Investigating the Numerical Modelling of the Construction Excavation of an Actual Super Shallow Large-Span Tunnel

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Abstract. Owing to the complexity of structural characteristics, it is difficult to accurately model the super shallow large-span tunnel. In this study, aiming at an actual tunnel, we investigate the refined modelling of super shallow large-span tunnel. First, the three-dimension finite element model of this actual tunnel is established considering the disturbance of the surrounding rock, construction sequence and the change of stress state of structure during the construction process. Second, with the generated finite element model, the variation rules of the crown displacement and the initial lining stress are analysed numerically. Finally, the results of the numerical simulation are compared with the measured. The results show that the established model can simulate the construction excavation accurately.

1. Introduction

For accurate simulating the process of tunnel excavation, it is difficult to obtain the results of the strain, stress, and displacement directly owing to the complexity of structural characteristics. To deal with this dilemma, the numerical analysis method is developed to simplify the complexity of construction of actual tunnels. The whole process of the tunnel excavation is well simulated by modifying the surrounding rock parameters [1].

When we model the detailed process of the tunnel excavation, the load release always attaches great importance to the accuracy of the results [2]. In this study, reversal stress method is adopted to simulate the process of load release. During the excavation process, the load of boundary is calculated and applied to the surrounding rock reversely in the next step. The birth-death element method is used to simulate the tunnel structure; the simulation of continuous tunnel construction can be achieved by the load step function. In addition, considering the nonlinear properties, the Drucker-Prager model is chosen as the constitutive model of the material of surrounding rock [3].

2. Application to the tunnel model

2.1. Numerical simulation

Owing to the complexity of structural characteristics, the numerical analysis is influenced by couples of factors, such as the excavation method, the construction sequence, the support type etc.; therefore, it is necessary to consider the mutual effect of all the factors during the analytical process of tunnel excavation.
2.1.1. Simulation of the initial geostress. When simulating the initial stress of surrounding rock, geostatic stress is considered without tectonic stress. In the first load step, the initial displacement is calculated under the geostress; thus, the displacement induced in the following process of construction includes the initial value. Actually, the initial settlement has already converged before the construction; therefore, it’s necessary to subtract the initial value to get the real displacement [4].

2.1.2. Simulation of load release. The core part of the construction simulation lies on the gradual release of geostress in the process of excavation. Stress relief method is developed to optimize the simulation, it’s believed that the initial stress state of the excavated boundary is destroyed and redistributed, which promotes to form the new displacement and stress field.

In the ANSYS analysis of excavation, gradual release of virtual force method is adopted to simulate the release of stress, based on stress relief method, by applying reverse virtual force to the excavation boundary. In other words, the initial load \( f_i \) of the excavation boundary is eliminated by the combined action of the release stress and virtual force. The nodal release load \( f_{ii} \) and virtual force \( P_{1i} \) is transformed using the following expression:

\[
\begin{align*}
    f_{ii} &= \alpha_i f_i \\
    P_{1i} &= (1-\alpha_i)(-f_i)
\end{align*}
\]  

In this project, the initial support is considered to bear all the loads without the effect of the second lining. To be specific, the virtual force \( P_{1i} \) is released and applied to the initial support. Besides, the release coefficient \( \alpha_i = 0.6 \) is adopted in this study.

2.1.3. Simulation of excavation and support. In ANSYS software, the simulation of excavation and support is achieved by birth-death element method. The elements are killed when excavated by multiplying a very small number to the stiffness matrix of the element and eliminating the element quality from the total mass matrix. In opposite, the dead element can be activated by modifying the material parameter when applying support.

2.1.4. Simulation of continuous construction. The continuous tunnel construction is simulated by the load step function, specifically, the birth-death state of all the elements is restored back to the very first load step by using the restart function [5]. Every single load step is accomplished in the solver, and the results can be seen in the post processor.

2.2. Modelling of excavation process

According to the above theory, the 3D FEM of an actual super shallow large-span tunnel is established to simulate the construction process.

2.2.1. Geometry and numerical parameter. The average embedded depth of the bi-arch tunnel is 7 m, with a unilateral five-centred arch profile. As shown in figure 1, the tunnel is buried between several different soil layers and rock stratum.

Table 1 summarizes the characteristics of the lining and the geomatatal, as it shows, the soils of homogeneous layer are provided with different characteristics. The initial support and temporary support are built of C25 reinforced concrete, while the middle partition is built in C50 reinforced concrete. Soil anchors with higher strength are designed to reinforce the surrounding rock, in order to restrict the development of the plastic zone.
Table 1. Properties of geomaterial used in the tunnel model

| Geomaterial         | E (MPa) | c’ (kPa) | φ (°) | ν   | γ  (kN/m³) |
|---------------------|---------|----------|-------|-----|------------|
| Surface soil        | 15      | 25       | 16    | 0.35| 17.5       |
| Clay                | 30      | 40       | 18    | 0.38| 19         |
| Limestone           | 180     | 100      | 22    | 0.45| 18         |
| Marlite rock        | 210     | 300      | 30    | 0.31| 21         |
| Anchorage zone      | 216     | 120      | 25    | 0.25| 21.5       |
| Initial support     | 30000   | /        | /     | 0.2 | 24         |
| Middle partition    | 35500   | /        | /     | 0.5 | 25         |

2.2.2. Construction procedures. The construction flow is shown in figure 2, specifically, the tunnel profile is provided into 8 parts according to the excavation sequence as is shown in figure 3. The tunnel is excavated in numerical order using the advanced excavation method, and the middle partition is built after the construction of part 2. The temporary supports are removed after every part of excavation, at last, the secondary lining is sprayed.

2.2.3. Establishment of the three-dimensional finite element model. In establishment of the tunnel model, the needs of practical engineering and calculation errors are considered [6]. Finite element analysis was carried out using the mesh presented in figure 4. This mesh consists of 55294 elements, which give rise to 68099 nodes. The surrounding rock is simulated by solid45 unity element, while the lining is simulated by shell63 element. To minimize their interaction with the tunnel construction, the lateral boundaries of the model are located a distance 35 m from the tunnel axis and the lower boundary is located 20 m beneath the tunnel. The longitudinal length of the mesh is fixed to 16 m, which is equal to...
excavation length. The boundaries conditions are simulated by applying constraint to limit the deformation [7]. This mesh is used to simulate the application of the proposed method. After the modelling process, computation is carried out in accordance with the actual construction procedures.

![3D mesh used in the numerical analysis](image)

**Figure 4.** The 3D mesh used in the numerical analysis

## 3. Results and discussions

### 3.1. Analysis of displacement

![Displacement nephogram](image)

**Figure 5.** The displacement nephogram

The analysis is carried out step by step according to the construction procedures, after excavation, the maximum displacement along y-axis achieves 12 mm. The displacement distribution can be seen in figure 5(a), the ground surface heaves slightly with the tunnel excavated and the crown appears to deflect. As for the horizontal displacement, it turns out to converge gradually. As shown in figure 5(b), the maximum horizontal displacement of left tunnel is 5.81 mm, while right tunnel achieves -7.06 mm. It’s found that the maximum horizontal displacement appears at the newly excavated zone.

![Comparison of measured and computed displacement along y-axis](image)

**Figure 6.** Comparison of the measured and computed displacement along y-axis
In practical engineering, the displacement of the tunnel crown is recorded. Figure 6 shows the comparison between the computed values and measured values. It's obvious that the settlement rate is quite large at the beginning of the construction, and turns to slow down as the construction continues. At last, the settlement converges. Besides, it can be seen the displacement of right crown is larger than the left one due to the excavation sequence. The comparison chart shows a similar trend between these two sets of data, so the model is quite reasonable.

3.2. Analysis of stress in middle partition

The middle partition is a significant part of the bi-arch tunnel, the stress state redistributes as the tunnel is excavated [8]. This part is chosen as the key point because of its large stress as shown in figure 6 and figure 7. It is mainly in compression for the load transferred from the upper surrounding rock. The tensile stress appears at the bottom part, so the reinforcement needs to be considered specially. Owing to its complex construction procedure, the partition may occur to be in torsion condition; thus, the condition of the partition is monitored in the process of construction.

4. Conclusions

In this paper, a numerical simulation of tunnel excavation is investigated using 3D finite element model. Comparing the analytical and measured results, and the following conclusion are drawn.

(i) After the excavation, the maximum displacement of left crown reaches 3.8 mm, while the right crown achieves 6 mm. It is shown that the simulated results are close to the measured values, so the established finite element model of this actual tunnel can be adopted to guide the construction and some subsequent analysis of structure.

(ii) The middle partition of a bi-arch tunnel is the key point of the construction process. For the tunnel design, it is necessary to strengthen the anti-bending capacity of the bottom wall and anti-overturning capacity of the partition.

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