Study on Resistance Coefficient Monitoring of Shallow Hydraulic Tunnel

YUAN Hong-hu1, Haung Shi-peng2, Wang Yu2*

1Beijing Institute of water, Beijing, 100048, China
2School of Mechanical Engineering, Xihua University
E-Mail: wangyu@mail.xhu.edu.cn (*Corresponding author)

Abstract: The acquisition of elastic resistance coefficient is crucial for the design of shallow hydraulic tunnel. In this paper, the resistance coefficient of the tunnel in the test section of the South Main Canal Project is monitored and analyzed. Considering the actual load mode of the tunnel lining, the load value acting on the lining is measured by the measurement instrument on the spot, and the elastic resistance acting on the tunnel lining is obtained. The elastic resistance coefficient acting on the tunnel lining is obtained through the deformation around the tunnel on the measuring side. The research conclusions and methods can provide reference for the support design of shallow hydraulic tunnel in loose soil layer.

1. Introduction
From the perspective of the development of underground structure theory, the design calculation methods that can properly reflect the mechanical characteristics of the interaction between the underground engineering lining supporting structure and the surrounding rock generally include empirical methods, structural mechanics methods, rock mechanics methods, and information feedback methods. At present, the method widely used in actual engineering design and recommended for hydraulic tunnel structure design is mainly the structural mechanics method (load structure method).

When studying elastic resistance coefficients, scholars generally follow the local deformation theory, namely the Winkler model, to perform analytical deductions or numerical calculations through various means. On-site load plate tests on rock masses to determine resistance coefficients. Cai Xiaohong, Lv Younian (1984), etc [1] established a calculation method for the resistance coefficient K of hydraulic circular tunnel under pressure based on the test results that the deformation curve of rock mass is broken or approximately broken, and according to the similar situation of stress-deformation curve and the linear strengthening model of plasticity theory, and obtained a general calculation formula. Cai Xiaohong (1988) [2] gave the calculation formula of rock resistance coefficient of circular pressure tunnel under plastic strengthening theory, plastic softening flow theory and Mohr-Coulomb yield theory respectively. Xu Shuanqiang and Yu Maohong (2004) [3] only considered the strengthening, softening, and tensile-compression strength effects of rocks in previous research results, but did not consider the intermediate principal stress effects of rocks, and proposed the unified strength theory as the strength criterion for rocks. Tu Zhongren (2004) [4] derived the calculation formula of surrounding rock resistance coefficient based on the unified strength theory, which has the advantages of considering the influence of intermediate principal stress and modifying the parameters can be degraded to other surrounding rock conditions or other strength theory. Ma Qing, et al [5] based on the unified strength theory, the surrounding rock of roadway is regarded as porous medium, considering...
the influence of groundwater seepage, the unified formula for calculating the resistance coefficient of surrounding rock of roadway is deduced. Li Bo, et al\textsuperscript{[6]} Based on the large cross-section tunnel of Shanghai-Kunming high-speed railway, the field test of radial hydraulic pillow was carried out on five tunnels, and 20 representative tunnels were selected for theoretical calculation of surrounding rock resistance coefficient. Zhang Zhiyong, et al\textsuperscript{[7]} based on the elastic solution of circular tunnel in infinite body, combined with the displacement formula of unloading disturbed zone and deep undisturbed zone, deduced the equivalent elastic resistance coefficient expression of surrounding rock in unloading zone of cavern excavation, and verified its rationality through comparative analysis of examples. Wang Zhilong et al\textsuperscript{[8]} Based on Hoek-Brown criterion, analyzed the stress and displacement of surrounding rock with the deep circular tunnel conforming to the ideal elastic-plastic model as the research object, and then obtained the calculation formula of the resistance coefficient of surrounding rock according to the Winkler assumption.

This paper considers the actual load pattern of the tunnel lining, uses measuring instruments to measure the load value acting on the lining, and obtains the elastic resistance force acting on the tunnel lining. By measuring the deformation around the tunnel, the elasticity acting on the tunnel lining is obtained. The resistance coefficient is expected to provide a reference for the support design of shallow hydraulic tunnels in the loose soil layer.

2. Engineering Background

The South Main Canal Project of Beijing South-to-North Water Transfer Project is located in the southern part of Beijing. It is located in the Yizhuang Water Plant Adjustment Pool in the southeast of Beijing, with a total length of about 27.188km\textsuperscript{[9]}. The starting point of the test section is located at the starting point of the south main canal-two square culverts on the south side of the Yongding River inverted siphon end of the main canal on the south side of Xiaoyue Garden in Fengtai District, and the ending point is on the southeast side of the gas pressure regulating station under construction, the pipeline pile number is 0+320~0+350m. There are three gas pipelines directly above the tunnel in the test section, the pipeline pile number is 0+330m, and there is a gas pressure regulating station on the northeast side of the test section, which is about 9m away from the center line of the south main canal. The layout plan of the 2# shaft section of the test section of the south main canal is shown in Fig1.\textsuperscript{[10]} The thickness of the tunnel covering is about 6m, the inner diameter of the tunnel is 3.4m, the excavation diameter is 4.6m, parallel independent tunnels, and the tunnel axis spacing is 7.5m.

![Fig.1 The layout plan of test section 2# shaft section](image)

According to the results of geological surveying and geological drilling, the engineering area is covered by alluvial and alluvial layers of the Quaternary Holocene System within the exploration depth range.

According to the requirements of the "Test Outline for the Test Section of the South Main Canal Project of the Beijing South-to-North Water Diversion Project" and combined with the actual conditions of the project, the first line of the left line 0+320~0+350 and the right line 0+320~0+350
Construction monitoring work is carried out. The installation position of the earth pressure box is shown in Fig. 2, and the layout of the monitoring points for the settlement of the vault and the convergent displacement around the tunnel is shown in Fig. 3.

Fig. 2 Schematic diagram of the location of the earth pressure gauge

Fig. 3 The layout of monitoring points for vault subsidence and convergent displacement around the tunnel

3. Elastic Resistance Of Shallow Hydraulic Tunnel In Loose Soil

The earth pressure gauge is used to measure the load value acting on the initial support of the tunnel on the spot. The installation position of the earth pressure box is shown in Fig. 2.

After the construction of the right tunnel is completed, the pressure values of the earth pressure gauges of each branch, the earth pressures of E2-1, E2-2, E2-3, and E2-4 are respectively 8.89 KPa, 5.37 KPa, 8.86 KPa, and 13.60 KPa. Since the earth pressure gauge measures the load value acting on the initial support of the tunnel, the earth pressure value is the elastic resistance of the tunnel. The distribution law of the elastic resistance of the tunnel with the angle is shown in Fig. 4.

Fig. 4 Distribution law of elastic resistance of 330 cross section
Taking into account the relationship between the elastic resistance and the buried depth of the tunnel, the buried depth is introduced into the calculation formula of the elastic resistance. The elastic resistance calculation formula considering the buried depth of the tunnel is:

\[ N = P_0 \left( b_1 + b_2 \sin \alpha + b_3 \sin^2 \alpha \right) \quad (1) \]

In the formula, \( N \) - elastic resistance; \( \alpha \) - angle; \( P_0 = \gamma (H + a) \); \( \gamma \) - bulk density of surrounding rock and \( \gamma = 21 \text{kN/m}^3 \); \( H \) - tunnel buried depth, 6m; \( a \) - Tunnel excavation radius, 2.3m; \( \sin \alpha = \frac{r - H}{r} \); \( \cos \alpha = x/r \).

From Fig. 4, the elastic resistance value of the key points on the cross-section can be obtained by inversion:

- \( P_0 = 8.89 \)
- \( b_1 = 0.3 \)
- \( b_2 = -0.3 \)
- \( b_3 = 1 \)

From this it can be obtained that the elastic resistance calculation formula is:

\[ N = 8.89 \left( 0.3 - 0.3 \sin \alpha + \sin^2 \alpha \right) \quad (2) \]

Comparing the elastic resistance value corresponding to each angle calculated by Equation 2 with the actual measured value, Fig. 4 shows that the elastic resistance calculation formula of the shallow hydraulic tunnel in this project can better reflect the elastic resistance distribution of the shallow hydraulic tunnel.

4. Convergent Displacement of Shallow Hydraulic Tunnel in Loose Soil

Park (2005) considered the non-uniform distribution characteristics of the elliptical displacement of the soil into the tunnel, and obtained the elastic solution of the shallow tunnel stratum deformation based on this as the boundary condition, and the obtained results are in good agreement with the measured values. Compared with Loganathan and Poulos (1998), the derivation of this method is simpler. Park (2005) summarized the convergence modes of tunnels and defined the following four convergence modes in tunnels:

![Fig. 5 The tunnel convergence mode](image)

B.C.-1: \( u_r (r = a) = -u_0 \)
B.C.-2: \( u_r (r = a) = -u_0 (1 + \sin \alpha) \)
B.C.-3: \( u_r (r = a) = -u_0 (1 + \sin \alpha - \frac{1}{2} \cos^2 \alpha) \)
B.C.-4: \( u_r (r = a) = -\frac{u_0}{4} (5 + 3 \sin \alpha - 3 \cos^2 \alpha) \)
In this formulas, \( \sin \alpha = -(z - H) / r \); \( \cos \alpha = x / r \).

In this formulas \( u_0 \):

1) Elastic solution \( u_0 = \frac{a}{2G}(P_a - P_i) \) (Thick-walled tube whose outer boundary tends to infinity and inner boundary \( a \))

2) Elastoplastic solution
\[
\begin{align*}
\frac{\sin \phi}{2G} & (P_a + c \cot \phi) R^2 \quad \text{(Assuming constant volume of plastic zone)}
\end{align*}
\]

3) Elastoplastic solution
\[
\begin{align*}
& u_0 = \frac{p_0 + c \cot \phi}{2G} (1 - 2\mu) \left[ 1 + \frac{\sin \phi}{1 - 2\mu} \left( \frac{r_p}{a} \right)^{1+n} \right] \left[ \frac{r_p}{1 - \sin \phi} \sin \phi \right] - \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
\end{align*}
\]

4) Elastoplastic solution
\[
\begin{align*}
& u_0 = \frac{a}{2G} \left[ 1 + \frac{\sin \theta (P_0 + c \cot \theta)}{(1 - 2\mu) c \cot \theta} \left( \frac{R}{a} \right)^{1+m} \right] \left[ \frac{r_p}{1 - \sin \theta \sin \phi} \right] - \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
& \left( \frac{r_p}{a} \right)^{k+n} \left( \frac{r_p}{a} \right) \left( \frac{r_p}{a} \right) - 1 \\
\end{align*}
\]

5) Definite solution \( u_0 = \frac{g}{2} \) (Park, 2005)

Figure 3 shows the layout of monitoring points for vault subsidence and convergent displacement around the tunnel. After the construction of the right tunnel is completed, the vertical displacement of the vault of the right tunnel of the 330 cross section is -0.43mm, and the horizontal convergence displacement of the upper line is -0.42mm. The horizontal convergence displacement of the lower line is -0.45mm. The distribution law of tunnel convergent displacement with angle is show in Fig.6

Fig.6 Convergent Displacement Distribution Law of 330 Cross Section Tunnel

Taking into account the relationship between tunnel convergent displacement and tunnel buried depth and surrounding rock parameters, the tunnel buried depth and surrounding rock parameters are introduced into the calculation formula of tunnel convergent displacement. Drawing on the four convergence modes of the Park (2005) tunnel, the calculation formula of the tunnel convergence displacement considering the buried depth of the tunnel and the surrounding rock parameters is:
In this formula, $U$ - Displacement; $\alpha$ - Angle; $u_0$ - Take the fourth type, considering the elastic-plastic convergence displacement,

$$u_b = \frac{a}{2G} \left[ (1-2\mu)\cot \theta \left[ \left( \frac{1}{1-2\mu} \cot \theta \left( \frac{R}{a} \right)^{1-\mu} \right)^{1-\mu} - 1 \right] \left( \frac{P_0 + c \cot \theta (1-2\mu + \sin \theta \sin \varphi)}{1-\sin \theta \sin \varphi} \right) \left( \frac{R}{a} \right)^{1-\mu} - 1 \right]$$

$$R = \frac{a}{2} \left[ \left( \frac{P_0 + c \cot \theta (1-\sin \theta)}{P_1 + c \cot \theta} \right)^{\frac{1-\sin \theta}{2\sin \theta}} \right];$$

$$G = \frac{E}{2(1+\mu)}; \quad k = \frac{1+\sin \theta}{1-\sin \theta}; \quad m = \frac{1+\sin \varphi}{1-\sin \varphi}; \quad P_0 = \gamma(H+a) = 21\times8.3 = 174.3\, \text{KPa}; \quad P_1 = 0;$$

$$\sin \alpha = -\left( \frac{z-H}{r} \right) / r; \quad \cos \alpha = x / r;$$

$\gamma$ - Bulk density of surrounding rock, $\gamma = 21\, \text{kN/m}^3$; $H$ - Tunnel buried depth, 6m; $a$ - Tunnel excavation radius, 2.3m.

From Fig.6, the displacement values of key points on the cross section are inverted to obtain:

$$u_0w = -0.21; \quad a_1 = 1; \quad a_2 = \frac{1}{3}; \quad a_3 = \frac{2}{3};$$

Therefore, the formula for calculating the convergent displacement of the right hole of the 330 cross section is:

$$U = -0.21 \ast (1 + \frac{1}{3} \sin \alpha + \frac{2}{3} \sin^2 \alpha)$$

Comparing the displacement value corresponding to each angle calculated by equation 4 with the actual measured value, Fig. 6 shows that the calculation formula for the convergence displacement of the shallow hydraulic tunnel assumed in this paper can better reflect the deformation of the shallow hydraulic tunnel.

5. Research on Elastic Resistance Coefficient of Shallow Hydraulic Tunnel

Assumed by Winkler, the elastic resistance coefficient:

$$K = \frac{P}{U}$$

It can be seen from formula 5 that the elastic resistance calculation formula 1 of shallow hydraulic tunnels and the calculation formula 3 of the convergent displacement around the tunnel can be obtained by the generation of elastic resistance coefficient calculation formula 5. The formula for calculating the elastic resistance coefficient of a shallow hydraulic tunnel considering the buried depth of the tunnel and the parameters of the surrounding rock is:

$$R^N = \left( \frac{P_0s + b_1 \sin \alpha + b_2 \sin \alpha \ast \sin \alpha}{U_0w(a_1 + a_2 \sin \alpha + a_3 \sin \alpha \ast \sin \alpha)} \right)$$

In the formula, $N$- Elastic resistance; $U$- Convergence displacement; $P_0s = 8.89; b_1 = 0.3; b_2 = -0.3; b_3 = 1; P_0 = \gamma(H+a); \sin \alpha = -\left( \frac{z-H}{r} \right) / r; \cos \alpha = x / r; u_0w = -0.21; a_1 = 1; a_2 = \frac{1}{3}; a_3 = \frac{2}{3}.$

The elastic resistance coefficient calculation formula 2 and the convergent displacement calculation formula 4 of the shallow hydraulic tunnel are replaced by the elastic resistance coefficient calculation formula 5. The calculation formula for the elastic resistance coefficient of the shallow hydraulic tunnel considering the tunnel depth and surrounding rock parameters is as follows:
8.89*(0.3 0.3*sin sin *sin )R= = 12-0.21*(1 sin sin *sin )33

In the formula, N-Elastic resistance; U- Convergence displacement.

6. Conclusion
In this paper, the monitoring and analysis of the resistance coefficient of the tunnel in the test section of the southern main canal project is carried out, and the calculation formula for the elastic resistance coefficient of the shallow hydraulic tunnel in the loose soil layer is established. The conclusions can be drawn from the above analysis as follows:

(1) Considering the actual load mode of the tunnel lining, using measuring instruments to measure the load value acting on the lining on the spot, the elastic resistance acting on the tunnel lining is obtained, and the calculation formula of shallow buried elastic resistance considering the buried depth of the tunnel is obtained by inversion.

(2) By measuring the deformation around the side tunnel, the calculation formula for the convergent displacement of the shallow tunnel considering the buried depth of the tunnel and the surrounding rock parameters is obtained by inversion.

(3) Substituting the formula for calculating the elastic resistance of shallow hydraulic tunnels and the formula for calculating the convergent displacement around the tunnel to the formula for calculating the coefficient of elastic resistance, the formula for calculating the coefficient of elastic resistance of the shallow hydraulic tunnel considering the tunnel depth and surrounding rock parameters is obtained, in order to provide a reference for the support design of shallow hydraulic tunnels in the loose soil layer.

References
[1] Cai Xiaohong, Lu Younian. Applying plastic strengthening theory to calculate rock resistance coefficient K of circular pressure tunnel[J]. Chinese Journal of Geotechnical Engineering, 1984(03): 44-56.
[2] Cai Xiaohong. Theory and calculation of rock resistance coefficient K of circular pressure tunnel[J]. Engineering Mechanics, 1988(03): 100-108.
[3] Xu Shuanqiang, Yu Maohong. Calculation of tunnel rock resistance coefficient considering the effect of intermediate principal stress[J]. Chinese Journal of Rock Mechanics and Engineering, 2004(S1): 4303-4305.
[4] Tu Zhongren. Calculation of resistance coefficient of surrounding rock of highway tunnel based on unified strength theory[J]. Journal of Chongqing Jiaotong University, 2006(01): 27-30.
[5] Ma Qing, Zhao Junhai, Wei Xueying. Research on resistance coefficient of roadway surrounding rock based on unified strength theory[J]. Rock and Soil Mechanics, 2009, 30(11): 3393-3398.
[6] Li Bo, Wu Li, Deng Zongwei, Chen Jian, Tang Aisong. Field test and theoretical study on resistance coefficient of surrounding rock of high-speed railway tunnel[J]. Rock and Soil Mechanics, 2015, 36(02): 532-540.
[7] Zhang Zhiyong, Zhuo Li, Xiao Mingli, Xie Hongqiang. Research on the equivalent elastic resistance coefficient of the surrounding rock of the tunnel and its influencing factors[J]. Journal of Yangtze River Scientific Research Institute, 2017, 34(09): 86-90.
[8] Wang Zhilong, Zhou Renqiang, Yang Nie, Wang Niannian, Liu Dagang. Calculation method and engineering application of tunnel surrounding rock resistance coefficient based on Hoek-Brown criterion[J]. Modern Tunnelling Technology, 2020, 57(05): 84-90.
[9] Beijing Institute of Water Conservancy Planning and Design. Preliminary Design Report of the South Main Canal Project of Beijing South-to-North Water Diversion Project[R]. Beijing: Beijing Institute of Water Resources Planning and Design, 2009.
[10] Beijing Institute of Water Resources Planning and Design. Supporting technology and
surrounding rock deformation laws of hydraulic tunnels in the loose soil layer of the test section of the southern main canal project of the Beijing South-to-North Water Diversion Project [R]. Beijing: Beijing Institute of Water Resources Planning and Design, 2010.