Analysis and Calculation of Lining Water Pressure of High Water Pressure Karst Tunnel

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Abstract. Karst stratum is one of the most difficult geological conditions encountered in the process of tunnel construction. In addition to the risk of water and mud gushing during construction, there are also diseases such as leakage and cracking of lining structure caused by high water pressure. Based on the new Yuanliangshan tunnel project, this paper uses the analytical calculation method to study the influence of the change of tunnel seepage and water pressure on the water pressure behind the lining during the construction process, and draws a conclusion: increasing the thickness of the grouting ring and reducing the permeability coefficient of the grouting ring can reduce the seepage volume of the tunnel, and then reduce the water head behind the lining. The tunnel drainage and the water pressure behind the lining are linearly negative correlated. Based on the above study, it is suggested that the new Yuanliangshan tunnel adopt the grouting scheme of water blocking and drainage limiting to deal with the high water pressure in karst stratum. The thickness of grouting ring is 5m, which has the best water blocking effect and economic benefit, and can ensure the water pressure behind the lining is within its bearing range.

1. Introduction
In the karst stratum, especially in the section with rich groundwater and high water pressure, the construction of tunnel often encounters the problem of mud inrush and water gushing, which leads to the leakage and cracking of lining structure, and seriously affects the safety of tunnel operation. A large part of the reason is the imbalance and irregularity of karst development, which makes the tunnel lining inadequate in the design of water pressure resistance. For this reason, scholars at home and abroad have done a lot of research on the external water pressure of high-pressure tunnel lining: foreign scholar Harr[1] has obtained the seepage field distribution of deep buried high-head tunnel by using analytical method; Dimitrios kolymbas[2] has derived the calculation formula of tunnel water inflow and lining water pressure under the condition of stable seepage; Jin hung Hwang[3] has proposed a semi theoretical analysis method for calculating seepage; ahmad Fahimifar[4] studied the calculation formula of lining water pressure and lining stress. In China, Zhang Youtian[5] proposed the analytical solution under the
combined action of seepage stress, and thought that the water load is the seepage physical force, not the boundary force; Wu Gang\cite{6} compared various analytical solutions with numerical solutions, and proved the reliability of the analytical solution; Wang Jianyu\cite{7} deduced the distribution of pore water pressure under the condition of stable seepage based on the simplified axisymmetric situation; Zou Jinfeng\cite{8} obtained the elastic-plastic non-linear of tunnel Linear analytical solution. Gao Xinqiang\cite{9} studied the suitable mathematical model of groundwater seepage field in fracture medium. In this paper, based on the new Yuanliangshan tunnel project, on the basis of previous research, the change of tunnel seepage and water pressure in the construction process is considered, and the analytic method is used to calculate the water pressure behind the tunnel lining in the high water pressure section of karst stratum, which provides theoretical basis for the design of grouting parameters and lining scheme.

The new Yuanliangshan tunnel is a second-line tunnel project, which is built through the existing horizontal guide expansion of Yuanliangshan tunnel of Chongqing Huaihua line I. The tunnel passes through Maoba syncline and tongmaling anticline with complex geology. There are 5 high-pressure water rich karst caves, including 3 in Maoba syncline section (the karst caves are located in the boat type catchment area of Maoba syncline, with the distance of 1 karst cavity 2842m, 55m; the distance of 2 karst cavities 3060m, 70m; the distance of 3 karst cavities The cavity is 3472m away from the inlet, 50m long). The water rich area is 2200m long. The groundwater is mainly fissure karst water, followed by bedrock fissure water, and there is a small amount of pore water distribution in loose rock stratum, with the highest water pressure of 4.6mpa.

2. Analytical calculation method for water pressure behind tunnel lining

According to the law of conservation of mass, the continuity equation of groundwater in porous rock mass is:

$$\rho \left[ \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) \right] + W = \frac{\partial}{\partial t}(\rho n)$$  \hspace{1cm} (1)

Formula: $\rho$ -liquid density(kg/m$^3$); $v_x, v_y, v_z$ -components of groundwater seepage velocity vector; $n$ -porosity; $W$ - source flow of water.

In order to obtain the formula for calculating the water pressure behind the tunnel lining, the following assumptions are made: 1. underground water seepage in tunnel obeys Darcy’s law(formula (2)); 2. regardless of the compressibility of water and rock mass skeletons, and the motion elements do not change with time (steady flow), the right side of formula (1) is 0; 3. no water supply or excretion $W = 0$; 4. the surrounding rock is an isotropic medium($k_x=k_y=k_z$).

$$\begin{cases} v_x = -k_x J_x = -k_x \frac{\partial H}{\partial x} \\ v_y = -k_y J_y = -k_y \frac{\partial H}{\partial y} \\ v_z = -k_z J_z = -k_z \frac{\partial H}{\partial z} \end{cases}$$ \hspace{1cm} (2)

Substituting Darcy’s Law (2) into (1) to obtain the differential equation of steady motion of groundwater in a homogeneous isotropic confined aquifer (3).

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = 0$$ \hspace{1cm} (3)

Zheng Bo and Wang Jianyu\cite{10} pointed out that the influence of the tunnel section shape on the lining water pressure reduction coefficient is small and can be ignored. The lining water pressure is mainly determined by the ratio of the permeability coefficient of the lining to the surrounding rock. In this paper, the tunnel lining is assumed to be circular for axisymmetric analysis and calculation (Fig. 1), simplifying the complex problems.
In Figure 1: P_r-Water pressure on surrounding rock surface; P_g-Water pressure on outer surface of grouting ring; P_l-Water pressure behind lining; H_r-Stable water head in far-field surrounding rock; H_g-Water head on outer surface of grouting ring; H_l-Water head behind lining; K_r-Permeability coefficient of surrounding rock; K_g-Grouting ring Permeability coefficient; K_l-lining permeability coefficient; r_r-radius of surrounding rock at far-field stable head; r_g-grouting circle radius; r_l-outer lining radius; r_0-inner lining radius; Q_0-tunnel drainage.

In order to obtain the axisymmetric solution, the following idealized assumptions need to be made on the basis of the above basic assumptions: 5. tunnel drainage seeps directly from the surface of the lining, \( Q = \text{const} \ (r) \), (meaning that the flow of different cross-sections is equal regardless of radius), and the direction of the flow line is perpendicular to the direction of the tunnel axis. 6. because the height of the groundwater head is relatively large relative to the thickness of the lining, the lining penetration force can be approximately equal to the surface force acting on the lining, which takes the pore water pressure there and the water pressure around the tunnel is symmetrically distributed with respect to the tunnel axis.

According to the theory of groundwater dynamics, the seepage should meet the continuity equation (3). In order to calculate the axisymmetric solution, a cylindrical coordinate system is established, with the radial direction as the \( r \) axis and the axial direction as the \( Z \) axis.

\[
\nabla^2 H = 0 \quad (4)
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial H}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 H}{\partial \theta^2} + \frac{\partial^2 H}{\partial z^2} = 0 \quad (5)
\]

The water flow is perpendicular to the \( Z \) axis, so \( \frac{\partial H}{\partial \theta} = 0 \). Since the tunnel is axisymmetric, then \( \frac{\partial H}{\partial r} = 0 \).

It can be concluded that \( \frac{\partial H}{\partial r} = C \).

According to Darcy's law, the amount of gushing water per meter of tunnel is as follows:

\[
Q = 2\pi r K \frac{\partial H}{\partial r} \quad (6)
\]

Transformed by formula and then integrated:

\[
\int_{r_1}^{r_2} dH = \frac{Q_0}{2\pi K} \int_{r_1}^{r_2} \frac{1}{r} dr \quad (7)
\]

Introduce boundary conditions: \( r=r_0, \ H=0; \ r=r_1, \ H=H_t; \ r=r_g, \ H=H_g; \ r=r_l, \ H=H_l; \)

\[
\begin{align*}
H_t - H_l &= \frac{Q_0}{2\pi K} \ln\left( \frac{r_2}{r_0} \right) \quad (8a)
H_g - H_t &= \frac{Q_0}{2\pi K} \ln\left( \frac{r_3}{r_1} \right) \quad (8b)
H_r - H_g &= \frac{Q_0}{2\pi K} \ln\left( \frac{r_3}{r_2} \right)
\end{align*}
\]
The above formula can be used to obtain the drainage volume per meter of tunnel (9) and the water head behind the tunnel lining (10), and the water head on the outer surface of the grouting ring can be obtained (11). At present, only the water pressure at the interface of the ring layer is obtained, and the changes in the water inflow and water pressure of the tunnel during the construction process are not considered.

\[
Q_0 = \frac{2\pi H_r K_f}{\ln \frac{r_i}{r_0} + \frac{K_f}{K_g} \ln \frac{r_f}{r_i} + \frac{K_f}{K_r} \ln \frac{r_f}{r_g}} \quad (9)
\]

\[
H_r = \frac{H_c}{\ln \frac{r_f}{r_i} + \frac{K_f}{K_g} \ln \frac{r_f}{r_i} + \frac{K_f}{K_r} \ln \frac{r_f}{r_g}} \quad (10)
\]

\[
H_g = \frac{H_c \ln \left(\frac{r_f}{r_i}\right)}{\ln \frac{r_i}{r_0} + \frac{K_f}{K_g} \ln \frac{r_f}{r_i} + \frac{K_f}{K_r} \ln \frac{r_f}{r_g} + \frac{K_g}{K_r} \ln \frac{r_f}{r_g} + \ln \frac{K_g}{r_i} + \frac{K_r}{K_g} \ln \frac{r_f}{r_g} + \ln \frac{K_r}{r_g}} \quad (11)
\]

3. Analytical calculation method for water pressure behind tunnel lining

The seepage of groundwater into the tunnel is a process in which the groundwater overcomes the seepage resistance of the circle under the action of the head pressure, the groundwater flows in the pores and finally flows out from the inner interface of the tunnel lining, the water head is consumed continuously and the head pressure drops to zero when the water reaches the inner boundary of the tunnel lining. The circle layer here refers to surrounding rock, grouting circle and lining, and the seepage resistance is expressed by permeability coefficient. This kind of layer resistance can be seen from formula (9).

It can be seen from Figure 2 that for the tunnel head, the larger the far-field stable head \(H_r\), the larger the amount of gushing water, and the two are linearly related; for the permeability coefficient, the greater the permeability coefficient of the rim, the greater the gushing water; In terms of rim thickness, the smaller the permeability coefficient, the greater the rim thickness, and the smaller the amount of gushing water. The relationship between the head of the tunnel and the amount of gushing water is relatively clear, and the relationship between the latter two and the amount of gushing water is worth studying.

3.1. Seepage volume of tunnel before grouting

Substitute \(K_f = K_g = K_r\), \(r_0 = r_i\), into (5) to get the tunnel seepage volume:

\[
Q_0 = \frac{2\pi H_r K_f}{\ln \frac{r_i}{r_0} + \frac{K_f}{K_g} \ln \frac{r_f}{r_i} + \frac{K_f}{K_r} \ln \frac{r_f}{r_g}} = \frac{2\pi H_r}{K_f} \quad (12)
\]

It can be seen from the formula that the water inflow of the tunnel is only hindered by the surrounding rock. At this stage, the water inflow \(Q_0\) of the tunnel has a linear relationship with the permeability coefficient \(K_f\) of the surrounding rock and the far-field head \(H_r\).

3.2. Seepage volume of tunnel after grouting

Substitute \(K_f = K_g, r_0 = r_i\), into (9) to get the tunnel seepage volume:
From Equation 13, it can be concluded that the seepage volume of the tunnel is hindered by the surrounding rock and the grouting ring at the same time. At this stage, the seepage volume of the tunnel is related to the permeability coefficient of the surrounding rock and the grouting ring and the thickness of the grouting ring. Using Equation 13, it is possible to calculate the variation law of the tunnel seepage volume with the grouting ring thickness under different permeability coefficients ($K_g = K_e/n$).

Fig. 3 Variation of Tunnel Water Infiltration with Grouting Ring Thickness under Different Grouting Permeability Coefficients

As can be seen from the figure above:

1) As the thickness of the grouting ring increases, the amount of water seepage in the tunnel continues to decrease, but the decreasing gradient gradually decreases. Under different permeability coefficients, there is an optimal thickness of the grouting ring. After exceeding this value, the grouting reinforcement effect is weakened.

2) With the same thickness of the grouting ring, as the permeability coefficient of the grouting ring decreases, the water seepage rate of the tunnel decreases faster. In addition, with the decrease of the grouting permeability coefficient, the thickness of the optimal grouting ring is also smaller. When $n > 50$, only 2m of grouting reinforcement, the seepage volume of the tunnel is reduced from $55 \text{m}^3 / \text{d} \cdot \text{m}$ to $10 \text{m}^3 / \text{d} \cdot \text{m}$, which is reduced by about 80%.

3) For the new Yuan Liangshan tunnel project, when $K_e/K_g \geq 50$, the effect of reducing the permeability coefficient on reducing the amount of gushing water is no longer obvious. As far as the grouting thickness is concerned, when the thickness of grouting circle is $\geq 7$m, the effect of grouting on reducing water inflow is becoming weaker.

3.3. Seepage volume of tunnel after lining

After lining is applied, the seepage volume of the tunnel is calculated according to formula 14. At this stage, the amount of water seepage in the tunnel is related to the permeability coefficient of the ring, the grouting ring and the thickness of the lining. According to the literature\cite{11}, the permeability coefficient of concrete is related to the impermeability level. The impermeability level of the concrete in the water-rich area and the pressure-bearing structural section of the Maoba syncline in the New Yuan Liangshan Tunnel is not lower than P12. Check the data to get the permeability coefficient of P12 concrete, which is $0.104 \times 10^{-9}$cm/s, which is taken as $K_l = 10^{-9}$ cm/s. The thickness of the lining is calculated by taking 40cm, 80cm and 100cm. The results are shown in Table 1.

$Q_o = \frac{2\pi H_s K_r}{ln \frac{r_s}{r_0} + \frac{1}{K_g} ln \frac{r_s}{r_1} + \frac{1}{K_r} ln \frac{r_s}{r_1}}$ (13)
Table 1 Seepage volume of tunnel under different lining thickness

| Water volume (m³/d·m) | Grouting ring thickness (m) | n=1    | n=10   | n=100  |
|-----------------------|-----------------------------|--------|--------|--------|
|                       | 40cm                        | 1      | 0.025619 | 0.025611 | 0.025531 |
|                       |                              | 3      | 0.025619 | 0.025598 | 0.025390 |
|                       |                              | 5      | 0.025619 | 0.025588 | 0.025280 |
|                       | 80cm                        | 1      | 0.013668 | 0.013665 | 0.013642 |
|                       |                              | 3      | 0.013668 | 0.013662 | 0.013602 |
|                       |                              | 5      | 0.013668 | 0.013659 | 0.013570 |
|                       | 100cm                       | 1      | 0.010946 | 0.010944 | 0.010929 |
|                       |                              | 3      | 0.010946 | 0.010942 | 0.010903 |
|                       |                              | 5      | 0.010946 | 0.010940 | 0.010883 |

Different from the calculation results in Figure 3, it can be seen from the calculation results in the above table that after the lining is applied, the water seepage volume of the tunnel decreases sharply, even though the lining thickness is 40 cm and \( Q_0 = 0.0256 \) m³/d·m. It is preliminarily judged that this is because the lining has a small permeability coefficient and a large lining obstruction, that is, the lining shares the main seepage resistance, which is similar to the case of full plugging.

4. Relation between tunnel seepage volume and lining water pressure

It can be known from the above analysis that the water seepage volume of the tunnel in the burrow stage and the post-grouting stage can be accurately calculated. After the lining is applied, the tunnel will withstand a large water pressure due to its small permeability coefficient. The lining permeability coefficient is required to determine the water pressure and water seepage behind the lining. Add the latter two (formula (8)) to eliminate the lining permeability coefficient to obtain the relationship between the water head behind the lining and the gushing water volume as follows:

\[
H_l = H_r - \frac{Q_0}{2\pi} \left( \frac{1}{K_g} \ln \left( \frac{r_g}{r_r} \right) + \frac{1}{K_r} \ln \left( \frac{r_r}{r_g} \right) \right) \quad (15)
\]

According to formula 14, it can be calculated that under different thickness of grouting reinforcement circle, the change law of tunnel drainage volume and water pressure behind the lining. As shown in Figure 4:
It can be seen from Figure 4 that increasing the thickness of the grouting ring and decreasing the permeability coefficient of the lining can reduce the water pressure behind the lining. The seepage volume of the tunnel has a linear relationship with the water pressure of the lining. It is a pair of contradictions to reducing water pressure. Therefore, when designing grouting parameters, we must consider both the purpose of blocking groundwater and the lining water pressure value within a safe range.

5. Design of grouting parameters for water blocking and limiting drainage in the new Yuanliangshan tunnel

5.1. Determination of grouting parameters

According to the above research on the interaction between the water pressure behind the lining and the tunnel seepage volume, the grouting parameters can be designed according to (Figure 5) in actual engineering.

![Fig. 5 Design flow chart of grouting parameters](image-url)
5.2. The new Yuanliangshan tunnel allowable water seepage control standard

During the construction process of the existing Yuanliangshan tunnel, the ground collapsed due to the occurrence of mud gushing water and groundwater leakage occurred in the lining structure during the operation period. The new Yuanliangshan tunnel adopts the plan of flat guideway expansion along the existing line, and it is located in the same hydrogeological unit as the existing line. Through the operation of the existing line for nearly ten years, the groundwater has been fully discharged, and its landing funnel has been formed and stabilized. The collapse scope and scale have not been enlarged, the original collapse point is basically stable, and the surface spring water loss is clear. The use of the flat guide scheme is located within the scope of the already formed groundwater dropping funnel, and new collapses and new spring points will not be formed on the original basis. For new tunnels, the drainage standard of 5m³/d·m of existing tunnels can be used. Because the existing tunnel adopts the "full plugging" scheme and fails to prevent the intrusion of groundwater, the new tunnel adopts the "water blocking and drainage limiting" scheme, which is designed to prevent and drain water according to the maximum water pressure of 3MPa.

![Figure 6 Design reference drawing of grouting parameters](image)

The red area indicates the set of grouting parameters that meet the requirements. From the above figure (a), it can be seen that when the grouting ring thickness is 1m and the grouting parameter n = 100, the tunnel is completely drained, and its maximum water seepage is about 6.5m³/d·m>5m³/d·m, which does not meet environmental protection requirements. It can be seen from the above figure (d) that when n≤10, the grouting parameters are not in the red area and do not meet the environmental protection requirements. Therefore, the grouting parameters those meet the requirements are shown in Table 2.
Table 2 Summary table of grouting parameters that meet the tunnel seepage control standards

| Number | $K_r/K_g$ | Grouting ring thickness (m) | Permeability coefficient $K_g$ (cm/s) | Seepage volume (m$^3$/d/m) |
|--------|----------|----------------------------|--------------------------------------|--------------------------|
| 1      | 30       | 7                          | $1.67 \times 10^{-6}$               | 4.70                     |
| 2      | 50       | 5                          | $1.0 \times 10^{-6}$                | 3.60                     |
| 3      | 50       | 7                          | $1.0 \times 10^{-6}$                | 2.88                     |
| 4      | 100      | 3                          | $5.0 \times 10^{-7}$                | 2.70                     |
| 5      | 100      | 5                          | $5.0 \times 10^{-7}$                | 1.84                     |
| 6      | 100      | 7                          | $5.0 \times 10^{-7}$                | 1.46                     |

All the schemes in Table 2 can meet the environmental protection requirements. From a technical perspective, the #2 karst cave in the new Yuanliangshan tunnel is a fine sand layer, and the permeability coefficient can be $5.0 \times 10^{-6}$ through cement-water-glass double grouting. But it is difficult to achieve $5.0 \times 10^{-7}$, so the three sets of 4, 5, and 6 design parameters are difficult to achieve. From the economic perspective, discuss the first, second, and third cases. The thicker the grouting circle, the more grouting amount is needed, especially the outer layer grouting amount, which easily causes the problem of material waste. It can be seen from Figure 3 that when the thickness of the tunnel grouting ring is greater than or equal to 7m, the effect of reducing the gushing water volume of the lining is getting smaller and smaller, increasing the grouting thickness by 2m and only reducing it by 0.73m$^3$/d/m. Therefore, No. 2 grouting scheme is more reasonable.

5.3. Grouting scheme and grouting effect

The advanced pre-reinforcement scheme of the new Yuanliangshan tunnel is full-section advanced curtain grouting. Double-layer Φ127 large pipe shed is partially grouted radially. The grouting materials are mainly superfine cement water glass double liquid slurry, supplemented by ordinary cement water glass double liquid slurry. The mixture ratio of common cement and double liquid slurry is water: Cement = 0.8:1, the mixture ratio of double liquid slurry is water: Cement = 0.8:1, and the gelling time is 5 hours. The mixture ratio of two liquid slurries is cement slurry: water glass = 1:0.5, the concentration of water glass is 40 Baume degrees, and the gelling time is 35S. The actual grouting effect is shown in Figure 7.

6. Conclusions and discussion

Through the above research, we can get the following conclusion: the tunnel seepage is related to the permeability coefficient and thickness of each circle layer. Increasing the thickness of each circle layer and reducing the permeability coefficient of each circle layer can reduce the tunnel seepage. There is a linear negative correlation between water seepage and water pressure behind lining. In order to reduce the water pressure behind the lining, we can increase the thickness of the grouting circle and reduce the permeability coefficient of the grouting circle. On the premise of ensuring that the drainage of the tunnel does not harm the ecological environment, considering the safety and economy of the tunnel lining structure, the optimal grouting parameters of the new Yuanliangshan tunnel passing through the high
water pressure section are determined through the analytical calculation, and the good grouting effect is obtained through the field verification.

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