Main Structure Design and Constructional Safety Control of Large-span Gravel Surrounding-Rock Tunnel

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Abstract: As the construction of large-span gravel surrounding-rock tunnel is very difficult which has serious security risks, it is significant to choose a set of reasonable structure design methods and safety control schemes. This paper taked a large-span gravel road tunnel in Jinan Expressway as an example. Through combining theoretical analysis with numerical simulation, the main structure design process of the large-span IV level surrounding-rock tunnel was divided into four steps, meanwhile concrete measure basis and testing methods were given. According to the engineering geological conditions and the structure design schemes, the construction schemes and monitoring measurement projects of large-span gravel surrounding-rock tunnel were determined to ensure the safety of tunnel construction. This paper provides a complete example scheme for the design and construction of the main structure of the large-span IV class surrounding-rock tunnel, which provides a reference for similar projects in the future.

1. Introduction

In recent years, large-span gravel tunnel has developed rapidly in the field of transportation construction in China. When the surrounding rock of tunnel is fractured rock mass and the excavation span is more than 15m, the construction of the tunnel is difficult and the safety hazard is high. For example, the Wuzhuling Tunnel¹, the Longtanwan Tunnel² and the Yingwuling Tunnel³ of the Rongwu Expressway all had landslide accidents, causing casualties of many construction workers. Therefore, how to ensure the safety of the tunnel into the hole, the main structure design and construction is very important for such tunnels.

At present, domestic scholars have carried out a series of studies on the design and construction of the main structure of large-span gravel tunnel. Wang mingnian and Wei longhai used three-dimensional discrete elements to conduct numerical analysis of the self-stability of the gravel soil tunnel, and drew a diagram of the relationship between span and the amount of gravel soil collapse⁴. Bai yunzhou⁵ summarized the loading and deformation characteristics of the surrounding rock of the long-span tunnel in Guangxi through element testing and finite element numerical simulation. Dong zhiming⁶ studied the discrimination of depth and shallow of the long-span tunnel. Jiang et al discussed the applicability of the surrounding rock pressure formula of long-span tunnel. Wang haizhen and sun xingliang proposed the construction method for tunnel excavation in surrounding rock sections of different levels according
to the characteristics of large-span tunnel excavation with large span, high-span ratio and easy collapse\cite{7}. Zhang yongli\cite{8} studied and compared the construction methods of large-span shallow buried weak surrounding rock tunnel. Guo yan\cite{9} introduced its novel construction method and control settlement technology by studying Huilongwan large-span highway tunnel. Qing weichen et al. studied the construction method of extra-large span tunnel with the background of the tunnel project of wumeng mountain to explore the optimal construction scheme\cite{10}. Wu zhengdong\cite{11} summarized and applied the construction technical points and construction safety control of the tunnel grade IV surrounding rock section with the Caihuliang highway tunnel project as the background. Wu Chuncheng\cite{12} used the finite element software ANSYS to simulate the structure of the tunnel and set up a complete monitoring and measurement system for the tunnel deformation.

These research results have accumulated rich experience in the design and construction of the main structure of large-span gravel tunnels, but there is rarely a complete design process for a specific engineering case. Based on this, this paper takes a large span gravel tunnel in Jinan as an example to design the main structure of the tunnel, and give the relevant construction safety control scheme to provide reference for similar projects in the future.

2. Project Overview

A tunnel of Jinan high-speed is a mountain tunnel with separate section. Its left line is 1740 m and the right line is 1888 m. It belongs the long tunnel. The span of the tunnel is designed to be 16.75 m, consisting of a single tube with four lanes. The dark tunnel is constructed with composite lining and the door is built with end-wall lining. Tunnel surrounding rock is IV level of layered rock mass. The overburden of the entrance and exit section is mainly gravel soil and highly weathered limestone, which is thin. The construction safety control requirements of the tunnel trunk are high due to the terrain of the cave body is relatively steep and the lithology of the cave body is mostly moderately weathered limestone with large cracks in the rock mass. Tunnel into the hole section is IV level of shallow buried surrounding rock, its profile is shown in figure 1(A). The figure is mostly IV level deep surrounding rock tunnel, its section is shown in figure 1(B). The exit section of the tunnel is shown in figure 1(C).

Fig.1 Construction longitudinal section of tunnel surrounding rock; A: Tunnel entrance section; B: Tunnel body section; C: Tunnel exit section

3. The main structure design procedure of tunnel

3.1. Step 1: Calculation of tunnel surrounding rock pressure

According to design specification of Highway tunnel\cite{13}, first of all, this paper determines the buried depth of the tunnel. Then, the surrounding rock pressure of the tunnel is calculated through the formulas of deep and shallow buried surrounding rock pressure and the parameters of IV grade surrounding rock, the results are shown in table 1 and figure 2.
### Table 1 The surrounding rock pressure calculation for IV class

| Rock grade | Excavation height (m) | Excavation width (m) | Burial Depths (m) | Deep-shallow bury | Vertical pressure (kN) | Horizontal pressure (kN) |
|------------|-----------------------|----------------------|-------------------|------------------|-----------------------|-------------------------|
| IV         | 12.96                 | 19.4                 | 20.5              | Shallow bury     | 319.3                 | —                       |
| IV         | 12.96                 | 19.4                 | 53.27             | Deep bury        | 184.46                | 36.89                   |

Fig. 2 Surrounding rock pressure chart; A: Surrounding rock pressure diagram of grade IV Shallow buried tunnel; B: Surrounding rock pressure diagram of class IV deep buried tunnel

3.2. Step 2: Numerical calculation of internal forces in secondary lining of tunnel.

In this section, the internal force of the tunnel lining is calculated by ANSYS to obtain the axial force diagram, bending moment diagram and the most unfavorable position of the tunnel section of the IV-level surrounding rock, which provides the basis for the tunnel safety control.

3.2.1. Modeling principles and calculation process. ANSYS is used to divide the whole section into several beam elements, spring is used to simulate the surrounding rock pressure and finally calculate its internal force. Numerical calculation steps are as follows: creating the tunnel model, applying horizontal and vertical loads, entering the solution, removing the tension spring and solving the calculation again. The static model after applying the surrounding rock pressure is shown in figure 3.

Fig. 3 ANSYS solution model diagram

3.2.2. Determination of numerical model parameters. The "load-structure" model is adopted to calculate the internal force of the secondary lining of the tunnel. The material property parameters of the model are shown in table 2.
| parameters                          | numerical value |
|------------------------------------|-----------------|
| Second lining thickness (m)        | 0.55            |
| elasticity modulus (Pa)            | $3.15 \times 10^9$ |
| poissson ratio                     | 0.2             |
| coefficient of elastic resistance  | $3 \times 10^8$  |
| Surrounding rock density (kg/m)    | $2.1 \times 10^3$ |
| Density of lining (kg/m)           | $2.3 \times 10^3$ |

3.2.3. Internal force calculation results of tunnel surrounding rock. The axial force and bending moment of the tunnel sections 1-1 and 1-2 (Figure 1) are calculated by ANSYS finite element analysis software. Taking figure 4(B) as an example, through the analysis of tunnel axial force diagram and bending moment diagram, it is found that the most unfavorable position of tunnel section is 1,2,3,4,5, and reinforcement is needed to ensure the safety of the tunnel. When the most unfavorable position of the tunnel is stable, the overall section of the tunnel is stable.

Fig4 Internal force diagram of tunnel surrounding rock; A: 1-1 Axis force diagram of shallow buried section of tunnel; B: 1-1 Moment diagram of shallow buried section of tunnel; C: 2-1 Axis force diagram of deep buried section of tunnel; D: 2-1 Moment diagram of deep buried section of tunnel

3.3. Step 3: Strength check and reinforcement.
Designing specification of Highway tunnel[13] is referred in this section to judge large and small eccentric compression of the reinforced concrete section. The safety factor of the compressive strength of reinforced concrete is not less than 2.0, the safety factor of the tensile strength is not less than 2.4 and the limit of crack width is 0.2mm. We conduct reinforced concrete strength check, crack check and reinforcement calculation of Class IV surrounding rock for the most unfavorable position of the tunnel 1, 2, 3, 4, 5 (Figure 3 and Figure 4). The results are shown in Table 3, Table 4 and Table 5.
Table 3 Safety check table for grade IV shallow buried tunnels

| Location                  | Number | Axial force (N) | Bending moment (N·m) | Second lining thickness (mm) | Steel area (mm²) | Partial press | Compressive safety factor | Check $e_0 - 0.55h_b$ |
|---------------------------|--------|----------------|----------------------|-----------------------------|-----------------|---------------|--------------------------|-------------------------|
| Right inverted arch       | 1      | -1843600       | -405810              | 550                         | 1520            | Big           | 3.32                     | -57.08                  |
| Right Wall                | 2      | -3105700       | 535140               | 550                         | 1520            | Big           | 2.63                     | -104.89                 |
| Left Wall                 | 3      | -3338300       | -224460              | 550                         | 1520            | Small         | 3.59                     | -209.96                 |
| Vault                     | 4      | -2718400       | 535140               | 550                         | 1520            | Big           | 2.57                     | -78.78                  |
| Left Wall                 | 5      | -1826300       | -405810              | 550                         | 1520            | Big           | 3.40                     | -59.15                  |

Table 4 Class IV safety check table for deep burial of surrounding rock

| Location                  | Number | Axial force (N) | Bending moment (N·m) | Second lining thickness (mm) | Steel area (mm²) | Partial press | Compressive safety factor | Check $e_0 - 0.55h_b$ |
|---------------------------|--------|----------------|----------------------|-----------------------------|-----------------|---------------|--------------------------|-------------------------|
| Right inverted arch       | 1      | -969930        | -213650              | 550                         | 1256            | Big           | 5.97                     | -56.93                  |
| Right Wall                | 2      | -1636000       | 285150               | 550                         | 1256            | Big           | 4.80                     | -102.90                 |
| Left Wall                 | 3      | -1717200       | -118500              | 550                         | 1256            | Small         | 6.86                     | -208.19                 |
| Left inverted arch        | 4      | -1420300       | 285150               | 550                         | 1256            | Big           | 4.65                     | -76.43                  |
| Left Wall                 | 5      | -944320        | -213650              | 550                         | 1256            | Big           | 5.89                     | -50.96                  |

Table 5 Summary of reinforcement results

| Surrounding rock classification | Area of unilateral reinforcement (mm²) | Reinforcement composition |
|---------------------------------|----------------------------------------|---------------------------|
| IV level Shallow burial         | 1520                                   | 4Φ22                      |
| IV level deep burial            | 1256                                   | 4Φ20                      |

4. Main structure construction and safety monitoring

4.1. Tunnel construction scheme design
It is proposed to adopt three-step excavation method for construction based on the tunnel level IV rock geological conditions and large span section requirements. The height of the steps is 5 m, 4 m and 3.96 m respectively and the width of the steps is 17.2m and 19.4m respectively. The whole adopts compound lining structure. The circulation footage of the tunnel is 1.8m and the height and width of the steps of the tunnel are shown in figure 5(A).

The primary lining is made of 25 cm thick C30 plain concrete, Φ8 bar-mat reinforcement (20 cm×20 cm) and I20b steel arch. The rock bolt is grouting with C25. In addition, the reserved deformation amount is 10 cm. The secondary lining is made of pouring C35 reinforced concrete with thickness of 55cm, 1.5 mm thick EVA waterproof board And 400 g/m² of non-woven cloth. The construction process of the tunnel is shown in figure 5(B).
4.2. Tunnel construction safety monitoring
The most disadvantageous position of the tunnel is monitored for surrounding displacement and crown settlement, and the selected measurement points are shown in figure 5(A). In the longitudinal section of the tunnel, a group of measuring points are selected every 25 m. The layout of measuring points of surface subsidence in the transverse section is shown in figure 6.

5. Discussion
Width of long-span tunnel hole section is large and its burial is shallow. Compared with the ordinary tunnel, the stability control of surrounding rock in the design process is more prominent, meanwhile the construction measurement has special difficulties. Level and steel ruler, as the traditional measurement means, has obvious deficiencies in the large-span gravel tunnel. In this design, the tunnel has a large span and the surrounding rock is broken, which makes the construction difficult. As a part of stress, the primary lining should be closed in the loop and applied to the inverted arch in time to form a closed structure and strengthen the support. When the temporary support of the tunnel is removed, the initial support tends to be greatly deformed. Therefore, this design adds a layer of steel arch around the tunnel to further strengthen the initial support structure of the tunnel. In addition, because monitoring should be strengthened during the construction of long-span tunnel, so this design carries out a variety of monitoring and measurement items to ensure the construction safety of the tunnel.
6. Conclusion
Taking a large-span gravel tunnel of Jinan high-speed as an example, this paper conducts the main structure design and construction safety monitoring of the tunnel, and provides a complete demonstration design process for similar cases in the future. The main conclusions are as follows:

1. The main structure design and construction of large-span crushed stone tunnel is carried out in three steps, that is, calculating the surrounding rock pressure of the tunnel, calculating the internal force of the secondary lining, strength checking and reinforcement.

2. ANSYS software was used for modeling and calculation to obtain the most unfavorable position of the tunnel and provide a basis for the design of the tunnel. According to the geological conditions and structural design scheme of the tunnel, the safety monitoring project of the tunnel is determined to ensure the stability of the tunnel.

3. No in-situ component test of the tunnel is designed this time. It is suggested that similar projects can test and analyse the stress and deformation of surrounding rock, initial support and secondary lining structure after the tunnel operation. In addition, the finite element ANSYS software can be combined to take different working conditions for the excavation of large-span crushed stone tunnel, and further analyse the structural stress of tunnel surrounding rock lining, which may improve the safety of large-span crushed stone tunnel excavation process and ensure the quality of tunnel engineering.

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