Numerical Researches on the Optimization of Construction Methods in Tunnels with Super Large Section

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Abstract. At present, the selection of construction methods in the tunnels with super large sections often relies on the experience for lack of a definite and feasible method. Based on the design method of formation-structure tunnels, the paper adopts FEM strength reduction to conduct numerical researches on the optimization of construction methods in tunnels with super large section. Taking a tunnel with super large section in a subway station as example, the paper first carries out numerical simulation on arch-wall method and double sidewall pilot tunnel method. Then it compares and analyzes the calculation results of surrounding rock displacement, stress on anchors and surrounding rock stability during construction. Finally, the paper suggests double sidewall pilot tunnel method. The analysis on the calculation examples shows that numerical method can quantitatively and directly display the difference between various construction methods and realize the optimization of construction methods in tunnels with super large section.

1. Introduction
The construction methods in tunnel engineering is not only the key to the tunnel design but also the essential part to ensure the engineering safety. At present, the methods for tunnels with super large sections are bench cut method, median septum excavation method(CD method), intersecting wall method(CRD method), double sidewall pilot tunnel method and upper arch-wall method[1~4] and so on. Since tunnel engineering with super large section has the properties of large span and complex surrounding rock, the selection of the construction method often relies on experience for the lack of definite and feasible method. FEM strength reduction, which is used in the formation-structure method based on numerical calculation in the paper, possesses the properties of stratigraphic-structural method. In addition, the method can also work out the safety stability factors of surrounding rock and the layout of plastic zone under ultimate state. Through the method, the paper first carries out numerical simulation on arch-wall method and double sidewall pilot tunnel method. Then it compares and analyzes the calculation results of surrounding rock displacement, stress on anchors and surrounding rock stability during construction. As a result, the optimization of construction methods in tunnels with super large section is realized.
2. Basic principles and technical route

2.1 Basic principles

The most important principle for the selection of construction method in tunnel engineering is that it should satisfy the requirements for the safety of surrounding rock during the construction. FEM strength reduction[5–7] is used in this paper to analyze the safety factors, which can simulate the strength reduction of surrounding rock under different circumstances and excavation through reduction the strength coefficients (cohesion c and inner friction angle φ). At the same time, it can also carry out elastic-plastic numerical calculation till failure state. When failure happens, the reduction multiple is the stability safety factor of surrounding rock. The program can generate the layout of plastic zone and failure information according to the FEM calculation results so as to evaluate the stability of surrounding rock quantitatively.

When FEM strength reduction is applied to analyze the stability of surrounding rock during construction, the key is how to judge whether the surrounding rock reaches the ultimate failure state according to calculation results to obtain the safety factor. At present, three criteria are used to judge the unstable failure[8–10]: 1. whether the plastic zone is cut through; 2. the mutation of displacement on the surrounding rock; 3. whether convergence happens based on the FEM calculation. The paper takes the mutation of displacement as the criterion and assisted by the other two criteria.

2.2 Technical route

In the numerical researches to optimize the construction method of tunnel engineering with super large section, numerical simulation of various methods should be conducted first, then comparison and analysis on the displacement of surrounding rock, anchor axial force and safety factors during construction of different methods are needed so as to assure the fixed construction method. The technical route is shown in figure 1.

![Technical route of selecting the construction method for tunnel engineering](image)

Figure 1. Technical route of selecting the construction method for tunnel engineering

3. Calculation example

Taking an excavation section in a subway station as an example, the largest span in the section is up to 32.582m, the height is 27.418m and the arch top is about 7–17m from the ground, which is a super shallow buried tunnel. The surrounding rock of the tunnel is sandy mud stone, belonging to grade IV.
The rock layer is medium thick and the combination between layers is weak since some parts are filled with cohesive soil. The numerical simulation takes plain strain model to simulate the section covered with plain soil and sandy mud stone, whose thickness are 7m and 10 m respectively. The buried depth of the tunnel is 17m. The numerical model is 240 m wide and 147m high. The net distance between the model edge and tunnel outline in the direction of width and height is larger than three times of the tunnel span and height. In the calculation, PLANE42 unit is used to simulate filling soil, surrounding rock and preliminary lining; BEAM3 unit is used to simulate the temporary support in the excavation; LINK1 unit is used to simulate the anchor. The physical parameters of rock and soil and the lining structure are shown in table 1.

| type                      | weight of soil /kN/m³ | elastic modulus /MPa | poison’s ratio | inner friction angle/° | cohesion /MPa |
|---------------------------|-----------------------|----------------------|----------------|------------------------|---------------|
| surrounding rock of grade IV | 24                    | 3                    | 0.35           | 27                     | 0.1           |
| filling soil              | 20                    | 0.02                 | 0.45           | 30                     | 0.025         |
| preliminary lining        | 25                    | 28                   | 0.2            | 52                     | 2.1           |
| secondary lining          | 25                    | 32.5                 | 0.2            |                        |               |
| temporary support         | 25                    | 28                   | 0.2            |                        |               |
| anchor and steel support  | 78                    | 200                  | 0.3            |                        |               |

The construction methods are arch-wall method and double sidewall pilot tunnel method, as shown in figure 2. Numerical model is shown in figure 3.

Figure 2. Construction methods

(a) Arch-wall of upper pilot tunnel method
(b) Double sidewall pilot tunnel method

Figure 3. Numerical models of different construction methods

3.1 Analysis on the stability of surrounding rock through arch-wall of upper pilot tunnel method

Figure 4(a) is the layout of plastic zone after zone 1 excavation, where the safety factor is 1.04. The plastic zone is mostly located in the two sides of the tunnel wall. Figure 4(b) is the layout of plastic zone after supporting and zone 1 excavation, where the safety factor is 1.59. The plastic zone is mostly located in the surrounding rock corresponding to the temporary supporting. Figure 5(a) is the layout of plastic zone after zone 3 excavation and without supporting, where the safety factor is 1.02. The plastic zone is mostly located in the top of pilot tunnel without supporting and forms slumping arch. Figure 5(b) is the layout of plastic zone after supporting, where the safety factor is 1.46. The plastic
zone is mostly located in the bottom of left and right pilot tunnels.

![Layout of plastic zone without supporting](image1)
![Layout of plastic zone after supporting](image2)

Figure 4. Layout of plastic zone after zone 1 excavation

![Layout of plastic zone without supporting](image3)
![Layout of plastic zone after supporting](image4)

Figure 5. Layout of plastic zone after zone 3 excavation

Figure 6(a) is the layout of plastic zone after zone 5 excavation and without supporting, where the safety factor is 1.01. The plastic zone is mostly located in the side walls of the lower pilot tunnel without supporting. Figure 6(b) is the layout of plastic zone after supporting, where the safety factor is 1.12. The plastic zone is mostly located symmetrically in the surrounding rock of the two sides in lower pilot tunnels. The calculation results of safety factors of the surrounding rock corresponding to each construction process are shown in table 2. It shows that the safety factor of excavation in the bottom of the lower pilot tunnel (zone 5) is the lowest, which is 1.01. The surrounding rock can hardly be stable. So the arch-wall of upper pilot tunnel method is not suitable for the engineering of this subway station.

![Layout of plastic zone without supporting](image5)
![Layout of plastic zone after supporting](image6)

Figure 6 Layout of plastic zone after zone 5 excavation

![Layout of plastic zone without supporting](image7)
![Layout of plastic zone after supporting](image8)

Figure 7 Layout of plastic zone after zone 5 excavation

| zone 1 excavation | zone 2 excavation | zone 3 excavation | Arch cover | zone 4 excavation | zone 5 excavation | secondary lining |
|-------------------|-------------------|-------------------|------------|-------------------|-------------------|-----------------|
| without supporting | 1.04 | 1.08 | 1.02 | 1.06 | 1.01 |
| supporting        | 1.59 | 1.42 | 1.46 | 1.7  | 1.26 | 1.12 | 2.16 |

3.2 Analysis on the stability of surrounding rock through double sidewall pilot tunnel method

Figure 7(a) shows the layout of plastic zone after zone 1 excavation and the safety factor is 1.17 at the moment. The plastic zone is mainly in the surrounding rock in both sides of the pilot tunnel. Figure 7(b) shows the layout of plastic zone after excavation and zone 1 excavation and the safety factor is
1.86. The plastic zone are mainly in the surrounding rock corresponding to the temporary supporting in the right and lower parts of the pilot tunnel. Figure 8(a) shows the the layout of plastic zone after zone 5 excavation and the safety factor is 1.2 at the moment. The plastic zone is mainly in the surrounding rock in both sides of the pilot tunnel. Figure 8(b) shows the layout of plastic zone after excavation and supporting in zone 5 and the safety factor is 1.84. The plastic zone are mainly in the surrounding rock corresponding to the temporary supporting in the middle and lower parts of the pilot tunnel, which have cut through. Figure 9(a) shows the the layout of plastic zone after zone 9 excavation and the safety factor is 1.25 at the moment. The plastic zone is mainly in the surrounding rock without supporting in the top of the pilot tunnel. Figure 9(b) shows the layout of plastic zone after excavation and supporting in zone 9 and the safety factor is 1.76. The plastic zone are mainly in the surrounding rock corresponding to the temporary supporting in lower part of the pilot tunnel. Figure 10(a) shows the the layout of plastic zone after zone12 excavation and the safety factor is 1.43 at the moment. The plastic zone is mainly in the lower part of the surrounding rock without supporting of the pilot tunnel. Figure 10(b) shows the layout of plastic zone after excavation and supporting in zone 12 and the safety factor is 1.59. The plastic zone are mainly in the surrounding rock corresponding to the supporting part of the pilot tunnel.

(a) Layout of plastic zone without supporting   (b) Layout of plastic zone after supporting
Figure 7. Layout of plastic zone after zone 1 excavation

(a) Layout of plastic zone without supporting   (b) Layout of plastic zone after supporting
Figure 8. Layout of plastic zone after zone 5 excavation

(a) Layout of plastic zone without supporting   (b) Layout of plastic zone after supporting
Figure 9. Layout of plastic zone after zone 9 excavation
The calculation results of safety factor corresponding to each construction step are shown in table 3, which shows that when the double sidewall pilot tunnel method is used, the excavation section is comparatively smaller and the supporting is more complete. So the enough safety shows this method is more suitable to the construction of the railway station.

Table 3. Calculation results of safety factor corresponding to each construction step

|                  | zone 1 excavation | zone 2 excavation | zone 3 excavation | zone 4 excavation | zone 5 excavation | zone 6 excavation |
|------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| without supporting | 1.17              | 1.24              | 1.16              | 1.23              | 1.2               | 1.13              |
| supporting       | 1.86              | 1.85              | 1.95              | 2                 | 1.84              | 1.69              |

3.3 Optimization of construction methods

The calculation results of the surrounding rock deformation through different methods are shown in table 4. The data show that the both ultimate values of the surrounding rock deformation have not exceeded the permission of construction safety.

Table 4. Calculation results of the surrounding rock deformation through different methods

| construction methods | maximum of the settlement in the arch top/cm | maximum of convergence in the arch waist/cm |
|----------------------|----------------------------------------------|--------------------------------------------|
| arch-wall in the upper pilot tunnel method | secondary lining closed | zone 5 excavation    | 6.01 | 0.45 |
| double sidewall pilot tunnel method | excavation and supporting in zone 12 | zone 5 excavation    | 5.85 | 0.52 |

As one of flexible supporting, anchor can release some stress with surrounding rock and control the deformation of surrounding rock. It is very important for the construction and operation of tunnel engineering to make full use of the tensile ability of anchors. The stress on the anchors through two methods are shown in table 5 and figure 11. The calculation results show that the axial force of the anchor in both methods can satisfy the requirements of the bearing capacity. The axial force of the anchor through arch-wall upper pilot tunnel method is the largest, which is 247.661kN and very close to 269.423kN, so it is not safe enough. Due to the stability safety of surrounding rock, deformation of surrounding rock and anchor force during construction, double sidewall pilot method is more suitable to the tunnel engineering of this subway engineering.

Table 5. Maximum of anchor force

| construction methods | maximum of anchor force/kN | excavation |
|----------------------|---------------------------|------------|
| arch-wall upper pilot tunnel method | 247.661 | zone 3 excavation |
| double sidewall pilot method | 175.07 | zone 12 excavation |
4. Conclusions
The paper puts forward the ideas and processes of optimizing the construction method of tunnel engineering with super large section through conducting the numerical simulation of arch-wall method and double sidewall pilot tunnel method. The following conclusions can be drawn though the engineering calculation example:

(1) The advantages of arch-wall upper pilot method have fewer construction processes, shorter period and more economical cost, but this method would enlarge the tunnel span and lead to risks of excavation in the upper part, which would cause the instability of surrounding rock;

(2) Comparatively, double sidewall pilot method has the advantages of lower difficulties in excavation, more dividing in section and more controllable in the deformation in the surrounding rock. At the same time, the surrounding rock is more safe due to the smaller excavation section and complete supporting;

(3) FEM strength reduction is induced based on the designing method of stratigraphic-structural, which can display quantitatively and directly the surrounding rock displacement, anchor force and the stability of surrounding rock during construction and so on. These can provide guides for the optimization of construction methods.

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