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Research Paper

STUDY ON DISTRIBUTION RANGE OF SURROUNDING ROCK RESISTANCE IN TUNNEL

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The surrounding rock resistance is one of the principal loads of structural design for tunnel. The determination of the distribution of resisting force will influence the calculation results of the structure, and the determination of the range of resisting force in tunnel will also influence internal force calculation and structure design. Accordingly, based on elastic-plastic theory, the range of resisting force of surrounding rock of all levels in tunnel were studied by the uncertainty analysis method. The results indicate that the range of resisting force of surrounding rock diminishes gradually with downgrading of surrounding rock. When the grade of surrounding rock reaches V and VI, the resisting force will not in existence in tunnel. Under such circumstance, the resisting force of surrounding rock will be not be considered in the internal force calculation and structure design. This conclusion will provide reference for underground engineering design and construction.

Keywords: Surrounding rock, Resisting force, Interval analysis, Tunnel

INTRODUCTION

The design of underground cavity generally refer to *Code for Design of Road Tunnel* (JTG D70–2004) in China. Accordingly, "the loading structure method is applied to the designs of integrated lining structure tunnel, integrated or composite lining in shallow-buried tunnel, lining in open cut tunnel and Song *et al.*, (2013). The determination of lining loads is important for loading structure method, which includes pressure and resistance of surrounding rock. The surrounding rock resistance refers to the capacity of surrounding rock to share the load with the lining, reflecting the physical and mechanical properties of surrounding rock. It is one of the important parameters for the design of tunnel lining (Zhu *et al.,* 2011). For years the Buckeye method is usually adopted in the analysis of distributing characteristics of surrounding rock resistance, which, however, is unable to reflect all the relevant factors, and the error of calculation results is large (Yun *et al.*, 2013).

The calculation of surrounding rock resistance will influence the design of underground cavity, internal force calculation

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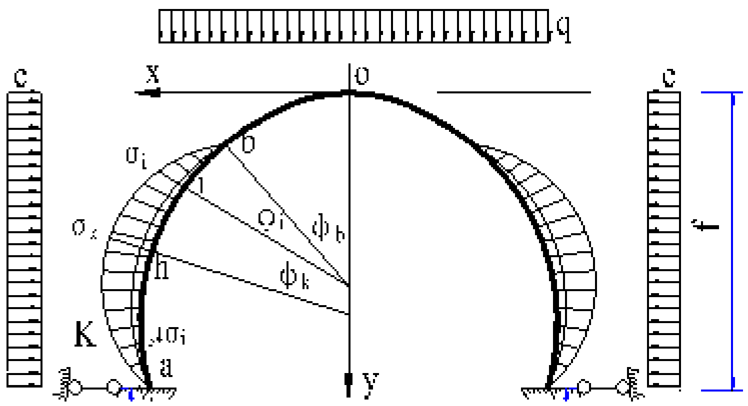
and structural stability analysis, therefore, the relevant research has attracted attention from the experts all over the world. For example, the distributing characteristics of surrounding rock resistance in unsymmetrical loading tunnel were discussed, and its distributing law was obtained (Qin *et al.*, 1964); the upper zero point determination method of elastic resistance was studied in vertical wall tunnel, the key idea of which is to replace elastic resistance with elastic bar. This study, however, includes complicated calculations, and the results are not in accordance with the local deformation theory (Fan *et al.*, 1962). Lu *et al.*, studied the characteristics of the lining section of single track railway tunnel that can attain a speed of 200 km per hour, and analyzed the influence of elastic resistance coefficient of surrounding rock on safety coefficient and bend moment (Lu *et al.*, 2009). Li *et al.*, analyzed the influence of elastic resistance coefficient on axial force and bending moment of vault and arch bottom (Li *et al.*, 2010). These research results provide guidance for tunnel design and construction. However, because the factors influencing the surrounding resistance are various, including the surrounding rock resistance coefficient, the stiffness, shape and size of lining structure, the magnitude of load and its combination, as well as the support time of lining structure. Moreover, the different geological environment might influence the distribution of surrounding rock resistance, which is important for the stability of underground structure and should be taken into consideration for design. To analyze this, based on the elastic-plastic theory, the distribution range of surrounding rock resistance is determined by uncertain analysis method, which can provide a new method for internal force calculation and design of underground structure.

DETERMINATION OF SURROUNDING ROCK RESISTANCE AND ITS DISTRIBUTION RANGE

Through quantitative experiments and detailed in-site monitoring analysis, the research shows that the surrounding rock not only apply pressure on the lining but also restrain the deformation of lining in the force-deformation process of the underground structure, which results in part of the structure separated from surrounding rock into the unbound regions and part of the structure pushed onto the surrounding rock into the resistance regions. In the resistance regions, the surrounding rock will create constraint reaction, and that is the surrounding rock resistance. In generally, the distribution range will be determined by three important points according to the structural deformation feature (Figure 1) (Qin *et al.*, 2013). The intersection angle between upper zero point of elastic resistance and vertical symmetrical centerline is about 40° to 60°. The lower zero point of elastic resistance is located at the foot of the wall, where the friction is so great that there is no any horizontal displacement, and the value of elastic resistance is zero. The maximal resistance point is supposed to exist at around the greatest span of the arch, and usually take $ah \approx \frac{2}{3}ab$ when calculating.

Above is the method to determine the value and distribution range of surrounding rock resistance in structure design. The distribution

Figure 1: Distribution Range of Surrounding Rock Resistance



range of surrounding rock resistance is determined through three important points, which, to some extent, can not reflect the influences of the lining stiffness and size, feature of load, lateral pressure coefficient and elastic resistance coefficient. Therefore, the distribution range of surrounding rock resistance needs further research to provide technical reference for the internal force calculation and structural design of underground chamber.

DETERMINATION OF DISTRIBUTION RANGE OF SURROUNDING ROCK RESISTANCE

Principles of Determining Surrounding Rock Resistance

To simplify the analysis, there are five assumptions as follows (Xia *et al.*,2004; Qin *et al.*, 2013): (1) the surrounding rocks are supposed to be the homogeneous and isotropic continuous medium; (2) the shape of underground chamber is regarded as circular with a radius of r_i; (3) the underground chamber is at a certain depth and is simplified into a hole problem in infinite body; (4) the three dimensional stress problem is simplified into plane strain problem, and the end effect of excavation surface is not considered in construction of underground chamber; (5) the initial stress field is shown by lateral pressure coefficient λ, that is (σ_z, $\lambda\sigma_z$, where σ_z is the vertical stress.

According to the assumptions above and elastic-plastic theory, after the tunnel was excavated, the radial displacement formula of circular tunnel can be obtained with different lateral pressure coefficient (Xia *et al.*, 2004), which is described in formula (1).

$$u_r = \frac{(1+\mu)\cdot(\sigma_z r_i)}{2E}$$

$$[(1+\lambda)-(3-4\mu)(1-\lambda)\cos 2\theta] \quad ...(1)$$

where, *E*, μ are the elastic modulus and Poisson's ratio of surrounding rock respectively.

Based on formula (1), the radial displacement of circular tunnel is related to the initial stress field (σ_z, $\lambda\sigma_z$) elastic modulus *E*, Poisson's ratio and the location of calculation point. Under given initial stress field, the excavation of tunnel might result in outward expansion of surrounding rock in a certain range. If the surrounding rock expansion is restrained, the surrounding rock resistance will be created.

Assuming the displacement of surrounding rock towards the tunnel is positive, and that towards the rock is negative, the deformation direction of the surrounding rock can help determine the value and range of the resistance, therefore, according to formula (1) the following conclusion can be obtained.

When $u_r > 0$, the surrounding rock is displaced towards tunnel and the unbound region is formed. According to formula (1), formula (2) can be obtained.

$$(1+\lambda)-(3-4\mu)(1-\lambda)\cos 2\theta > 0$$

or $$\cos 2\theta > \frac{1+\lambda}{(3-4\mu)(1-\lambda)} \qquad ...(2)$$

When $u_r > 0$, the surrounding rock is displaced towards parent rock and the resistance region is formed, where the surrounding rock resistance will be created. According to formula (1), formula (3) can be obtained.

$$(1+\lambda)-(3-4\mu)(1-\lambda)\cos 2\theta < 0$$

or $$\cos 2\theta > \frac{1+\lambda}{(3-4\mu)(1-\lambda)} \qquad ...(3)$$

When $u_r = 0$, the surrounding rock displacement is zero, which is the separation between the unbound region and the resistance region. According to formula (1), formula (4) can be obtained.

$$\cos 2\theta = \frac{1+\lambda}{(3-4\mu)(1-\lambda)} \qquad ...(4)$$

Determination of Distribution Range of Surrounding Rock Resistance

Determination of Poisson's Ratio and Lateral Pressure Coefficient

In the process of underground chamber excavation, the surrounding rock stress is gradually changing, which will cause the change of the values of Poisson's ratio μ and lateral pressure coefficient λ. Based on *Code for Design of Road Tunnel* (JTG D70-2004) in China, the values of Poisson's ratio of surrounding rock of all levels are shown in Table 1, and the values of lateral pressure coefficient of surrounding rock of all levels are shown in Table 2.

Table 1: Normal Values of Poisson's Ratio of Surrounding Rock of All Levels

Surrounding Rock Grade	I	II	III	IV	V	VI
Poisson's ratio	<0.20	0.20~0.25	0.25~0.30	0.30~0.35	0.35~0.45	0.40~0.45

Table 2: Lateral Pressure Coefficients of Surrounding Rock of all Levels

Surrounding Rock Grade	I, II	III	IV	V	VI
Lateral pressure coefficient	0	<0.15	0.15~0.30	0.30~0.50	0.50~1.0

According to Table 1 and 2, under the pressure of surrounding rock, the values of Poisson's ratio μ and lateral pressure coefficient λ are not constant, but vary in a variation range. Therefore, the deterministic analysis method is not supposed to be adopted, instead, the new uncertainty analysis method should be introduced in the analysis. In this paper, the interval analysis method will be adopted to determine the range of surrounding rock resistance.

Determination of the Range of Surrounding Rock Resistance

In the late 1950s Moore proposed and developed the interval analysis method (Ramon E Moore *et al.,* 2009). Based on interval mathematics and Taylor series expansion, the interval analysis method is used to deal with uncertainties. At first this method is mainly used to deal with floating point arithmetic in calculation. Later it is introduced to the analysis of engineering for it can reflect the uncertainty of parameters in engineering. In the interval arithmetic, if the same interval variable appears more than once or there are correlations between interval variables, this will lead to interval expansion of calculation results (Ramon E Moore *et al.,* 2009; Huang, 2009).

To avoid the expansion, formula (4) will be simplified as formula (5) by means of mathematical algorithms of interval analysis method.

$$\cos 2\theta = \frac{1}{3-4\mu} \cdot \frac{1+\lambda}{1-\lambda} = \frac{1}{3-4\mu} \cdot \left(1+\frac{2\lambda}{1-\lambda}\right) = \frac{1}{3-4\mu} \cdot \left(1+\frac{2}{1/\lambda - 1}\right)$$

so $$\cos 2\theta = \frac{1}{3-4\mu} \cdot \left(1+\frac{2}{1/\lambda - 1}\right) \qquad ...(5)$$

Here the typical surrounding rock of IV grade is taken for example, and the calculations of the surrounding rock of other grades can be done correspondingly. Based on Table 1 and 2, $\mu = [0.30, 0.35]$ and $\lambda = [0.15, 0.30]$ are the interval range for the surrounding rock of IV grade.

So, $$\cos 2\theta = \frac{1}{3-4[0.30, 0.35]} \cdot \left(1+\frac{2}{1/[0.15, 0.30] - 1}\right) = [0.7738, 1.5873]$$

And because $|\cos 2\theta| \le 1$,

$$\cos 2\theta = [0.7738, 1.0].$$

Accordingly, there is point with zero displacement in the surrounding rock of IV grade. That is to say, under the pressure, there are resistance regions in the surrounding rock. Take the horizontal plane with center of the circle as the symmetry axis, and only take the upper section into consideration, the range of the resistance regions in the surrounding rock of IV grade is calculated according to formula (3) and formula (4), namely, the range of the resistance regions in surrounding rock of IV grade is 0 to 19.65°.

Similarly, the range of the resistance regions of surrounding rock at other levels can be calculated. The results are shown in Table 3.

Table 3: Ranges of the Resistance Regions of Surrounding Rock of all Levels

Surrounding Rock Grade	I	II	III	IV	V	VI
cos 2θ	[0.3333,0.4545]	[0.4545,0.50]	[0.50,1.0]	[0.7738,1.0]	no zero point	no zero point
The ranges of the resistance regions	0~35.27°	0~31.48°	0~30.00°	0~19.65°	no resistance region	no resistance region

With the decline of the surrounding rock quality, the range of the resistance regions gradually diminishes under the pressure of surrounding rock. When the surrounding rock quality downgrades to V and VI, there is no resistance region in the surrounding rock. Therefore, the beneficial influence of surrounding rock resistance will not be considered in the process of the lining design and stability analysis when the grades of surrounding rock are as low as V and VI.

CONCLUSION

The surrounding rock resistance is one of the principal loads in structural design for tunnel. The range of distribution of resisting force will influence the calculation results of internal force. The determination of the reasonable range of surrounding rock resistance is important to avoid the uncertainty of assumption on resistance, and is of great importance for internal force calculation and lining design of underground structure. In this paper, based on the elastic-plastic theory and uncertain analysis method, the distribution range of surrounding rock resistance of different qualities is discussed. The results indicate that the range of the resistance regions is gradually diminished with the decline of the surrounding rock quality. When the surrounding rock quality downgrades to V and VI, there is no resistance regions in surrounding rock and therefore the beneficial influence of surrounding rock resistance will not be considered in the process of the lining design and stability analysis when the grades of surrounding rock are as low as V and VI.

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