Influence of three-bench three-step excavation method on longitudinal deformation profiles in three-centered arch tunnels

Xiao Y M¹, Qiao Y F¹,²,*, He M C¹

1. Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, 200092, China

2. Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, 200092, China.

*Corresponding author (yafei.qiao@tongji.edu.cn)

Abstract. Longitudinal deformation profiles, one of the three curves in the convergence-confinement method, is widely used to analyse tunnel deformation and optimize tunnel supports. Due to the complex geological and excavation method, accurate wall deformation of the whole excavation process can hardly be obtained by in situ monitoring or analytical calculation. In this paper, a 3D numerical model with homogeneous rock layer, considering three-bench three-step excavation, is established to analyse the wall deformation of the face during the whole excavation process. Deformation increases sharply at the face when the rock mass is removed. The pre-deformation is then highlighted in different construction steps, which is quite different from the full-face excavation. Compared with the full-face excavation method, the pre-deformation of the upper bench and the mid bench are almost the same, while the pre-deformation of the low bench is larger. Finally, a new fitting formula is proposed for the normalized radial displacements occurring ahead of and behind the excavation of the tunnel for the three-step excavation method. The new formula can predict the longitudinal deformation of tunnel well and provide theoretical guidance for supporting.

1. Introduction

One of the most important issues in the design of tunnel support system is the determination of surrounding rock mass deformation due to the excavation. The longitudinal deformation profiles (LDP), one of the basic components of the Convergence-Confinement Method (CCM), plays an important role in the prediction of surrounding rock deformation. Furthermore, it provides a reference for the time of support application.

The longitudinal deformation relates the tunnel wall deformations to the location along tunnel axis, behind and ahead of the tunnel face (figure 1). The deformation at the face (X=0m) is called pre-deformation(\(u_0\)). At present, the longitudinal deformation curve is mainly obtained by empirical formula and three-dimensional numerical simulation. The equation of LDP was introduced by Panet (1995) on basis of circular tunnel and elastic constitutive model. Then Guilloux et al (1996) found the pre-deformation of the face can grow within limits. Overall, Unlu and Gereck (2003) proposed a new LDP related to Poisson’s ratio based on the Panet’s formula (1995) and pre-deformation proposed by Guilloux et al (1996). Vlachopoulos and Diederichs (2009) noted that the influence of the radius of the plastic circle on the tunnel deformation curve and put forward the formula of the LDP considering the...
the radius of the plastic circle. In addition, the rock type (Mousivand et al., 2017), the shape of tunnel (González-Nicieza et al., 2008), tunnel depth and tunnel radius (Mousivand et al., 2017) were the mainly considered factors to the LDP. In recent years, TBM was adopted in the excavation of tunnel. Oke et al. (2018) and Fuente (2019) analyzed the differences between TBM and drilling and blasting methods in LDP.

On the other hand, with the implementation of the “Belt and Road” and the Development of Western China, the ground conditions of tunnel crossing are becoming more and more complicated, Water diversion in Central Yunnan, Muzhailing tunnel and so on. Full-face excavation method can no longer meet the stability requirements of the tunnel. Hence three step method, CD method and CRD method are widely used in tunnel construction.

However, LDP strictly depends on the method of tunnel excavation, but few of the proposed equation for calculation of the LDP are only based on the method of tunnel excavation. Therefore, in this paper a FLAC3D numerical model of three-centered arch tunnel is established, adopting the three bench three step excavation method. An improved formula based on Unlu and Gercek (2003) is proposed.

2. Characteristics of LDP induced by three-bench three-step excavation

2.1. Numerical model of LDP
In order to obtain the longitudinal deformation curve during the process of tunnel excavation, a 3D numerical model is established by FLAC3D (see figure 1). To eliminate the boundary effect, the distance between the tunnel and the boundary is more than 4 times of the tunnel span (100m(X-axis) × 100m(Y-axis) ×100m(Z-axis)). The cross of the tunnel is an 11.86m three-centered arch with the invert. In the model, along the tunnel axis, the displacement boundary conditions are applied to the boundaries, the displacements along with the normal direction are restrained. A force boundary conditions of 1MPa are applied to the rest of boundaries. This model has a total of 184000 units and 192910 nodes.
Figure 2. Numerical model: (a) 3D model; (b) Location of monitoring points

Table 1. Material properties used for simulation model.

| Parameter | Shear modulus (GPa) | Bulk modulus (GPa) | Cohesion (MPa) | Friction angle (°) |
|-----------|---------------------|-------------------|---------------|-------------------|
|           | 0.481               | 1.44              | 0.2           | 27                |

The elastic-plastic model based on Mohr-Coulomb is applied to this model. The parameters of surrounding rock (IV) are shown in Table 1, which is taken from Specifications for Design of Highway Tunnels (JTG3370.1-2018). The tunnel construction process is modelled using a three-bench three-step method. Each excavation step corresponds to an advancement of the tunnel face of 3 m. In order to study the longitudinal deformation profiles of the tunnel, monitoring points are arranged along the longitudinal direction of the tunnel at the vault, arch waist and arch bottom (see figure 2b).

2.2. The Characteristic analysis of LDP

Different from the full-face excavation method, the face position of the three-bench three-step method is different at the same time. Therefore, in this paper, it is considered that for each bench at the same step, $x = 0$ at the face position. The longitudinal deformation curves of different benches are shown in figure 4. The normalized radial displacement ($u$) represents the ratio of the radial displacement ($u_r$) to the displacement at infinity behind the face ($u_{\infty}$). The normalized distance from face ($X$) represents the ratio of the distance from the face ($x$) to the tunnel radius ($R$).

Figure 3. The displacement magnitude: (a) rock; (b) tunnel

In front of the face, due to the extrusion of the core soil on the face of the tunnel, a part of the convergence deformation has appeared (see figure 3), which is called pre-deformation. The pre-deformation is closely related to the rock restraint at the face. With the excavation, the normalized pre-deformation value of different benches increases gradually, as presented in figure 4. The normalized pre-deformation of upper bench (point A) is about 0.2. The normalized pre-deformation of mid bench (point B) is about 0.3 and in front of the face, the deformation value is larger than that of the upper step, which is related to the Poisson’s ratio of rock (Guilloux 1996). Compared with the upper and
middle benches, the deformation of the lower bench appears far away from the face and the normalized pre-deformation is about 0.6 (see figure 3).

A rapid increase occurs in deformation after removing the rock mass close to the monitoring point behind the face, due to the longitudinal constraint of the face, the deformation of tunnel wall increases gradually with the advance of tunnel face.

2.3. Comparison with full-face excavation method

The shape of longitudinal deformation profiles of full-face excavation method is similar to that of three bench excavation method (see Unlu and Gercek in figure 4). However, in the full-face excavation method, the longitudinal deformation profile of tunnel is close to that of middle bench in the front of the face. In addition, the increase rate of deformation is greater than the full-face excavation near the face. What’s more, the three bench three step excavation method is often used in controlling the deformation of tunnel.

The LDP of three bench method and full-face excavation method are quite different near the tunnel face. Therefore, the longitudinal deformation profile of three-step method needs to be proposed.

![Figure 4. Comparison of the LDP between three-bench three-step method and the empirical formula](image)

3. Modification of the longitude deformation profile

3.1. The LDP proposed by Unlu and Gercek (2003)

Unlu and Gercek (2003) proposed two functions according to the LDP on the basis of Guilloux et al (1996). One of the functions is suitable for the region located ahead of the face.

For $X < 0$

$$U_a = U_o + A_A \left[ 1 - e^{-a_b X} \right]$$  \hspace{1cm} (1)

Another one has a high correlation for the region located behind the face.

For $X > 0$

$$U_b = U_o + A_A \left[ 1 - \left( \frac{B_b}{B_b + X} \right)^{1/2} \right]$$  \hspace{1cm} (2)

Where $U_o$ is the radial displacement at the face location and $A_A$, $A_B$, $B_A$, $B_B$ are related to Poisson’s Ratio:

$$U_o = 0.22v + 0.19$$

$$A_A = -0.22v - 0.19 \quad ; \quad B_A = 0.73v + 0.81 \quad ; \quad A_B = -0.22v + 0.81 \quad ; \quad B_B = 0.39v + 0.65$$  \hspace{1cm} (3)
The expression proposed by Unlu and Gereck(2003) for calculating the radial deformation considers the distance away from the face, elastic constitutive model and Passion’s ratio, which neglect the influence of excavation method. The influence of bench length on the longitudinal deformation profiles.

3.2. The influence of bench length on the longitudinal deformation profiles
During the construction of the tunnel, the bench height is almost constant in different tunnel to meet the needs of the working space. In order to shorten the construction period, the workers may change the length of the bench, which can influence the LDP, especially the pre-deformation. The influence of bench length on pre-deformation is analysed by setting several common bench lengths (2m, 3m, 4m and 5m).

On the basis of pre-deformation in Unlu and Gereck (2003) formula, bench parameter \(k\) are introduced to consider the effect of bench length on pre-deformation.

\[
k = \frac{U_0'}{U_0}
\]

Where \(U_0\) is the pre-deformation of three-bench three-step excavation method.

As shown in figure 5, at a certain length of the bench, the bench parameters in upper bench are almost constant and roughly equivalent to the full-face method. The parameters in mid bench and low bench rise with the length of the bench longer. Moreover, the values of upper bench are smaller than mid bench. This demonstrate that the unloading can lead to the increase of the pre-deformation.

![Figure 5. Influence of bench length on bench parameter](image)

3.3. Modification of the LDP
On this basis, the elastic-plastic model is adopted in the improved formula. The influence of excavation method on LDP curve is considered by introducing excavation function and bench coefficient. In the same way, the LDP has been divided into two parts in order to overcome the different tendency in the LDP.

For the region located in front of the face, the following function has been found to be suitable (see figure 6).

\[
U_0' = kU_0 + \hat{A}_0 \left[1 - e^{-f_e(x)B_m}\right]
\]

\[
f_e(x) = ax^2 + bx + c
\]

Where \(x = \text{abs}(X)\), \(U_0\) is the radial displacement at the face, \(k\) is the bench coefficient; \(\hat{A}_0\), \(B_m\) are related to Poisson’s Ratio and \(k\); \(f_e(x)\) is the excavation function. The parameters \(k, a, b\) and \(c\) are shown in Table 2 (The value of \(k\) is for a step length of 3m).
Generally speaking, the deformation should be zero when the monitoring section is far away from the face. Hence, $A_k = -kU_a$.

Similarly, for the part located behind the face, the following function has a high correlation coefficient (see figure 6).

\[
U'_b = kU_a + A_k \left[ 1 - \left( \frac{f_b(x)}{\sqrt{\frac{f_a(x)B_a}{f_b(x)B_b}} + x} \right)^2 \right] \tag{7}
\]

\[
f_b(x) = \frac{1}{dx + e} \tag{8}
\]

Where $A_k$, $B_k$ are related to Poisson’s Ratio and $k$; $f_b(x)$ is the excavation function. The parameters $d$ and $e$ are shown in Table 2 (The value of $k$ is for a step length of 3m).

In a similar way, $kU_a + A_k = 1$, when $x$ is large enough

![Figure 6 Fitting formula of LDP](image)

### Table 2. Parameters that defined in the formula

|            | k     | a     | b     | c     | d     | e     |
|------------|-------|-------|-------|-------|-------|-------|
| Upper bench| 0.8633| -0.1958| 1.4042| -3.5957| 0.0533| 0.5362|
| Mid bench  | 1.0885| -0.1239| 0.4369| -1.8570| 0.0700| 0.5270|
| Lower bench| 2.1863| -0.0266| -0.0287| -0.8292| 0.1127| 0.3675|

In equations (4) and (7), the value of excavation function is only related to excavation method. When full face excavation is adopted, the value of excavation function is 1. Then, the modified formula degenerates to the formula of Unlu and Gercek (2003).

### 4. Conclusion

In this paper, a 3D numerical simulation is carried out to study the longitudinal deformation profiles in three-centered arch with the invert. The longitudinal deformation profiles at different benches are discussed. Based on these investigations, the following conclusions can be drawn:

1. The pre-deformation of upper and lower bench is closer to that of full-face excavation, but the pre-deformation of lower bench is much larger than that of full-face excavation.
2. The fitting formula of longitudinal deformation profile considering three bench excavation method and bench length is proposed, and it fits well with the numerical results.

### 5. References

[1] Fuente D L M, Taherzadeh R, Sulem, J, Nguyen X S and Subrin D 2019 Rock Mech. Rock Eng. 52 2361-76.

[2] Guilloux A, Bretelle S and Bienvenue F 1996 J. Revue française de géotechnique 76 3-16.
[3] González N C, Álvarez V A E, Menendez D A and Gonzalez P C 2008 Tunn. Undergr. Space Technol. 23 25-37.
[4] Mousivand M, Maleki M, Nekooei, M and Mansoori M R 2017 Geotech. Geol. Eng. 35 1185-98.
[6] Unlu, T and Gereck H 2003 Tunn. Undergr. Space Technol 18 547-53.
[7] Oke J, Vlachopoulos N and Diederichs M 2018 Rock Mech Rock Eng 51 1495-1519.
[8] Oreste P P 2003 Tunn. Undergr. Space Technol 18 347-63.
[9] Panet M 1995 Le calcul des tunnels par la méthode convergence-confinement. M. Presses ENPC.
[10] Paraskevopoulou C and Diederichs, D 2018 Tunn. Undergr. Space Technol 71 62-80.
[11] Specifications for designs of highway tunnels. JTG 3370.1-2018. S. Beijing: China Communications Press Co.
[12] Tao Z J, Cao J D, Liu Y, Guo A P, Huang R F, Yang X J, Di Y and Lin H 2020 Adv. Civ. Eng. 2 1-14.
[13] Vlachopoulos N and Diederichs M S 2009 Rock Mech. Rock Eng. 42: 131-46.