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Calculation of surrounding rock pressure of large section underground excavation metro station based on the construction process

Y T Zhang¹, X G Jin^{2,*}, Y J Dai¹, H L Li² and W G Yang¹

¹ China Construction Tunnel Construction Co., Ltd. Chongqing, China

² School of Civil Engineering, Chongqing University, Chongqing, China

*Email: jinxiaoguang@cqu.edu.cn

Abstract. The traditional calculation method of the surrounding strata pressure of the tunnel does not consider the tunnel construction process. The excavation of the large-section tunnel mostly adopts the section excavation method, which is to excavate and support at the same time. The stress state of the pressure of surrounding strata changes gradually during the excavation process. The traditional calculation results of tunnel surrounding strata pressure are generally large. In this paper, the large-section tunnel is simplified into three parts, and the degree of influence (η_1 , η_2 , η_3) of the excavation height h and width b of the advance pilot hole and the distance d between the advance and rear pilot tunnels on the surrounding rock pressure calculation are analyzed. The regression equation for calculating the influencing factors (tunnel depth H , tunnel span B , internal friction angle ϕ , and rock weight γ) of surrounding rock pressure (p) is established. Through the numerical analysis, the influence coefficient η is obtained, the weight coefficient is introduced, and the computing formula of the pressure of surrounding strata of the large-section tunnel excavation is derived. The formula is used to the computing of the pressure of surrounding strata with a large-section subway station and the correct conclusion is obtained.

Keywords: Large Section Tunnel; Construction Process; The pressure of surrounding strata; Numerical Simulation

1. Introduction

At present, pressure arch theory, engineering analogy, indoor model test, and numerical simulation analysis combined with monitoring measurement are mainly used in the calculation of the pressure of surrounding strata in large-section tunnel [1-7], but there are few studies on the compute method of surrounding strata pressure considering the construction process of tunnels with large section. Zhu Zhengguo (2014)[8], Tan Lixin (2015)[9], Chen Qiao (2019)[10], etc. analyzed the calculation of surrounding strata pressure based on the excavation process of large section tunnel and metro station and obtained very meaningful conclusions. The traditional calculation method of the pressure of surrounding rock merely concerned the ultimate condition after tunnel excavation, which is the state design method [1, 11]. However, in engineering practice, most of the tunnels are limited by their cross-section characteristics and geological conditions, so that few of them can be excavated at one time. For the subway station in urban rail transit, because of its large section and complex influencing factors, the effect of the excavation process is not attended when the traditional method is



applied to compute the surrounding strata pressure, so it is not entirely appropriate to directly apply it to the design of station tunnel. According to the code for the design of the railway tunnel (*TB 10003-2016*) [2], the calculated pressure value of surrounding rock is generally greater than the actual value, which leads to conservative structure design and waste of engineering economy. Different from the traditional method, the process calculation method considers the effect of the tunnel construction process. In this method, the whole tunnel is divided into some small pilot tunnels. According to the computing of the pressure of each pilot tunnel, the overall design is carried out after comprehensive consideration. The process design method concentrates on the excavation process and the design load of the support structure is no longer the load produced by one-time excavation, but the result of the interaction of different excavation sections. And the surrounding strata pressure of the respective excavation section is also calculated based on the final state of a single small span pilot tunnel. The state design method is the precondition and basis of the process design method, and the process design concept is more in line with the actual situation of the project.

2. Compute method of the pressure of surrounding strata based on the excavation process

2.1. Basic assumptions

(1) The tunnel section is divided into three pilot tunnels on the left, the middle, and the right, and each pilot tunnel is divided into three steps for excavation, which can be simplified as a one-time opening completed cavern. The numerical simulation shows that when the height and width of the tunnel are 8 m and 12 m respectively, the redistributive stress difference between upper and lower step excavation and the one excavation is not more than 10% in the V-Class surrounding strata condition.

(2) The final pressure of the surrounding strata of the tunnel is the weighted combination of the pressure of surrounding strata of the partial excavation pilot tunnel.

(3) The effect of core rock on the pressure of surrounding strata is not considered.

(4) The rock mass is a single homogeneous material, regardless of groundwater and bias pressure.

2.2. Calculation idea

According to the sequence in the actual construction project, the process calculation method first calculates the pressure of surrounding strata of each of the three pilot tunnels in the left, middle, and right, and considers the mutual influence of each pilot tunnel excavation, to obtain the load conditions of each pilot tunnel considering the construction process, and then the pressure of surrounding strata value of the whole large-section tunnel is obtained through superposing in a certain way. The calculation idea based on the construction process is as follows:

(1) Divide the tunnel section according to the excavation method;

(2) Considering the interaction of each pilot tunnel excavation, the influence coefficient of the construction process on the pressure of surrounding strata is introduced, and the pressure of surrounding strata is determined according to the calculation formula under the pressure arch theory;

(3) The pressure of surrounding strata caused by the excavation of each pilot tunnel is combined based on certain rules, and finally, the pressure of surrounding strata of the whole station tunnel is calculated.

In the actual project, the excavation process of the tunnel is carried out step by step. The first excavation of the pilot tunnel will disturb the surrounding strata, which will affect the surrounding strata pressure of the later excavation; similarly, the later excavation will also affect the pressure of surrounding strata of the already excavated pilot tunnel, so it is necessary to consider this point when calculating the pressure of surrounding strata of the large-section station tunnel. Therefore, the influence coefficient α is introduced here to indicate the mutual influence of successive excavation of the pilot tunnel. The value α is related to the location and geometric dimension of the pilot tunnel. Three factors are considered here: the excavation height h and width b of the pilot tunnel and the distance d between the advance pilot tunnel and the rear pilot tunnel. According to these factors, the sub-index relationship of influence coefficient α can be expressed as follows:

$$\alpha_{ij} = \eta_1 \cdot \eta_2 \cdot \eta_3 \quad (1)$$

In the formula, η_1 is the influence index of the ratio of the excavation height of the advance pilot tunnel to the tunnel height about the pressure of surrounding strata of the rear pilot tunnel; η_2 is the influence index of the ratio of the excavation width of the advance pilot tunnel to the tunnel span on the pressure of surrounding strata of the rear pilot tunnel; η_3 is the influence index of the ratio of the horizontal distance between the advance pilot tunnel and the rear pilot tunnel to the tunnel span on the pressure of surrounding strata of rear one. If the value of η_k ($k = 1, 2, 3$) is less than 1, set it to be equal to 1. According to the pressure of surrounding strata P which is obtained by the pressure arch theory, the surrounding rock pressure of the single pilot tunnel concerning the effect of the excavation process is:

$$p_i = \alpha_{ij} p \quad (2)$$

The multiple linear regression equation is established by selecting four main influencing factors: internal friction angle φ , tunnel span B , tunnel depth H , and rock mass gravity γ

$$p = \beta_0 + \beta_1 H + \beta_2 B + \beta_3 \varphi + \beta_4 \gamma \quad (3)$$

In the formula, β_1 , β_2 , β_3 , and β_4 are partial regression coefficients; β_0 is the linear regression's constant term set. By substituting them into this model, the linear regression equation could be acquired as follows:

$$p = -83.6625 + 0.1758H + 6.4003B - 0.5789\varphi + 6.6057\gamma \quad (4)$$

3. Influence of construction process (factors) on Calculation of the pressure of surrounding strata

3.1. Influence of ratio of excavation height of successive pilot tunnel to η_1

To study the relationship between the height h of the advance pilot tunnel and the influence index, the adjacent advance pilot tunnel with different height was established based on the rear pilot tunnels which mean unexcavated pilot tunnels. The tunnel height after the excavation of the advance pilot tunnel is 0.25 times, 0.5 times, 0.75 times, and 1 time of the height of the rear one respectively. The span of the advance pilot tunnel and the rear one is 10 m, and the tunnel height is 15 m. The tunnel section is a straight wall tunnel section, the spacing between the pilot tunnels is 0, and the middle value of IV-class surrounding rock with 50 m buried depth is taken as the calculation model, as shown in Figure 1.

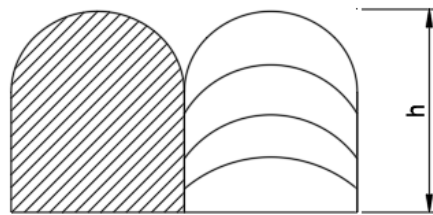


Figure 1. Schematic diagram of the influence of different heights on the excavation process of adjacent pilot tunnels.

According to the calculation method of the pressure of the surrounding strata combined with the pressure arch theory, the pressure of the surrounding strata value of the rear pilot tunnel in Figure 1 calculation model was calculated. Compared with the pressure of the surrounding strata of a single-hole tunnel under the same working condition, the calculated results are listed in Table 1.

As shown in Table 1 when the advance pilot tunnel is excavated, the excavation height of the advance pilot tunnel has a significant impact on the pressure of the surrounding strata of the rear pilot tunnel, and the pressure of the surrounding strata affected by the pilot tunnel is more significant than

that of the single-hole tunnel. The influence index η_1 can be obtained by calculating the ratio of the two. When the excavation height is less than 1 time of h , it is $1.23 \sim 1.39$ and is always greater than 1.

Table 1. Comparison of surrounding rock pressure between the rear pilot tunnel and single-hole tunnel under the different height of advance pilot tunnels.

Height of advance pilot tunnels	1 times the height of the rear pilot tunnel	0.75 times the height of the rear pilot tunnel	0.5 times the height of the rear pilot tunnel	0.25 times the height of the rear pilot tunnel
The pressure of the surrounding strata affected by the pilot tunnel /kPa	164.46	158.55	151.45	145.53
The pressure of the surrounding strata of single hole tunnel /kPa	118.32	118.32	118.32	118.32
Impact indicator η_1	1.39	1.34	1.28	1.23

Although the overlying rock mass of the rear pilot tunnel is not excavated, the upper rock mass of the rear pilot tunnel has been disturbed due to the excavation of the advanced pilot tunnel. When the pilot tunnel is excavated again, the loose rock will produce further expansion, increasing the first part of the pressure arch theoretical calculation method ($p = p_1 + p_2 = \gamma \cdot H_1 + k \cdot s$). In other words, the rock mass in the loose area will increase, increasing the surrounding strata pressure. According to the data listed in Table 1, the relationship between η_1 and the ratio x of the height of the advance and rear pilot tunnel can be fitted out:

$$\eta_1 = 0.216x + 1.175 \quad R^2 = 0.9986 \quad (5)$$

In the formula, x is the ratio of the excavation height of the advance pilot tunnel to that of the rear pilot tunnel; η_1 is the influence index of the ratio of the excavation height of the advance pilot tunnel to that of the rear pilot tunnel on the pressure of the surrounding strata of the rear pilot tunnel.

3.2. Influence of ratio of excavation width of the successive pilot tunnel to η_2

To study the relationship between the width b of the advance pilot tunnel and the influence index, the rear pilot tunnel is taken as the benchmark, and the adjacent advance pilot tunnel with different width is established respectively. The width of the advance pilot tunnel is 0.25 times, 0.5 times, 0.75 times, and 1 time of the width of the rear pilot tunnel respectively. The section form of the rear pilot tunnel is a straight wall tunnel section with a span of 10 m and a height of 15 m. The spacing between the two pilot tunnels is 0, and the middle value of IV-class surrounding rock with a buried depth of 50m is taken as the calculation model, as shown in Figure 2.

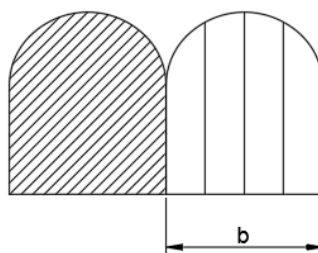


Figure 2. Schematic diagram of the influence of different widths on the excavation process of adjacent pilot tunnels.

According to the calculation method of pressure arch theory, the pressure of the surrounding strata of the rear pilot tunnel in Figure 2 calculation model was calculated. Compared with the pressure of the surrounding strata of a single-hole tunnel under the same condition, as shown in Table 2.

Table 2. Comparison of the pressure of the surrounding strata between the rear pilot tunnel and single-hole tunnel under different widths of advanced pilot tunnels.

Width of advance pilot tunnels	1 times the height of the rear pilot tunnel	0.75 times the height of the rear pilot tunnel	0.5 times the height of the rear pilot tunnel	0.25 times the height of the rear pilot tunnel
The pressure of the surrounding strata affected by the pilot tunnel /kPa	169.20	157.37	143.17	130.15
The pressure of the surrounding strata of single hole tunnel /kPa	118.32	118.32	118.32	118.32
Impact indicator η_2	1.43	1.33	1.21	1.10

According to Table 2, when the excavation width of the advance pilot tunnel is less than 1 times that of the rear one, the pressure of the surrounding strata increases with the augment of the width, and the influence coefficient index is 1.10-1.43. According to the data listed in Table 2, the relationship between η_2 and the ratio y of the width of the advance and rear pilot tunnel can be fitted out:

$$\eta_2 = 0.444y + 0.99 \quad R^2 = 0.9989 \quad (6)$$

In the formula, y is the ratio of the excavation width of the advance pilot tunnel to that of the rear pilot tunnel; η_2 is the index of the influence of the ratio of the excavation width of the advance pilot tunnel to that of the rear pilot tunnel on the pressure of the surrounding strata of the rear pilot tunnel.

3.3. Influence of ratio of horizontal distance and span of the successive pilot tunnel to η_3

To study the relationship between the distance d of the advance pilot tunnel and the rear pilot tunnel and the influence index η_3 , the rear pilot tunnel is taken as the benchmark, and the adjacent advance pilot tunnel of different horizontal distances are established respectively. The horizontal distance between the two is 1 time, 1.25 times, 1.5 times, and 2 times the width b of the rear pilot tunnel respectively. The section form of the rear pilot tunnel is a straight wall tunnel section with a span of 10 m and a height of 15m, and the middle value of IV-class surrounding rock with a buried depth of 50 m is taken as the calculation model, as shown in Figure 3.

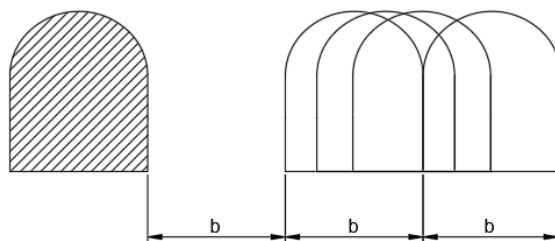


Figure 3. Schematic diagram of the influence of different horizontal distances on the construction process.

According to the calculation method of pressure arch theory, the pressure of the surrounding strata of the rear pilot tunnel in the above calculation model is calculated. Compared with the pressure of the

surrounding strata of a single-hole tunnel under the same condition, the calculated results are shown in Table 3.

Table 3. Comparison of the pressure of the surrounding strata under different horizontal distances of the pilot tunnel.

Horizontal distances of the pilot tunnel	2 times the width of the rear pilot tunnel	1.5 times the width of the rear pilot tunnel	1.25 times the width of the rear pilot tunnel	1 times the width of the rear pilot tunnel
The pressure of the surrounding strata affected by the pilot tunnel /kPa	121.87	126.60	133.70	139.62
The pressure of the surrounding strata of single hole tunnel /kPa	118.32	118.32	118.32	118.32
Impact indicator η_3	1.03	1.07	1.13	1.18

According to table 3, with the increase of the spacing, the influence factors caused by the horizontal distance are gradually smaller. When the horizontal distance is too large, the influence caused by the distance will become weaker and ends up being almost non-existent. However, it is also found that if the excavation distance is too small, the rock mass between the pilot tunnels will not remain stable without support. If there is no horizontal distance between the two pilot tunnels which means they are closely excavated, it is considered that $\eta_3 = 1$. According to the data listed in Table 3, the relationship between η_3 and the ratio z of the horizontal distance of the advance and rear pilot tunnel and the span of the rear pilot tunnel can be fitted out:

$$\eta_3 = -0.150z + 1.318 \quad R^2 = 0.9375 \quad (7)$$

In the formula, z is the ratio of the horizontal distance of the advance and the rear pilot tunnel to the span of the rear pilot tunnel. η_3 is the influence index of the ratio of the horizontal distance of the advance and the rear pilot tunnel to the span of the rear pilot tunnel on the pressure of the surrounding strata of the rear pilot.

4. Calculation method and application of the pressure of the surrounding strata in Metro Station Tunnel

Formula (2) only represents the pressure of the surrounding strata of each pilot tunnel, rather than the strata pressure of the whole subway station tunnel. And the distribution of the above pressure of the surrounding strata is uneven, which is unsuitable to the design of engineering support structure. To get a reasonable load of the subway station tunnel, it is necessary to normalize the load value of each pilot tunnel, and then the uniform load is obtained, so the weight coefficient λ is introduced. The ratio of the pressure of the surrounding strata of each pilot tunnel to the total strata pressure of the station tunnel is the weight coefficient λ of the pilot tunnel, which is less than 1. The calculation formula is as follows:

$$\begin{cases} \lambda_i = \frac{S_i}{S_T} \\ S_i = \alpha_{ij} p_i b_i \\ S_T = \sum S_i \end{cases} \quad (8)$$

In the formula, λ_i is the weight coefficient of the i -th pilot tunnel; S_i is the total roof load of the single pilot tunnel; S_T is the total roof load of all pilot tunnel; b_i is the width of the i -th pilot tunnel; the rest is the same as the above.

After the weight coefficient of each pilot tunnel is obtained, the overall pressure of the surrounding strata of the tunnel can be obtained. Firstly, the surrounding strata pressure p_i of each pilot tunnel is calculated according to the pressure arch theory; secondly, the influence coefficient α_{ij} of each pilot, the tunnel is calculated to get the pressure of the surrounding strata $\alpha_{ij}p_i$ concerning the construction process; finally, the pressure of the surrounding strata of different pilot tunnels is normalized and the weight coefficient is introduced to obtain the strata pressure calculation formula of the whole large-section metro station tunnel.

$$p_0 = \sum \lambda_i \cdot \alpha_{ij} \cdot p_i \quad (9)$$

In this formula, p_0 is the pressure of the surrounding strata of a large-section subway station tunnel; λ_i is the weight coefficient of a single pilot tunnel; α_{ij} is the influence coefficient of each pilot tunnel; p_i is the pressure of the surrounding strata of each pilot tunnel.

The subway station of Chongqing rail transit underground excavation was chosen for investigation and examination. The tunnel span and the buried depth of the station were 23.30 m and 35 m, and the class of the surrounding strata was IV. The construction of the station adopts the double side wall pilot pit method. The core rock was arc-shaped, with a minimum thickness of 6.90m and the width of heading on both sides is 8.20 m. The construction steps are depicted in Figure 4. When computing the pressure of the surrounding strata that is affected by the excavation process, the section of the tunnel was simplified, as depicted in Figure 5.

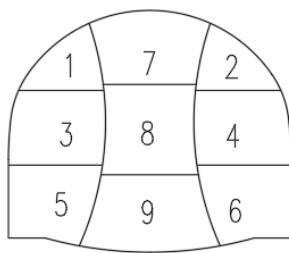


Figure 4. Construction steps of the station.

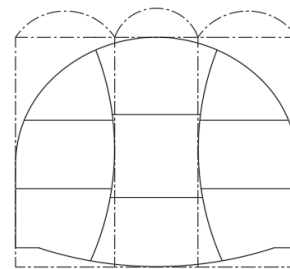


Figure 5. The simplified model.

1) By substituting the gravity of rock mass γ , tunnel span B , buried depth H , and internal friction angle φ of the selected station into the equation (4), the value of the pressure of the surrounding strata of three pilot tunnels could be acquired, $p_1 = p_2 = 128.27kPa$, the pressure of the surrounding strata of the middle pilot tunnel was $p_3 = 119.95kPa$.

2) According to formula (5) ~ (7), the influence coefficient α_1 of the excavation of the left pilot tunnel (the advance pilot tunnel) was obtained, $\alpha_1 = 1$, the influence coefficient α_2 of the excavation of the right pilot tunnel was obtained, $\alpha_2 = \eta_1 \cdot \eta_2 \cdot \eta_3 = 1.39 \times 1.43 \times 1.18 = 2.34$, and the influence coefficient α_3 of the middle pilot tunnel was obtained,

$$\alpha_3 = \eta_1 \cdot \eta_2 \cdot \eta_3 = 1.39 \times 1.43 \times 1 = 1.98.$$

3) According to formula (8), the roof loads of three pilot tunnels were obtained. The left $S_1 = \alpha_1 \cdot p_1 \cdot b_1 = 1051.82 \text{ kN/m}$, the right $S_2 = \alpha_2 \cdot p_2 \cdot b_2 = 1655.31 \text{ kN/m}$, and the middle $S_3 = \alpha_3 \cdot p_3 \cdot b_3 = 2056.07 \text{ kN/m}$; therefore, the total roof load of the three pilot tunnels were $S_T = 4763.20 \text{ kN/m}$. Then the load weight coefficients of the three pilot tunnels were $\lambda_1 = 0.22$, $\lambda_2 = 0.35$, $\lambda_3 = 0.43$ respectively.

4) According to formula (9), the pressure of the surrounding strata of metro station constructed by the double side wall heading method was obtained: $p_0 = \sum \lambda_i \cdot \alpha_{ij} \cdot p_i = 219.92 \text{ kN/m}^2$.

5. Conclusion

Based on the excavation process of the large section tunnel, the large section tunnel is simplified into three parts. Based on a large number of numerical analyses, the influence of the excavation height, width of the advance pilot tunnel, and the distance between the advance pilot tunnel and the rear pilot tunnel on the compute of the pressure of the surrounding strata is studied. The regression equation of the factors affecting the calculation of the pressure of the surrounding strata is established, and the calculation formula of the pressure of the surrounding strata of the large section tunnel is derived. The calculation formula is applied to the compute of the pressure of the surrounding strata of the large section underground excavation subway station, which provides the basis for the calculation of the pressure of the surrounding strata of the tunnel with a large section.

Acknowledgments

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