Comparative Analysis of Different Construction Methods for Mine Tunnels

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Abstract. The construction of mining tunnels in cities often has a great impact on the stratum and surrounding environment. Relying on a drainage tunnel project in Wuhan, Plaxis3D finite element analysis software is used to simulate tunnel excavation under four typical construction methods. The ground conditions, tunnel size, burial depth, support and construction scheme are all guaranteed to be the same. The characteristics and rules of ground settlement, crown settlement and horizontal convergence caused by construction are mainly analyzed. The following results are obtained: For the four construction methods, the rules of ground settlement, crown settlement and horizontal convergence by tunnel excavation are basically the same. Except for the arch bottom uplift, the calculation results of the tunnel constructed by the double side drift method are the smallest, and the calculation results of the tunnel constructed by the bench method are the largest. The tunnels excavated by the CRD method and the CD method have similar calculation results and have relatively little impact on the stratum. The research results can provide references for other related projects in Wuhan.

1. Introduction

The urban tunnels constructed by the mining method often have large excavation sections, and the surrounding environment is complex, which has a large disturbance to the stratum. O Reilly, New[1] et al. studied the ground settlement caused by different construction methods for different strata. Based on a large amount of measured data, they proposed the actual settlement tank width, formation loss and ground settlement prediction formula. Attewell[2] et al. summarized the deformation rule of surrounding rock induced by subway tunnel construction under the clay stratum through on-site measurements. Wang Lichuan[3] elaborated on the aspects that should be noted when using CRD and CD construction...
methods in weak rock. Tai Qimin et al. used the combination of numerical simulation and on-site measurements to study the surface deformation characteristics of five typical sections under different excavation sequences, layouts and grouting methods. Jia Peng et al. used three-dimensional numerical simulation method to model the different excavation processes of a shallow tunnel with cover to depth ratio of less than 1. The key parameters such as crown and ground settlement, displacements of lining and the stress changing were compared and analyzed.

Based on a tunnel project in Wuhan, this paper uses Plaxis 3D finite element analysis software to simulate the different construction methods under the same stratum conditions. The characteristics and rules of ground settlement, crown settlement and horizontal convergence caused by construction are analyzed. The analysis results provide the reference for the design and construction of large-section tunnels under similar conditions.

2. Calculation model establishment

2.1. Engineering background
The elevation of a mine tunnel section in Wuhan is about 40m. The 50m depth stratum in this section is characterized by artificially filled soil with uneven thickness on the surface, followed by red clay and limestone. The stable water level is about 2.0m below the ground.

2.2. Different construction methods simulation scheme
In the case of ensuring the same tunnel size, depth, support scheme and construction plan, the double side drift method, the bench method, CRD and CD method are respectively simulated the construction. The tunnel is 13.56m wide and 7.01m high. The tunnel structure adopts composite lining structure. The primary support uses grouting reinforcement with pipe shed, sprayed steel fiber concrete and steel frame. The secondary support is made of molded concrete or reinforced concrete. After the completion of the full-section excavation, the secondary lining shall be applied in time.

For the double side drift method, the whole section is divided into 6 parts for excavation. Construction sequence is I→II→III→IV→V→VI. For the CD and CRD method, the whole section is divided into four parts for excavation. Construction sequence is I→II→III→IV. The bench method, full section divided into two parts for excavation. Construction sequence is I→II. The tunnel excavation is 1.2m per step. Full-section distribution excavation shall be constructed at 2-3m intervals. The excavation sections of the four methods are shown in Figure 1.
2.3. Numerical calculation model

The finite element software Plaxis3D is used to establish a numerical analysis model. In order to reduce the influence of the boundary effect, the model length × width × height is: 100m × 30 × 50m. The soil layer is distributed from the surface as follows: filled soil (2m), red clay (20m) and limestone (28m). The groundwater level is 2m below the ground. The soil is simulated with solid elements and the M-C constitutive model is used. The tunnel has a depth of 12.49m and a length of 30m, 1.2m per step. Both the primary and secondary linings are modeled using plate elements. A contact unit is provided between the lining and the soil contact surface. The soil layer and structural parameters are shown in Table 1. The anchor support and the advanced reinforcement area are simulated by the equivalent method of stiffness. The 15-node high-order triangular unit is used for meshing, totaling 30,529 units and 47,707 nodes. The model is shown in Figure 2.

### Table 1. Parameters of soil layers and structure for calculation

| stratum / structure                      | $\gamma$ (kN·m$^{-3}$) | $c$ (kPa) | $\phi^\circ$ | $\psi^\circ$ | $E$ (MPa) | $v$  | $d$/m |
|------------------------------------------|-------------------------|-----------|--------------|-------------|-----------|-----|-------|
| filled soil                              | 17.6                    | 8         | 8            | 0           | 15        | 0.35|
| red clay                                 | 16.4                    | 30.8      | 26.2         | 0           | 20        | 0.25|
| limestone                                | 23                      | 2         | 56           | 26          | 11.4e3    | 0.2 |
| Anchor equivalent reinforcement area     | 19.5                    | 30.8      | 26.2         | 0           | 106       | 0.25|
| primary linings                          | 7                       | -         | -            | -           | 31.5e3    | 0.2 |
| temporary support                        | 22                      | -         | -            | -           | 30e3      | 0.2 |
| secondary linings                        | 7                       | -         | -            | -           | 31.5e3    | 0.2 |
| Advanced reinforcement area              | 7                       | -         | -            | -           | 25e3      | 0.2 |

Figure 2. Three-dimensional computing model

3. Analysis of calculation results

3.1. Ground settlement analysis
In order to reduce the influence of the boundary, sections y=15 and x=50 at the tunnel axis are taken respectively. The ground transverse settlement and the longitudinal ground settlement are shown in figure 3 and figure 4. They are obtained after tunnel excavation being completed under different construction methods. The maximum ground transverse settlement and longitudinal ground settlement of different construction methods are shown in Table 2. It can be seen from the figure that after the tunnel excavation is completed, the shape of the ground transverse settlement curve of the ground is basically similar to the peck curve.

For the four construction methods, there is basically no difference in the range of influence of ground transverse settlement. The influence range is within 30m from the tunnel axis. The maximum transverse and longitudinal settlements obtained from the construction of the double side drift method are the smallest. The maximum transverse settlement is 10.8mm, which occurs at 0.26m to the left of the tunnel axis. The maximum longitudinal settlement is 17.3mm, which occurs at 28.77m from the tunnel excavation surface. In comparison, the maximum transverse and longitudinal settlements obtained from the bench method are the largest. The maximum transverse settlements is 26.6mm, which is 146.3% larger than the double side drift method, and occurs at 0.37m to the left of the tunnel axis. The maximum longitudinal settlement is 32.3mm, which is 86.7% larger than the double side drift method and occurs at 27.94m from the tunnel excavation surface. The maximum transverse settlements of the CRD method and the CD method are 14.6mm and 13.5mm, which are 35.2% and 25% larger than the double side drift method, respectively. The maximum longitudinal ground settlement are 21.1mm and 20.0mm, which are 22% and 15.6% larger than the double side drift method, respectively. The reason is that in addition to the bench method, the other three construction methods have temporary support and participation in the construction process.

### Table 2. Maximum settlement

| Four construction methods | The double side drift method | CRD method | CD method | The bench method |
|---------------------------|-----------------------------|------------|-----------|------------------|
| The maximum ground transverse settlement/mm | -10.8 | -14.6 | -13.5 | -26.6 |
| The maximum longitudinal ground settlement/mm | -17.3 | -21.1 | -20.0 | -32.3 |

3.2. Crown settlement analysis

Figure 5 is the stratum settlement nephogram of under different construction methods at the y = 15 section. Table 3 shows the maximum crown settlement and uplift of tunnels arch bottom with different construction methods. The analysis shows that after the tunnel is excavated, the crown will have different degrees of settlement, and different construction methods have an obvious impact on the crown settlement. The maximum crown settlement of the double side drift method is the smallest, which is 20.4mm. The maximum crown settlement of the bench method is the largest, which is 44.3mm. This
value is an increase of 117.2% over the double side drift method. The maximum difference of the crown settlement between CRD method and CD method is only 0.1mm, and the values are 25.6mm and 25.5mm, respectively. They are 25.5% and 25% more than the double side drift method, respectively.

The maximum rule of arch bottom uplift is just the opposite of the crown settlement. Compared with the crown settlement value, the uplift of the arch bottom is less affected by the construction method. The maximum uplift of tunnels arch bottom of the double side drift method is the largest, which is 9.8mm. In comparison, the CRD method, the CD method, and the bench method decrease by 23.5%, 11.2%, and 22.4%, respectively.

![Figure 5. The settlement nephogram of stratum and tunnel](image)

![Table 3. Maximum crown settlement and arch bottom uplift](table)

3.3. Horizontal convergence analysis
When using the mine tunnelling method to excavate a tunnel, because the excavation of the tunnel section has an unloading effect on the soil, the surrounding soil must compress the tunnel. The horizontal convergence of the tunnel arch waist is obvious. For the tunnels excavated by four different construction methods, the cross section at y = 15m is selected, and the reference points A and B are selected at the left and right arch waists of the tunnel, as shown in Figure 6. The changes of the horizontal displacement
of the tunnel with the calculation steps under four different working conditions are shown in Figures 7 and 8, respectively.

As shown in figures, as the tunnel excavation progresses, the horizontal convergence at the left and right arch waist increases continuously for the four construction methods, and the maximum increase occurs when excavation reaches the monitoring section. Because there is no temporary support for the excavation by the bench method, the increase in horizontal displacement is particularly significant when the selected section is excavated. With the excavation of the tunnel, the convergence rate rapidly decreases, and the horizontal displacement of the cross-section arch waist is basically stable. As shown in the table, the horizontal displacement values at the left and right arch waists of the double side drift method are the smallest, being 8.0mm and 7.1mm, respectively. In comparison, the bench method has the largest horizontal convergence values at the left and right arch waists, which are 20.2mm and 21.0mm, with corresponding increases of 152.5 and 195.8%, respectively. The CRD method and the CD method increased the horizontal displacement values at points A by 26.3% and 33.8%, and the horizontal displacement values at point B increased by 22.5% and 42.3%, respectively.

![Figure 6. Reference point](image)

![Figure 7. The horizontal displacement values at point A](image)

![Figure 8. The horizontal displacement values at point B](image)

| Table 4. The horizontal displacement values |
|--------------------------------------------|
| Four construction methods | The double side drift method | CRD method | CD method | The bench method |
|---------------------------|-------------------------------|------------|-----------|-----------------|
| The horizontal displacement values at point A/mm | 8.0 | 10.1 | 9.8 | 20.2 |
| The horizontal displacement values at point B/mm | -7.1 | -9.5 | -10.1 | -21.0 |
4. Conclusion
This paper uses Plaxis\textsuperscript{3D} finite element analysis software to simulate four construction methods under the same stratum conditions with a drainage tunnel project in Wuhan as the background. Calculations proves that:

For the four construction methods, the shape of the ground transverse settlement is basically similar to the peck curve. The maximum ground transverse settlement caused by the tunnel constructed by the double side drift method is the smallest. When using the CRD method, the CD method, and the bench method, the corresponding maximum ground transverse settlement increased by 35.2%, 25%, and 146.3% respectively, compared to the maximum ground transverse settlement caused by the tunnel using the double side drift method. The longitudinal ground settlement rule of the ground caused by the four construction methods is basically the same. When adopting the double side drift method, the corresponding longitudinal ground settlement is the smallest. When using the CRD method, the CD method, and the bench method, the corresponding longitudinal ground settlements increased by 22%, 15.6%, and 86.7%.

The maximum crown settlement caused by the tunnel constructed by the double side drift method is the smallest. The maximum values of the corresponding crown settlement caused by the CRD method, the CD method and the bench method increased by 35.2%, 25%, and 146.3% respectively. The rule of arch bottom uplift is just the opposite. The maximum uplift of tunnels arch bottom caused by the double side drift method is the largest. The maximum uplift of tunnels arch bottom caused by the bench method is the smallest.

From the positive and negative of the horizontal convergence value of the reference point, it can be seen that the left and right arch waists of the tunnel receive squeezing from the soil by four construction methods. During the excavation of the selected section, the horizontal convergence values of the reference points change suddenly. The horizontal convergence values of the two reference points at the left and right arch waists of the tunnel constructed by the double side drift method are the smallest. In comparison, when using the CRD method, the CD method, and the bench method, the corresponding reference point A horizontal convergence values increased by 26.3%, 33.8%, and 152.5% respectively. The reference point B horizontal convergence values increased by 22.5%, 42.3%, and 195.8%, respectively.

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