A Hybrid Construction Method for Shallow Buried Urban Tunnel with Ultra-Small Clear Distance

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Abstract. During the construction process, it is difficult to ensure the structural safety of shallow buried tunnel with the ultra-small clear distance since the tunnel is prone to instability and the surrounding rock and soil are in an adverse stress condition. To address this issue, a hybrid construction method is proposed to enhance tunnel stability and reinforce the surrounding rocks and soil. First, aiming at an actual tunnel, numerical analysis are provided to compare the effectiveness of different construction methods such as the bench method, advanced reinforcement method, and grouting reinforcement method. Second, the performance of the combination of advanced reinforcement and grouting reinforcement are discussed, and, on the basis of this discussion, the hybrid construction method, combining the advanced small pipes reinforcement, middle rock wall reinforcement, and grouting reinforcement, is proposed. And the characteristics of proposed method is compared with the traditional CRD construction method. The results reflect that using the hybrid construction method can enhance the stability of the tunnel and its effect is similar to that of the CRD method. Finally, the effectiveness of proposed hybrid construction method is verified by using the measured data obtained during the construction of an actual tunnel with the ultra-small clear distance. The results shown that the proposed method can enhance the stability of the tunnel and improve the bearing capacity of the surrounding rock and soil.

1. Introduction
Small clear distance tunnel is a common adopted structure for urban tunnel considering the limitations of line conditions. For some special situation, the combination of the ultra-small clear distance and shallow buried depth have to be considered for one tunnel structure. It is difficult to guarantee the stability of surrounding rock of shallow buried urban tunnel with ultra-small clear distance, and the interference between the two holes is large [1, 2]. Therefore, how to ensure the construction safety of these tunnels is a difficult problem.

The construction of small clear distance tunnel has been investigated by some researchers [3-5] in many aspects such as the stability of surrounding rock, the influence of grouting reinforcement and advanced support, etc. However, most of these studies were aimed at the small clear distance tunnel, and it is still difficult to evaluate the application effect of various reinforcement measures in shallow buried tunnel with ultra-small clear distance and carry out reasonable construction. Taking Yu Han road tunnel as the engineering background, this study compared application effects of various reinforcement
measures, and proposed a hybrid construction method combining the advanced small pipes reinforcement, middle rock wall reinforcement, and grouting reinforcement. Then the effectiveness of proposed hybrid construction method was verified.

2. Numerical analysis of a hybrid construction method

2.1. Brief introduction of an actual tunnel project

The Yuhan Road Tunnel belongs to the second phase of the south extension of the Shun He Elevated Highway in Jinan City. The length of bored section is about 2.3 km and the buried depth of the entire line is 6-10 m. The maximum longitudinal slope of the entire line is 2.6%, and the minimum longitudinal slope is 0.9%. The rock and soil layer in the area where the tunnel is located is mainly filled with fill soil, loess, silty clay, clay, gabbro, limestone, and marl. The surrounding rock is in poor condition, and it is V-grade soil-rock combination weak surrounding rock. The length of soil surrounding rock section whose strength is lost in contact with water is 917 m. The rocky surrounding rock section is 1418 m long and karst is developed. Twin tunnel design is adopted for the bored section, and the distance between the two tunnels is 3-5 m. This tunnel is a shallow-buried ultra-small clear-distance tunnel, which is excavated by a hybrid construction method.

2.2. Generation of the finite element model of the Yuhan Road tunnel

To simulate the excavation process, a commercial numerical tool (ANSYS) was employed. The basic section of the model is a small clear-distance tunnel. Because the surface in the area where the tunnel is located is not undulated, the ground surface can be simplified to a horizontal plane. Generally speaking, the influence of tunnel excavation on surrounding rock will be less than 5% outside the range of 3 times tunnel diameter and less than 1% outside the range of 5 times tunnel diameter. In order to minimize the interference of boundary conditions on the calculation results of the finite element model and reduce the amount of calculation, the calculation range of this model is about 4 times of the tunnel diameter. The bottom boundary of the model is a plane 20 m below the tunnel, and the upper boundary is the ground surface. The width of the model is about 80 m, the vertical height is 37 m, and the longitudinal length is 80 m. The surrounding rock material is a complex mechanical material with plastic deformation. The Drucker-Prager constitutive model was adopted for calculation in the finite element simulation. The grouting reinforcement area was simulated by changing the model material parameters. The lining structure is made of elastic material, and the role of steel arch frame needs to be considered.

The solid45 solid element was used to simulate the surrounding rock and grouting reinforcement area, the shell63 shell element was used to simulate the tunnel support structure (temporary support, inverted arch and initial support). In order to build a 3D model by scaling, the mesh200 element was used to divide the plane element mesh. The material parameters determined from the survey data and related design documents are shown in Table 1.

The load application is based on the assumption that 40% of the load is released first when the tunnel is excavated, and the remaining load is released after the initial support is applied. The secondary lining was used as a strength reserve, and the dead element was used to simulate the excavation effect. Considering the displacement of the model at the boundaries, the boundary conditions imposed on the model are: the left and right boundaries are only restricted in the X direction, the lower boundary is only restricted in the Y direction, the upper boundary is not restricted, the front and back boundaries are only restricted in the Z direction. The finite element model was established as shown in Figure 1.

Based on this model, the simulation of different construction methods can be completed using only different procedures, activating related elements, and changing material parameters. Figure 2 shows the position of key points around the cave. Point z1 and y1 were used to indicate the position of the vault so as to extract the vertical displacement of the vault. The relative displacement of point y3 and y7 was used to indicate the horizontal convergence of the first hole. The relative displacement of point z3 and
z7 was used to represent the horizontal convergence of the second hole. A positive value in the result indicates that the two points are relatively close, and a negative value indicates that the two points are relatively far away.

### Table 1. Material parameters of the Yuhan Road tunnel.

| Material Name                          | Density (kg/m³) | Poisson’s ratio | Deformation modulus (MPa) | Cohesion (KPa) | Friction angle (°) |
|----------------------------------------|-----------------|-----------------|---------------------------|----------------|-------------------|
| Clay                                   | 1900            | 0.36            | 36.8                      | 15             | 28                |
| Moderately weathered limestone         | 2200            | 0.45            | 1300                      | 100            | 25                |
| Strongly weathered marl                | 1900            | 0.31            | 1100                      | 80             | 21                |
| Initial support                        | 2400            | 0.2             | 36200                     | /              | /                 |
| Grouting reinforcement area in soil surrounding rock | 2040            | 0.32            | 910                       | 208            | 28                |
| Grouting reinforcement area in rocky surrounding rock | 2240            | 0.32            | 2050                      | 460            | 29                |
| Invert arch                            | 2400            | 0.2             | 33000                     | /              | /                 |
| Large pipe roof                        | 7700            | 0.3             | 210000                    | /              | /                 |

**Figure 1.** Finite element model

**Figure 2.** Location of key points around the hole

2.3. Analysis of the construction effect using the hybrid construction method

In order to give full play to the advantages of various reinforcement measures, the hybrid construction method was proposed. Advanced small pipes reinforcement and advance medium rock wall reinforcement are used before tunnel excavation in the hybrid construction method 1. Then the tunnel is excavated by bench method with grouting reinforcement. The hybrid construction method 2 is similar to the hybrid construction method 1, except that advanced small pipes reinforcement is replaced with advance large pipe roof reinforcement. Numerical simulation method was used to study the effect of the hybrid construction method. The results of the bench method with grouting reinforcement, CRD method, hybrid construction method 1, and hybrid construction method 2 are shown in Figure 3 and 4.

From Figure 3, it can be seen that the hybrid construction method has a significant effect on reducing the vault displacement. The results show that the hybrid construction method is not a simple superposition of advanced reinforcement and grouting reinforcement, but that the advanced reinforcement and grouting reinforcement play a mutually reinforcing role. It can also be seen in the figure 3 that the role of the hybrid construction method in reducing deformation is close to that of the CRD method, and the hybrid construction method plays an important role in ensuring the stability of surrounding rocks.
When the hybrid construction method is used for construction, the displacements of the vaults of the first hole and the second hole are almost the same, which shows that the interference between the two holes is suppressed. It can be seen that the hybrid construction method 2 has a stronger effect on reducing the vault displacement than the hybrid construction method 1, and the hybrid construction method 2 is a more effective method.

From Figure 4, it can be seen that the hybrid construction method has almost no effect on improving the stress condition of surrounding rocks, and the effect of CRD method on reducing surrounding rock stress is obvious. However, when the hybrid construction method is used for construction, the middle rock wall and the rock surrounding are strengthened, and the bearing capacity is improved, which is very beneficial for ensuring construction safety.

3. Verification to the effectiveness of the hybrid construction method using the measured data
The numerical simulation results were verified by the monitoring data. The numerical simulation section belongs to the rocky surrounding rock section. The construction method is the hybrid construction method 1 that uses advanced small pipe reinforcement, advance medium rock wall reinforcement, and grouting reinforcement. The monitoring data and numerical simulation results are shown in Figure 5. As shown in figure 5, the numerical simulation results are not significantly different from the actual
results, indicating that the numerical simulation method can reflect the actual engineering situation, and the hybrid construction method is effective.

Figure 5. Comparison between the numerical simulation and the measured results

4. Conclusions
Compared with traditional construction method, using the hybrid construction method can effectively reduce the displacement of the vault convergence of the cave, improve the surrounding rock bearing capacity and ensure construction safety. The hybrid construction method 2 that uses the advance large pipe roof reinforcement, the advance medium rock wall reinforcement and the grouting reinforcement is more effective than other methods. Considering the ease of construction and economy, when the main body of the tunnel is located in a rocky stratum, the hybrid construction method 1, taking the advanced small pipes reinforcement, the advance medium rock wall reinforcement and the grouting reinforcement, is recommended. Compared with the CRD method, the hybrid construction method has the advantages of faster speed, smaller interference between the two holes and smaller vault displacement, so it is an effective method for shallow-buried tunnel with the ultra-small clear-distance.

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