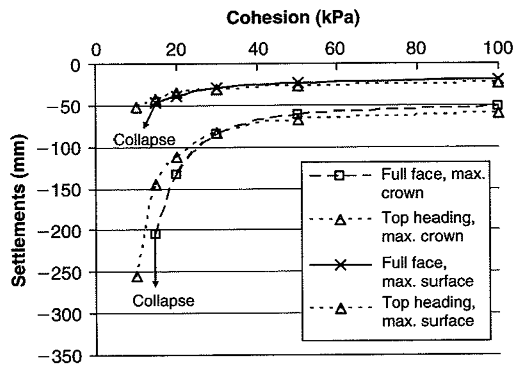


Figure 6. Settlements at crown level and surface, $\varphi = 25°$, $K_0 = 1.0$, cohesion varied.

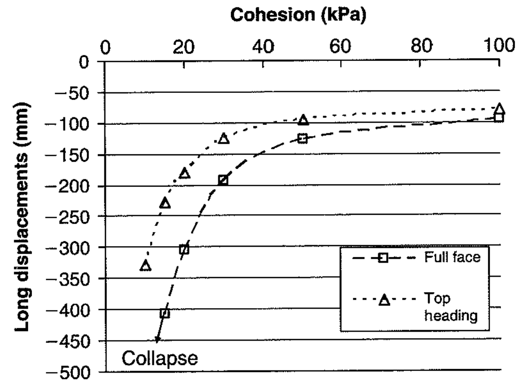


Figure 7. Face displacements, $\varphi = 25°$, $K_0 = 1.0$, cohesion varied.

With a further decrease of cohesion below 20 kPa the final crown settlements increase with the full-face excavation more than those with the staged excavation.

When the cohesion is reduced to 10 kPa the tunnel excavated full face collapses while the top heading remains stable.

3.3 *Influence of coefficient of stresses* K_0

A variation of the coefficient of stresses was investigated for cohesion of 30 kPa. It showed that this parameter had a minimal influence on the development of displacements with different construction methods.

3.4 *Influence of friction angle*

A high sensitivity of displacements to this strength parameter was revealed even with small changes of its value, keeping the cohesion at 20 kPa and K_0 at 1.0. Crown and surface settlements increase significantly

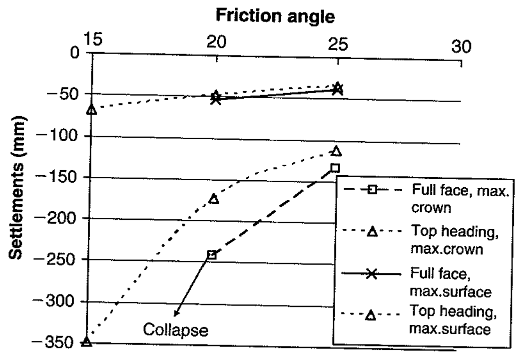


Figure 8. Crown and surface maximal settlements, c = 20 kPa, $K_0 = 1.0$, friction varied.

for a lowering of 5 degrees in the friction angle, from 25° to 20° (see Fig. 8).

When the friction angle is reduced to 15°, the tunnel excavated full-face collapses.

In case of a pronounced variation of the friction of the ground, tunnelling with full-face excavation appears to be risky, because displacements escalate rather fast and can not easily be controlled on site.

3.5 *Variation of face pressure*

In cases, where the full-face excavation would lead to failure (in this case c = 10 kPa) a pressure was applied on the face at each excavation step. A parametric study for top heading stage was also made to find with what pressure same level of crown settlement, surface settlement or facial displacement occurs. As pointed out before, only a small amount of the face bolts' strength in shallow tunnels is activated, approximately 100 kN. This still is an optimistic estimation, as the activated force in each anchor depends on the position and overlapping length (Leitner 2005). Assuming such a load mobilised in each anchor, we found that full-face excavation demands 24 face bolts and top heading excavation 12 face bolts to achieve nearly the same crown and surface settlements. If the design criterion is only face displacement the full face excavation would require 16 bolts more than the face of the top heading.

Additionally, one can observe that an increase of the bolt density beyond a critical value decreases the displacements only in an insignificant way. Such an effect has been already proved, but only for deep tunnels. A critical bolt density of $0.5\,b/m^2$ and $0.2\,b/m^2$, up to which there is a significant influence of the bolts on the displacements was found for full face excavation by Cosciotti (2001). In our study, an optimum face pressure of 30 kPa for both methods and for each examined displacement was found (see Figs. 9–10), meaning $0.3\,b/m^2$ for top heading stage and $0.6\,b/m^2$

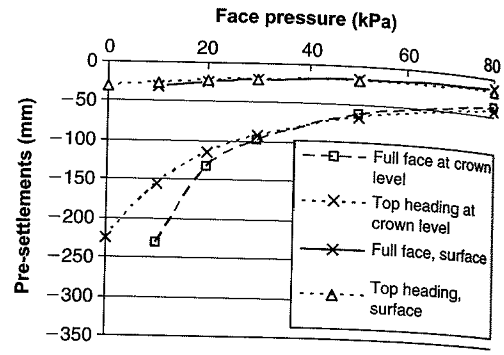


Figure 9. Pre-settlements at crown level and surface, $\varphi = 25°$, $K_0 = 1.0$, c = 10 kPa, face pressure varied.

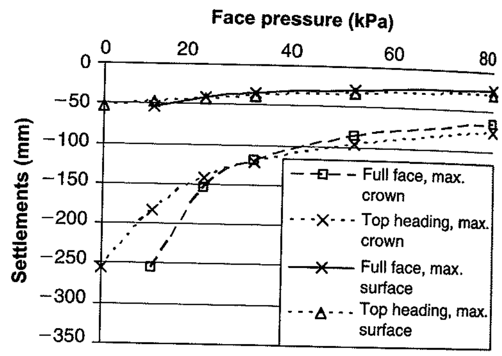


Figure 10. Settlements at crown level and surface, $\varphi = 25°$, $K_0 = 1.0$, c = 10 kPa, face pressure varied.

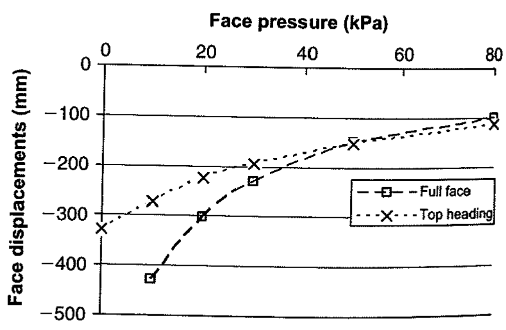


Figure 11. Face displacements, $\varphi = 25°$, $K_0 = 1.0$, c = 10 kPa, face pressure varied.

for full face excavation, which is close to the findings of Cosciotti (2001). Face pressure more than 50 kPa makes full-face excavation slightly better than the staged excavation with respect to roof settlements (Fig. 9). However, in such a case the number of bolts is large (40 bolts).

4 CONCLUSIONS

The results of this parametric study demonstrated that for a crucial value of cohesion, the sequential excavation leads to smaller pre-displacements and total displacements than with the full-face approach. The portion of predisplacements dominantly controls the rate and final value of crown and surface settlements.

Collapse occurred at a cohesion value equal to 10 kPa with full face driving, while the top heading remained stable. Full-face tunnel excavation also led to collapse for a soil with cohesion of 20 kPa and friction angle of 15°. This means that for very poor ground the most safe tunnel construction method is sequential excavation. The friction angle proved to be more influential parameter on evolution of displacements than the cohesion. Consequently, in a geological environment with low or frequently changing of friction angle, staged construction of a tunnel reduces the risk of abrupt and uncontrollable propagation of displacements as well as a collapse.

As recent research has shown, forces mobilized in the face bolts are rather low. When using the bolt strength for the estimation of the equivalent face pressure, the effect of the bolts is overestimated.

The study also showed that with the sequential excavation a considerably lower amount of face support is required than with the full-face method to achieve the same deformation magnitudes. It has shown, that with sequential excavation support of the bench face is not required, providing a sufficient distance between top heading and bench excavation is maintained.

The effectiveness of face bolting progressively decreases beyond a density of 0.3 bolts/m^2 and 0.6 bolts/m^2 for the top heading and full-face excavation respectively.

The study shows, that in very poor ground sequential excavation is preferable in terms of crown, face, and surface displacements and risk of collapse of the face. To achieve an equivalent level of safety, the full-face excavation would require a considerable number of face bolts.

The final decision on which construction method is preferable for specific soil conditions has to be based on an analysis of time, costs, and risk associated with each method.

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