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Effects of different bench length on the deformation of surrounding rock by FEM

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ABSTRACT: Bench cut method has been extensively used in mountain tunneling. This is mainly due to its flexibility to adapting to different ground conditions. Induced displacements are empirically controlled by adjusting the speed of excavation, the bench length, partial-face excavation and closure of invert. In this paper, a series of three-dimensional, numerical, elastoplastic analyses were conducted to investigate the effects of different bench length on the deformation of surrounding mass in soft rock. The closure of invert was also investigated to their role in controlling the final displacement. When bench cut method adopted in soft rock, the bench length should not be too long or too short and 0.5 times of tunnel diameter around for bench length is appropriate.

1 INTRODUCTION

In mountain tunneling, the bench cut method is used extensively due to its simplicity and flexibility to adapting to different ground conditions. And the method provides an advantage of simultaneous excavation of the upper and lower sections. The key issue of adopting this method is selecting a length and a shape of bench to assure the stability of the face, especially for tunneling in soft rock. In addition, auxiliary methods are used as required. When the ground is good enough, having enough self-supporting properties, the bench length can be reduced to 0 m (full face cut). In the case of a weak ground, the bench length is empirically decided. It is therefore important to evaluate and compare the effect of different bench length on the deformation of surrounding rock and on the stability of excavation front.

Usually, numerical analyses work as a kind of model test in which many relevant design variables can be investigated in parametric studies (Ng & Lee, 2005; Karkus & Fowell, 2003; Galli et al., 2004). In this way it is possible to quantify the relative importance of each possible intervention in order to choose the most effective measures from the economic and safety point of view.

Seki et al. (1994) conducted a series of three-dimensional finite-element elastic analyses of unlined tunneling to determine the effect of bench length and shape. The initial stress was given by external force, ignoring the dead weight effect. They found that the longer the bench, the smaller the displacement due to squeezing at the face. Moreover, they found that the bench length scarcely exerted influence upon settlement of the crown. Finally they concluded longer bench tended to offer a great safety factor and leaving the core was effective for increasing the face stability.

Farias et al. (2004) conducted a series of three-dimensional elastic finite element analyses of tunneling by the New Austrian Tunneling Method (NATM) to investigate relative importance of relevant techniques for settlement control. The techniques included partial-face excavation, free span distance and support activation. The tunnel has 9.6 m of diameter and the soil cover is 10 m. They found that tunnel support lining including free span and closure of invert was the most relevant single factor analyzed in reducing induced settlements. The closer to face the lining was concreted, the smaller the displacements. Moreover, they found the bench helped to keep horizontal pressure in the excavation face.

Eberhardt (2001) conducted a series of comprehensive, three-dimensional, elastic and elasto-plastic, numerical analyses of tunneling in the central Swiss Alps with different assumed initial stress states to demonstrate three-dimension stress rotation ahead of an advancing tunnel face. The diameter of tunnel was 10 m and the bench length was 10 m. They found that high stress concentrations in association with large rotation of the maximum principle stress were

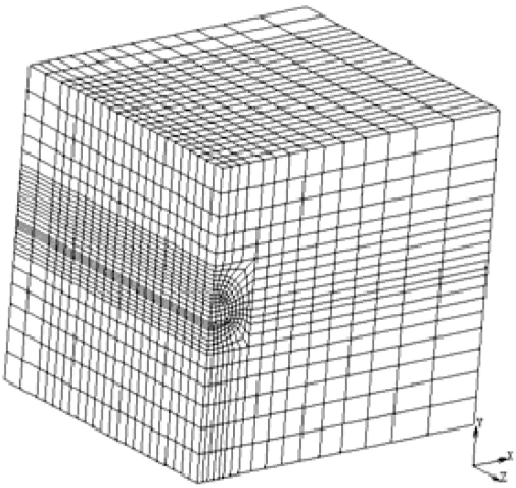

Figure 1. Three dimensional finite element mesh.

observed when the initial maximum principle stress alignment was horizontal and parallel to the tunnel axis.

In this paper, a series of three-dimensional, elasto-plastic, numerical analyses were carried out to investigate the effects of different bench lengths on the deformation of surrounding mass in soft rock. The objectives of these analyses are to find optimum bench lengths for different rock mass.

2 THREE-DIMENSIONAL NUMERICAL MODELLING

2.1 *Numerical approximations*

A hypothetical tunnel excavation in soft rock was modeled in this three-dimensional numerical study. The diameter of the tunnel (D) was taken as 12 m, with a constant cover depth 30 m. The tunnel was assumed to be a bench excavation and lined with spray shotcrete and bolt. The finite element program, MARC, was adopted to model the tunnel excavation.

The three-dimensional finite element mesh used in the present analyses is shown in Figure 1. The bedrock was set 37.2 m below the bottom of the tunnel and the domain expands laterally 80 m from the tunnel centerline. The model took advantage of symmetry of the problem. Boundary conditions are totally fixed at the bottom of the model and only vertical displacements are free in the vertical sides. The model consisted of 10114 elements and 10373 nodes. Eight-noded brick elements and four-noded shell elements were used to model the rock and concrete lining, respectively. And two-noded truss elements were used to model bolt. The mesh was divided into 22 longitudinal blocks of variable sizes. The first 20 blocks length corresponds 1/4 of the tunnel diameter (D). The last 2 block length is 1/2 D. A monitored section, located in the middle of the mesh (i.e., at $z = -30$ m), was studied during every stage of excavation and construction. To account for the relatively large stress and strain gradients near the tunnel opening, small finite elements were used.

Table 1. Rock parameters used in the finite element analyses.

Rock	E/GPa	ν	γ/KN*m^{-3}	C/MPa	$\varphi/(°)$
IV_{upper}	6	0.3	23	0.7	39
IV_{lower}	2	0.35	20	0.2	27
V_{lower}	1	0.35	17	0.05	20

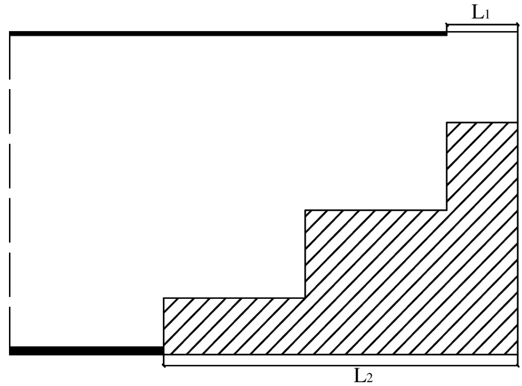

Figure 2. Schematic representation of L_1 and L_2.

An elastic – perfectly plastic rock model, using Drucker – Prager failure criterion with a nonassociated flow rule, was adopted in this study. The tunnel lining and bolt were modeled as linear elastic. The Young's modulus and Poisson's ratio for the tunnel lining were taken to be 25 GPa and 0.2, respectively. The unit weight of the tunnel lining was 22 kN/m^3. For bolt, the Young's modulus of 210 GPa with Poisson's ratio of 0.3, were adopted. Table 1 provides the rock parameter used in this study. These values were based on Code for design of Road Tunnel (2004).

2.2 *Numerical modeling procedures*

A given cross-section was divided into three parts: upper section, lower section and invert section. For simplicity, upper bench length equals to lower bench length (L_b). The free distance between excavation face and the support heading will be referred as free span (L_1). The distance between the excavation face and the first whole lining section will be referred as full support distance (L_2). The schematic representation of these was shown in Figure 2.

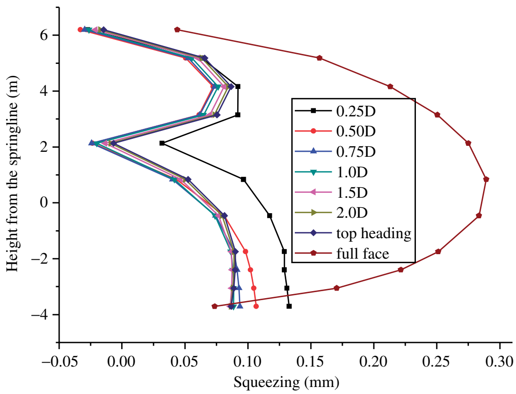

Figure 3. Distribution of squeezing at the face (IV_{upper} rock).

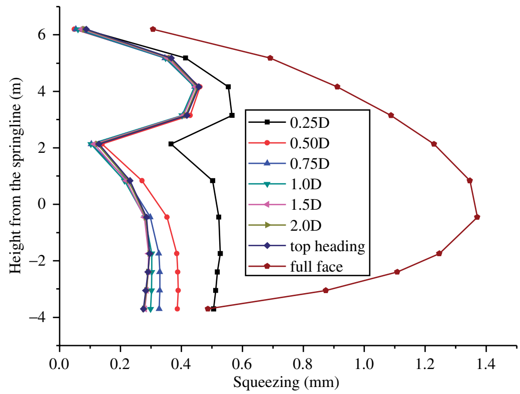

Figure 4. Distribution of squeezing at the face (IV_{lower} rock).

Tunnel excavation and construction were simulated by deactivating the rock elements within the proposed tunnel excavation zone and by activating the support. The tunnel excavation rate was modeled 3.0 m (i.e., D/4) per day, which was used as a step size in the numerical analyses. No support was applied to the tunnel face. The unsupported length equals 3 m (i.e., $L_1 = 3$ m). The excavation sequences are:

1 Excavate upper section rock until the upper bench length equal L_b, and install tunnel lining to the previously excavation span simultaneously. Leave free span of 3 m.
2 Excavate upper section rock and lower section rock until the lower bench length equal L_b, and install tunnel lining to the previously excavation span simultaneously. Leave free span of 3 m.
3 Excavate upper section rock, lower section rock and invert section rock, and apply lining.
4 Advance the tunnel by repeating step 3 until the upper tunnel face has passed 3.0D from the monitoring section.

The initial stress was given by gravity because of shallow tunnel. The different bench lengths (0-2D), top heading cut and full face cut were studied in the analyses.

3 ANALYTICAL RESULTS

3.1 *Squeezing at the tunnel face*

When a large displacement is created because of squeezing at the tunnel face, toppling or collapse by slipping of the tunnel face is very likely to take place. Figures 3–5 show, for each bench length, the distribution of squeezing (in the Z direction, i.e., tunnel driving direction) along the tunnel centerline at the monitoring section. Figure 6 shows the relationship between

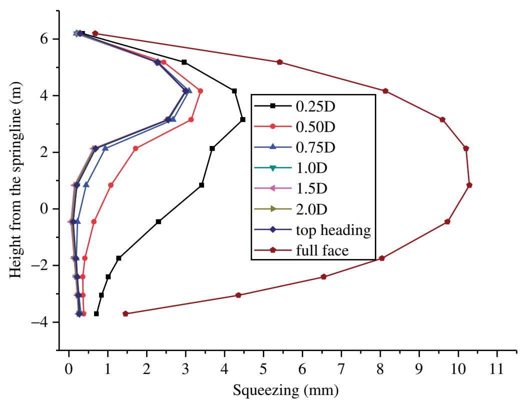

Figure 5. Distribution of squeezing at the face (V_{lower} rock).

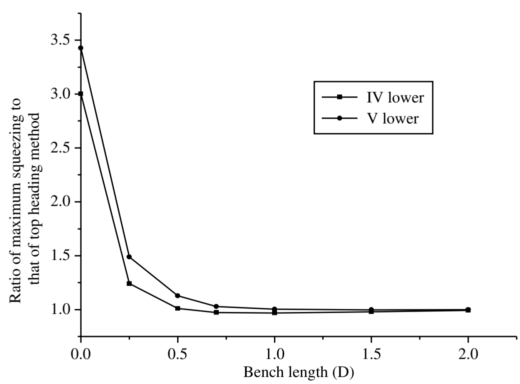

Figure 6. Relationship between bench length and maximum squeezing displacement.

bench length (IV_{lower} and V_{lower} rock) and maximum squeezing displacement.

For different rock, as the bench length increases, the squeezing distribution tends to the distribution of

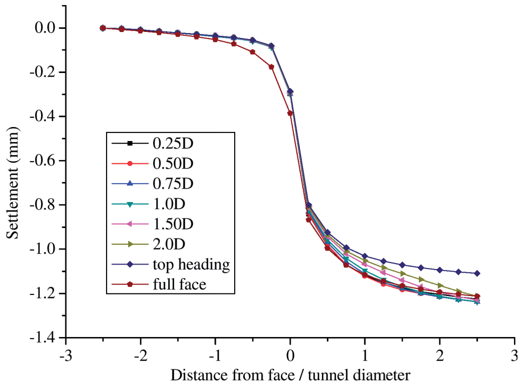

Figure 7. Crown settlement versus face distance for different bench length (IV_{upper} rock).

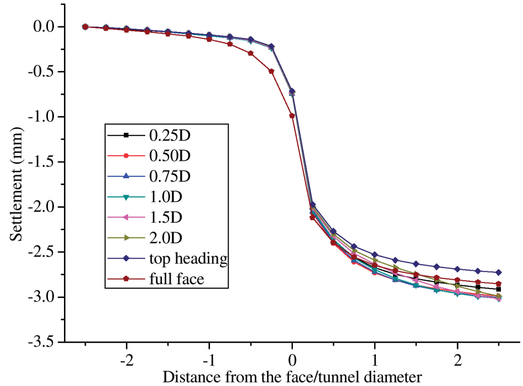

Figure 8. Crown settlement versus face distance for different bench length (IV_{lower} rock).

top heading cut. An increase in bench length greatly decreases the maximum squeezing. The longer the bench, the smaller the squeezing: for V_{lower} type rock, compared with the results for the top heading method, the squeezing of the full face method is 3.43 times, with 0.25D bench length 1.49 times, with 0.50D bench length 1.13 times, and with 0.75D bench length 1.03 times. For another two types of rock, as the bench lengths increase, the changing trends of squeezing are the same as the trend of V_{lower} type rock. However, with the deterioration of rock, the stable value of bench length (when the bench longer than stable value, there is no significant change of squeezing) is different. For the IV_{upper}, IV_{lower} and V_{lower} rock, the stable values of bench length are 0.50D, 0.50D and 0.75D, respectively.

It is very interesting to note that for IV_{upper} rock the computed squeezing displacements at the top and bottom of upper section are negative values. That is due to load transfer in longitudinal direction resulted from arcing in the unsupported zone. That has an effect similar to the classical Terzaghi's "trap door" experiment.

3.2 *Crown settlement*

When a large displacement of the crown at the face is produced, the tunnel face or its vicinity is prone to failure. Figures 7–9 show the crown settlements at the monitoring section versus the normalized distance of the excavation face to monitoring section, for different bench lengths. A negative value of distance indicates that the excavation face has not reached the monitoring section yet. A significant percentage of the final stabilized settlement is induced before face passage. This can only be adequately reproduced in three-dimensional analyses.

The crown settlement before the face passage does not significantly depend upon the bench length. However, compared with full face method, the crown settlement of bench method before the face passage has a remarkable decrease. As the bench length increases, the stabilized settlement becomes larger and closer to the value of settlement of top heading cut. For V_{lower} rock, the stabilized settlement is 5.85 mm for 0.25D bench length, 6.41 mm for 0.50D bench length, and 6.83 mm for 0.75D. When the bench length is greater than 1.0D, the stabilized settlement value is larger than 7.0 mm, but the "exact" value could not be obtained in this study for the limitation of the model. The reason for settlement decreasing mainly attributes to full activation with invert closure. As the bench length decreases, the value of L_2 becomes smaller too. From this point of view, to keep tunnel face stability, the bench length should not be too long for soft rock. On the other hand, to prevent tunnel squeezing, it is necessary to make bench length long enough. Consequently, the bench length too long or too short is not helpful to stability of excavation face, and there is a reasonable value of bench length for some rock. For

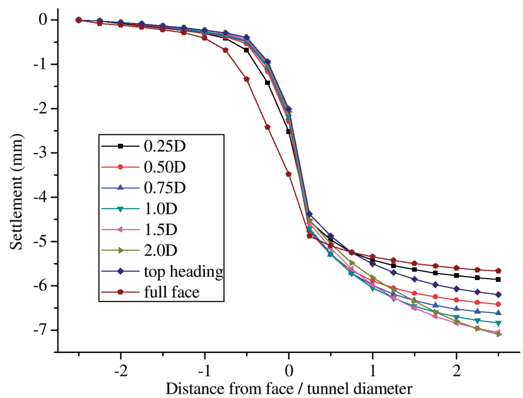

Figure 9. Crown settlement versus face distance for different bench length (V_{lower} rock).

good rock (i.e., IV_{upper} rock), because the stabilized settlement is small, it is not necessary to reduce bench length to decrease the settlement and the bench length can be set to one larger value which benefits the simultaneous excavation of the upper and lower sections. For bad rock (i.e., IV_{lower} and V_{lower} rock), the bench length should not be too long, and 0.5 times of tunnel diameter around for bench length is appropriate.

As mentioned in the introduction, Seki et al. (1994) conducted three-dimensional finite-element analyses to investigate the effect of bench length and shape on the tunnel face stability. In their studies, they concluded that longer benches are made in poorer grounds. However, in this study, the contrary result can be obtained. This is because Seki's modeling was elastic and the tunnel was unlined. The stabilized settlement is the same for different bench length.

4 CONCLUSIONS

The bench cut method by which the upper and lower sections are excavated at the same time is used extensively in mountain tunneling. Results were presented from a detailed three-dimensional finite element analyses directed towards the effects of different bench lengths on the deformation of surrounding mass in soft rock.

The longer the bench, the smaller the displacement due to squeezing at the face. When the bench length is longer than stable value, there is no significant change of squeezing, compared with the squeezing of top heading method. The stable values of bench lengths are different for different rock.

Compared with full face method, the crown settlement of bench method before the face passage has a remarkable decrease, and it does not significantly depend upon the bench length.

There is a reasonable value of bench length for some rock. The bench length should not be too long or too short and 0.5 times of tunnel diameter around for bench length is appropriate for soft rock.

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