

Research Article

Grouting Design of Rich Water Tunnels and the Calculation of Distance between Annular Blind Pipes

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The rich water tunnel often uses “water blocking and drainage limiting” waterproofing and drainage systems. On the one hand, the drainage system is set behind the lining to reduce the water pressure. On the other hand, the stratum grouting is used to control the discharge flow of groundwater. In the drainage system, it is important to determine the distance between the annular blind pipes, but there is no clear calculation formula, which leads to the designer often relying on experience. First, the groundwater drainage system is constructed. Based on Darcy’s law and the law of conservation of mass, the formula for calculating the seepage discharge and the seepage pressure with the parameters of annular blind pipe spacing is derived. At the same time, the design parameters of the grouting circle are optimised, and then the formula of annular blind pipe spacing is derived according to the design value of the antiwater pressure of the secondary lining structure and the allowable seepage discharge of the tunnel. Finally, based on the case study of the Hongtu extra-long tunnel under construction, it is verified by field monitoring data. The results show that (1) grouting reinforcement is an important means to reduce water seepage, and tunnel water seepage can be adjusted by changing the thickness and permeability coefficient of the grouting reinforcement circle, in which the thickness of the reinforcement circle should not be too large, and the permeability coefficient should not be less than 1/80 of the surrounding rock permeability coefficient; (2) according to the derived formula, the water pressure of the secondary lining structure decreases in a parabolic manner from the middle of the two rows of annular blind pipes to the place where the annular blind pipes are set; (3) the allowable water seepage of the tunnel and the design value of the water pressure resistance of the lining structure should be considered when determining the distance between annular blind pipes; and (4) based on the derived formula, the distance between the annular blind pipes in the test section of the Hongtu extra-long tunnel is determined to be 8 m.

1. Introduction

For a tunnel with abundant groundwater, groundwater continuously flows into the tunnel during the whole construction process and operation period, which brings great challenges to the structure and ecological environment [1–4]. Considering factors such as structural safety and the ecological environment, the design criterion of controlled drainage is adopted mainly in the tunnels. On the one hand, the drainage system is installed at the back of the lining to reduce the water pressure. On the other hand, groundwater discharge is controlled by grouting. At this time, the

drainage and guiding system should be designed reasonably, and the thickness and permeability coefficient of the grouting circle should be determined [5–7].

The parameter design of the grouting circle has been studied extensively. Based on the complex function and seepage mechanics theory, Pan et al. [8] used conformal transformation to analyse the sensitivity of the seepage field of the deep-buried tunnel to the variation of grouting parameters. By means of laboratory model tests and numerical simulations, Yang et al. [9] studied the distribution law of water pressure inside the grouting circle and the characteristics of water pressure linkage outside the grouting circle,

inside the grouting circle, and outside the second lining. The influence of grouting reinforcement on seepage and structure was introduced in [10–12]. Liu et al. [13] deduced the distribution rule of groundwater seepage pressure and seepage flow formula by assuming that there is an isotropic radial stable seepage field around the circular tunnel. They concluded that, with the decrease in the permeability coefficient and the increase in the thickness of the reinforcement circle, the seepage pressure and seepage flow on the secondary lining decreased dramatically. When the reinforcement parameters reached the limit value, the seepage pressure and seepage flow of groundwater basically decreased, keeping the same law. He et al. [14] deduced the nonlinear analytical solution of water load based on the support system of limited drainage of the blind pipe and the water separation effect of the waterproof board. Zhang et al. [15] proposed a new concept of active control drainage design in view of the contradiction between the tunnel drainage volume and the structural water load; that is, through the active adjustment of the strength and impermeability of the surrounding rock reinforcement circle and the initial support structure, the dual control of the drainage volume and the stress of the secondary lining structure was realised.

In the above studies, the tunnel drainage system is not considered, or the support structure and drainage system are considered in a unified way, and the equivalent permeability coefficient is used instead. Then, the numerical value is retrieved by numerical simulation. In fact, the composite lining is composed of a permeable layer, a waterproof board, and a supporting structure. The waterproof board is considered to be an impermeable structure, and the seepage water is discharged mainly through the drainage system to achieve the purpose of directional drainage of the seepage water and protect the stability of the lining. Based on Darcy's law and the conservation of mass law, this paper deduces the calculation formula of tunnel water seepage and the water seepage pressure that the secondary lining structure and the waterproof board must bear, optimises the design parameters of the grouting circle, and then deduces the formula of the circular blind pipe spacing according to the design value of the secondary lining structure water pressure resistance and the allowable water discharge. Finally, based on the construction of the Hongtu extra-long tunnel case study, we go through the field monitoring data to verify.

2. Theoretical Formula Derivation

2.1. Calculation Model and Basic Assumptions. The tunnel drainage system consists mainly of a circular blind tube, a longitudinal drainage pipe, a transverse drainage pipe, a central ditch, and a geotextile behind the secondary lining structure (acting as a water guide and waterproof). We assumed that the tunnel longitudinal drainage pipe and transverse drainage pipe could quickly transport the seepage water to the tunnel drainage ditch. At the same time, we assumed that the tunnel is circular (other types of tunnel like horseshoe can be converted into a circular structure), r_0 is

the inner radius of the secondary lining structure, r_1 is the outer radius of the secondary lining structure, r_2 is the inner radius of the primary support, r_3 is the outer radius of the primary support, r_g is the outer radius of the grouting circle, and the model is shown in Figure 1.

Based on the above analysis, the following assumptions were made.

- (1) Homogeneous isotropy of surrounding rock, grouting circle, support structure, and geotextile
- (2) The tunnel is in a stable seepage state
- (3) Water flow obeys Darcy's law and is incompressible
- (4) The tunnel has a large burial depth
- (5) The water head is set at the annular blind pipe as 0

2.2. Model Solution. According to the theory of groundwater mechanics [16], a vertical shaft in an infinite aquifer is taken as an example for theoretical analysis. According to the theory of groundwater mechanics,

$$\frac{d}{dr} \left(r \frac{dh}{dr} \right) = 0, \quad (1)$$

$$p_R - p_r = \frac{\gamma_w Q}{2\pi K} \ln \frac{R}{r}, \quad (2)$$

where r and R are the radii of any two points in the distant field in the formation, K is the permeability coefficient between r and R , γ_w is the water weight, P_r and P_R are the water pressure at r and R , and Q is the amount of water seepage.

According to Section 2.1, the tunnel is in a stable seepage state and the conclusion derived from the shaft is completely suitable for the tunnel. Formula (2) was successively applied to the secondary lining structure, circular blind tube and geotextile, initial support, grouting circle, and surrounding rock, in which K_s , K_r , K_g , and K_a are, respectively, the permeability coefficient of the supporting structure (initial support and secondary lining), the surrounding rock, the grouting reinforcing circle, and the geotextile. The permeability coefficient of the waterproof plate is approximately 0, so the water flow through the waterproof plate and the second lining structure is 0. According to the measured data, the Japanese scholars believe that it is reasonable to take $2H$ as the influence radius, where H is the head of static water; thus,

$$\text{geotextile : } p_2 - p_1 = \frac{\gamma_w Q}{2\pi K_a} \ln \frac{r_2}{r_1}, \quad (3)$$

$$\text{initial support : } p_3 - p_2 = \frac{\gamma_w Q}{2\pi K_s} \ln \frac{r_3}{r_2}, \quad (4)$$

$$\text{grouting reinforcing : } p_g - p_3 = \frac{\gamma_w Q}{2\pi K_a} \ln \frac{r_g}{r_3}, \quad (5)$$

$$\text{surrounding rock : } \gamma_w H - P_g = \frac{\gamma_w Q}{2\pi K_r} \ln \frac{2H}{r_g}, \quad (6)$$

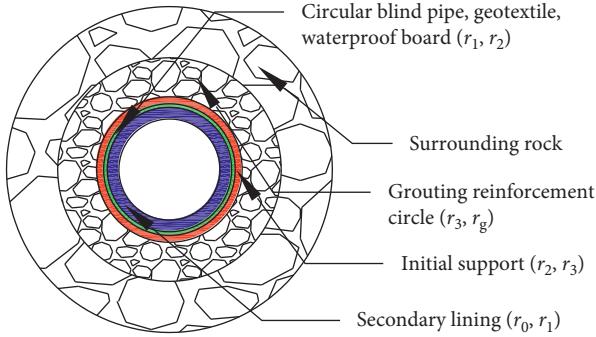


FIGURE 1: Calculation model.

There are five unknowns in equations (3)–(6): P_1 , P_2 , P_3 , P_g , and Q , which are water pressure on the inside of the geotextile, water pressure on the outside of the geotextile, water pressure on the outside of the initial support, water pressure on the outside of the grouting circle, and water seepage. The equations cannot be solved. Next, the method of determination of P_1 is analysed.

2.3. Working Principle of Geotextile and Annular Blind Pipe. The circular blind pipes, longitudinal and transverse drainage pipes, and drainage channels in the tunnel constitute a three-dimensional drainage system. The fissure water leaking into the rock mass around the tunnel leaks into the longitudinal drainage pipe along the annular drainage blind pipe between the second lining of the tunnel and the initial support, then flows into the tunnel drainage ditch through the transverse drainage pipe, and finally exits the tunnel by the longitudinal slope. According to the assumption that the permeability coefficients are all infinite except for the geofabric, the longitudinal and transverse drainage pipes of the tunnel can quickly transport the water flowing from the annulus to the tunnel drainage ditch, so the water head at the annulus blind pipe is assumed to be 0. At the same time, the seepage water into the geotextile through the initial support depends on the head pressure and gravity along the tunnel axial flow into the annular blind tube. In consideration of a conservative and simplified calculation, the influence of the axial slope and the seepage dead weight of the tunnel are ignored, and the annular blind pipe is expanded approximately into a rectangle, as shown in Figure 2.

The annular blind tube is divided into two main types: full-package waterproof and half-package waterproof [17, 18]. All-enveloped waterproofing is the installation of blind pipe, geotextile, and waterproofing board between the initial support and the secondary lining of the tunnel. The half-package of waterproofing is installed only on the sidewall and vault, not on the invert. We assume that the ratio between the length of the annular blind pipe and the inner perimeter of the initial support of the tunnel is α ($0 < \alpha \leq 1$). As shown in Figure 2, the width of the geotextile is L , the thickness is a , the distance between circular blind pipes is b , and the amount of water passing through the initial support is Q . Then, the flow into a

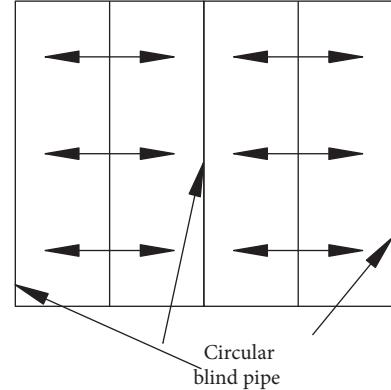


FIGURE 2: Working principle of the circular blind tube.

single circular blind pipe through the geotextile is L . Since the longitudinal slope is ignored, the coordinate axis as shown in Figure 3 is established by taking half of the symmetry:

Analysis of the section shown in Figure 3: the flow through this section is AV_x , and we assume that the flow into the geotextile through the initial support flows completely into the annular blind pipe. Then, the flow through this section must be $(Q/\alpha)[L((b/2) - x)]$, and the expression is

$$aLV_x = \frac{Q}{\alpha} \left[L \left(\frac{b}{2} - x \right) \right]. \quad (7)$$

According to Darcy's law, the seepage velocity is proportional to the water head gradient. Then,

$$V_x = K_a \frac{dh}{dx}. \quad (8)$$

Equations (7) and (8) are combined, and according to the boundary condition, the head at the circumferential blind pipe is 0. Integral calculation:

$$h = \frac{Q}{2\alpha a K_a} (bx - x^2). \quad (9)$$

Equation (9) shows that the water head drops in a parabola from the middle position of two rows of annular blind pipes to the position of the annular blind pipes.

2.4. Calculation of the Water Seepage Pressure of the Waterproof Plate. In equation (9), the water head between the annular blind pipes is distributed in a parabolic curve, and the water head can be integrated to obtain the seepage pressure borne by the geofabric structure, which can be expressed as follows:

$$\int_0^{(b/2)} \gamma_w L h dx = P_1 L \frac{b}{2} \quad (10)$$

The calculation result is

$$P_1 = \frac{\gamma_w Q b^2}{12 \alpha a K_a}. \quad (11)$$

By combining equations (3)–(6) and (11), we can get

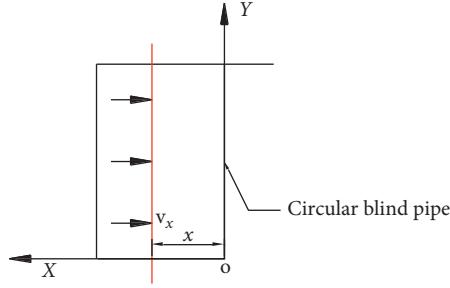


FIGURE 3: Calculation of the geotextile seepage.

$$Q = \frac{H}{(1/2\pi)((1/K_a)\ln(r_2/r_1) + (1/K_s)\ln(r_3/r_2) + (1/K_g)\ln(r_g/r_3) + (1/K_r)\ln(2H/r_g)) + (b^2/12\alpha a K_a)}, \quad (12)$$

$$h = \frac{H}{(1/2\pi)((1/K_a)\ln(r_2/r_1) + (1/K_s)\ln(r_3/r_2) + (1/K_g)\ln(r_g/r_3) + (1/K_r)\ln(2H/r_g)) + (b^2/12\alpha a K_a)} \cdot \left(\frac{bx - x^2}{2\alpha a K_a}\right), \quad (13)$$

The water head in the middle of the two rows of annular blind pipes is the largest. In this case $x = (b/2)$, substitute formula (13) to obtain

$$h_{\max} = \frac{H}{(1/2\pi)((1/K_a)\ln(r_2/r_1) + (1/K_s)\ln(r_3/r_2) + (1/K_g)\ln(r_g/r_3) + (1/K_r)\ln(2H/r_g)) + (b^2/12\alpha a K_a)} \cdot \frac{b}{8\alpha a K_a}. \quad (14)$$

Formulas (12)–(14) show that the influence of water seepage Q and the maximum head height that the secondary lining structure must bear are related to the permeability coefficient and thickness of each structure and the distance between blind pipes, which is the result of the comprehensive influence and restriction of many factors.

3. Parameter Analysis

The radius of the tunnel is 6.0 m, and the ratio of the thickness of the second lining and the initial support to the radius of the tunnel is 0.1 and 0.06, respectively. Wei et al. [19] carried out an experimental study on the permeability and filtration properties of geotextiles and took the permeability coefficient of geotextiles as 5×10^{-3} m/s. The height of the hydrostatic head is 400 m, the permeability coefficient of the surrounding rock is 10^{-8} m/s, and the ratio of the initial support and the surrounding rock permeability coefficient is 0.001. According to the relevant parameters in formulas (12) and (13), the seepage amount and the water head borne by the second lining structure are analysed.

3.1. Grouting Reinforcement Circle. Based on the assumption that the thickness of geotextile a is 5 mm and the distance between the circular blind pipes b is 10 m, the influence of the thickness of the grouting circle and the permeability coefficient on the water seepage and the height of the water head borne by the secondary lining structure is analysed.

3.1.1. Thickness of the Circle Reinforced by Grouting. We assume that the ratio of the permeability coefficient between the surrounding rock and the grouting circle is 50, the ratio of the thickness of the grouting circle to the radius of the tunnel is t , and the curves of the seepage volume Q and the maximum head height borne by the second lining and t are shown in Figures 4 and 5.

Figure 4 shows that the seepage water decreases nonlinearly with the increase in the thickness of the grouting circle, and the specific relationship can be divided into three sections. When t is less than 1.2, the seepage water decreases sharply with the increase in the thickness of the grouting circle. When t is between 1.2 and 3.0, the seepage water decreases linearly with the increase in the thickness of the grouting circle. When t is greater than 3.0, the decreasing rate of the seepage water decreases significantly with the increase in the thickness of the grouting circle. At this point, the sensitivity of the thickness of the grouting circle to the seepage water Q decreases, and the effect of increasing the thickness of the grouting circle to reduce the seepage water in the tunnel is no longer significant.

Figure 5 shows that the water head height borne by the secondary lining structure is distributed along the axial direction of the tunnel in a parabola. The head height in the middle of the two rows of annular blind pipes is the largest, and the maximum height decreases nonlinearly with the increase in the ratio t . Formula (13) shows that the water head outside the secondary lining structure presents a periodic change along the axial direction of the tunnel in the

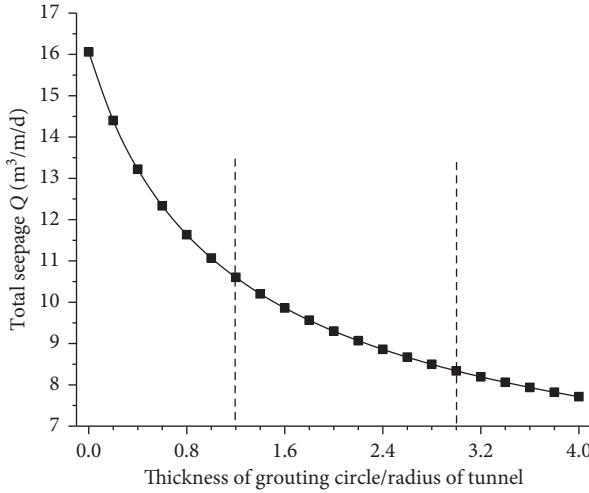


FIGURE 4: Relationship between the grouting circle thickness and the water seepage.

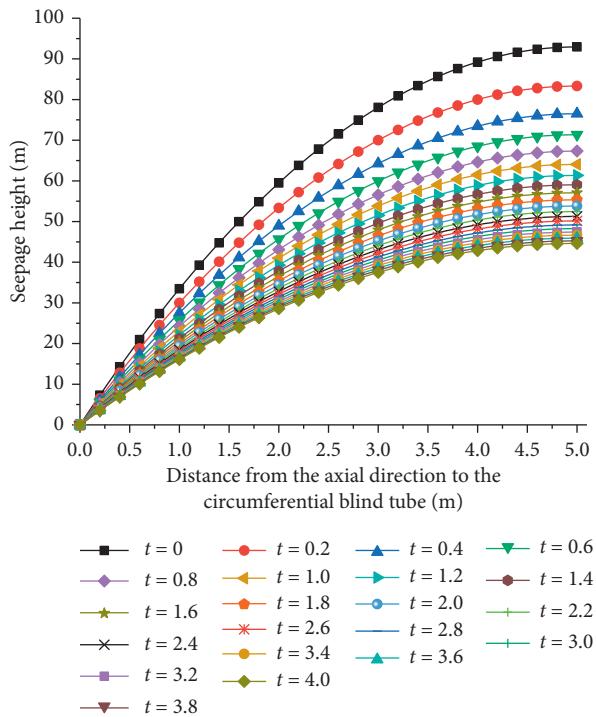


FIGURE 5: Relationship between the grouting circle thickness and the water head.

unit of the annular blind tube spacing, which is similar to the research conclusion in the literature [20, 21].

3.1.2. Permeability Coefficient of the Grouting Circle. According to the research conclusion in Section 3.1.1, we assume that the ratio of the thickness of the grouting circle to the radius of the tunnel is 2.0, and the ratio of the permeability coefficient between the surrounding rock and the grouting circle is m . The relationship between the seepage amount and the water head with m is analysed, as shown in Figures 6 and 7.

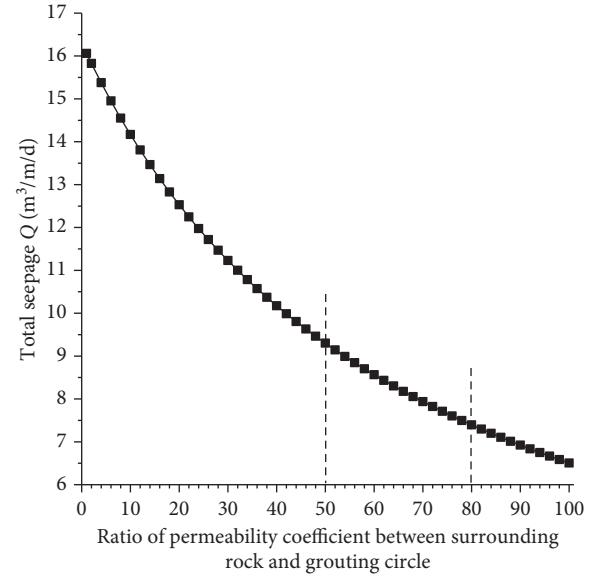


FIGURE 6: Relationship between the permeability coefficient and the water seepage of the grouting circle.

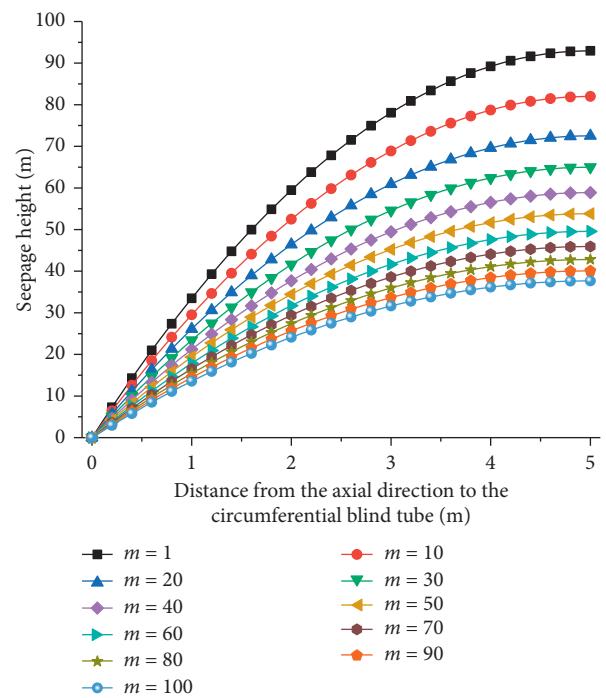


FIGURE 7: Relationship between the permeability coefficient of the grouting circle and the head height.

Figures 6 and 7 show that the effect of m on the seepage volume and the water head is similar to the effect of the ratio t between the thickness of the reinforced circle and the radius of the tunnel. The sensitivity is also divided into three phases, and the critical points are $m = 50$ and 80 .

According to Section 3.1, grouting reinforcement is an important means to reduce the amount of seepage water and the water pressure borne by the secondary lining structure.

The calculated values of the amount of the seepage water and the water pressure of the tunnel support structure can be adjusted by changing the thickness and permeability coefficient of the grouting reinforcement circle [22].

3.2. Annulus Blind Tube Spacing. The design of the tunnel drainage system is relatively complex. In the annular blind pipe, the pore water is discharged in a timely manner and the seepage pressure is small. The pore water in the middle of the two annular blind pipes cannot be discharged in a timely manner, resulting in an accumulation, and the seepage pressure reaches the maximum. If the spacing is too large, a large amount of water will accumulate behind the support structure, and this water will exert a great effect on the structure, causing cracks in the lining and eventually causing leakage in the tunnel [23]. Therefore, the annulus blind pipe spacing should be designed reasonably to avoid the high head in the middle of the two rows of annulus blind pipes, which may affect the safety of the structure.

Suppose $t = 2.0$, $m = 50$. The distance between the annular blind pipes is set at 1–20 m, the seepage volume and the maximum head height are calculated, and the curve is drawn as shown in Figure 8.

Figure 8 shows that the relationship between the maximum head height and the seepage volume increases and decreases with the increase in the annulus blind pipe spacing. When the design of the annulus blind pipe spacing is larger, the seepage pressure is larger, which can easily cause a lining crack. If the spacing is too small, water seepage will increase, which will have a negative impact on the local ecological environment. Therefore, the annular blind tube spacing should be reasonably designed to meet the two constraints.

3.3. Thickness of the Geotextile. The geotextile has the functions of protection, isolation, filtration, and drainage. The waterproof layer between the composite lining layers of the mountain tunnel is located between the initial support and the secondary lining and is composed of the inner geotextile and the outer waterproof plate, which is the core part of the tunnel waterproofing and drainage system [24].

According to the standard [25], the thickness of geotextile a is set as 0.9, 1.3, 1.7, 2.1, 2.4, 2.7, 3.0, 3.3, 3.6, 4.1, and 5.0 (unit: mm), respectively. The curves of the relationship between the thickness of geotextile and the amount of seepage and the height of the water head are drawn as shown in Figures 9 and 10.

Figure 9 shows that the seepage water quantity Q increases with the increase in the geotextile thickness a . When a is within 0.9–2.7 mm, the seepage water increases sharply with the increase in the geotextile thickness. When a is between 2.7 and 5.0 mm, the water inflow increases linearly with the increase in a .

Figure 10 shows the head height decreases with the increase in a . Like Figure 9, the height of the water head increases nonlinearly with the increase in a at the beginning, and the decrease in the height of the water head tends to be gentle with the continuous increase of a .

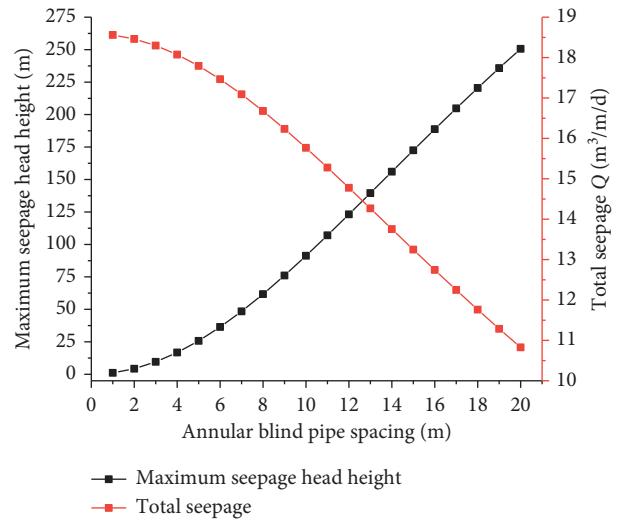


FIGURE 8: The curve of the relationship of the distance between the circular blind pipes, the water seepage, and the maximum head height.

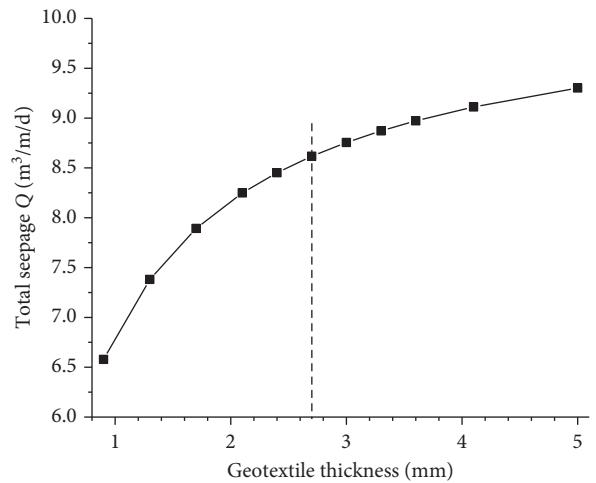


FIGURE 9: Relationship between geotextile thickness and water seepage.

Comprehensive analysis of Figures 9 and 10 shows that the thickness of the geotextile increases, and the cross-sectional area of the water flowing into the blind pipe will increase. Water seepage will flow more easily into the annular blind pipe and then out of the tunnel, thereby increasing water seepage and reducing the water pressure on the secondary lining structure.

4. Solve the Annular Blind Tube Spacing

Section 3.2 shows that reducing the annular blind pipe spacing will make it easier for the water infiltrating into the annular blind pipe, thus reducing the seepage pressure borne by the secondary lining structure. However, reducing the annular blind pipe spacing will increase the flow rate of the

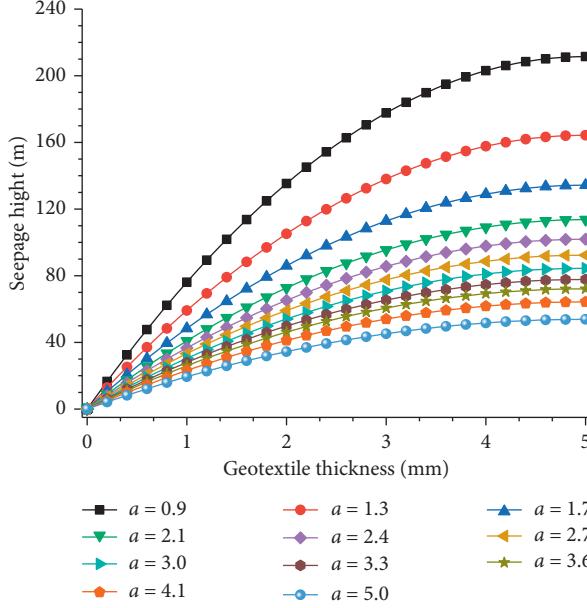


FIGURE 10: Relationship between the geotextile thickness and the seepage height.

initial stage infiltration support and cause damage to the surrounding environment of the tunnel. Therefore, the setting of the annular blind tube spacing should be considered comprehensively.

Equation (12) is the amount of water for the initial support for infiltration. To protect the local ecological environment, the amount of water Q should not be greater than Q_{allowed} . Pan et al. [26] introduced the concept of

ecological water demand for vegetation in ecology and agriculture, combined with the groundwater dynamics method and the empirical formula, and determined the maximum amount of water allowed to be discharged from the tunnel. Equation (14) is the maximum head height that the secondary lining structure must bear, assuming that the designed water pressure resistance value of the secondary lining structure is p . Available:

$$12\alpha a K_a \left(\frac{H}{Q} - \frac{1}{2\pi} \left(\frac{1}{K_a} \ln \frac{r_2}{r_1} + \frac{1}{K_s} \ln \frac{r_3}{r_2} + \frac{1}{K_g} \ln \frac{r_g}{r_3} + \frac{1}{K_r} \ln \frac{2H}{r_g} \right) \right) \leq b^2 \leq \frac{P}{\gamma_w H} \frac{\alpha a K_a}{(1/8)(P/(12\gamma_w H))} \frac{1}{2\pi} \left(\frac{1}{K_a} \ln \frac{r_2}{r_1} + \frac{1}{K_s} \ln \frac{r_3}{r_2} + \frac{1}{K_g} \ln \frac{r_g}{r_3} + \frac{1}{K_r} \ln \frac{2H}{r_g} \right). \quad (15)$$

According to equation (15), the reasonable value range of annular blind pipe spacing can be obtained by setting reasonable design parameters of grouting circle and geotextile thickness.

5. Analysis of Calculation Examples

5.1. Engineering Background. The Hongtu extra-long tunnel is a double hole single-track tunnel with a 6337 m left line and a 6336 m right line. Through the middle and low mountain landform area, the surface elevation is 245–1060.0 m, and the relative elevation difference is approximately 715 m. The bottom elevation of the designed tunnel is 239–344 m, and the maximum buried depth is approximately 739 m. There are several fault-fracture zones around the axis of the tunnel.

In the process of tunnel construction, there are many times of water inrush, and the water inrush on the face is shown in Figure 11. In this bid section (reverse slope), a pump is set at the portal to discharge water and record the drainage flow. The drainage at the portal is shown in Figure 12, and the daily drainage is shown in Figure 13. The average flow is $9592 \text{ m}^3/\text{d}$ within 106 d, the maximum flow is nearly $20000 \text{ m}^3/\text{d}$, and the measured water pressure is 2.0 MPa.

5.2. Parameter Selection. The noncircular tunnel is transformed into a circular tunnel by the equal generation method of analysis. Literature [27, 28] analysed the radius of the equivalent generation circle. In this paper, the radius of the external circle of the tunnel section is taken as the radius



FIGURE 11: The tunnel water disasters.



FIGURE 12: Drainage and flow monitoring.

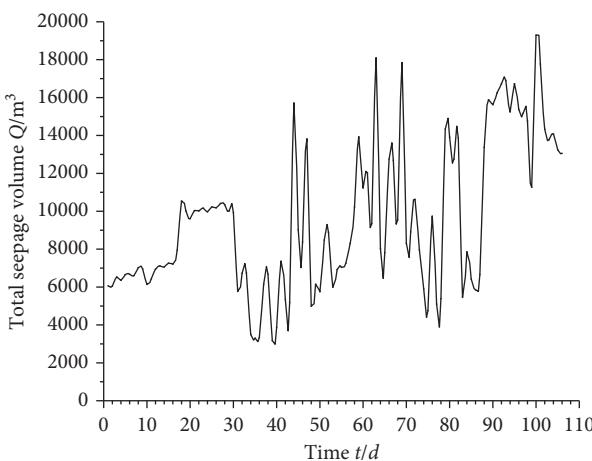


FIGURE 13: Daily discharge curve.

of the equal generation circle, and the expression is as follows:

$$r_0 = \frac{\sqrt{4h^2 + b^2}}{4 \cos(\arctan(b/2h))}. \quad (16)$$

In equation (16), r_0 represents the radius of the original tunnel after iso-generational circle treatment, b represents the cross section span of the original tunnel, and h is the cross section height of the original tunnel.

We calculate that the radius of the iso-generational circle $r_0 = 6.2$ m. Initial support and second lining are, respectively, 30 cm and 50 cm. According to the data provided by the survey and design company, the permeability coefficients of the surrounding rock, the grouting circle, and the support structure are 5×10^{-6} m/s, 10^{-7} m/s, and 5×10^{-9} m/s, respectively. The permeability coefficient of the geotextile is 5×10^{-3} m/s and the thickness is 4.1 mm. The local allowable seepage water is $4.5 \text{ m}^3/\text{m}/\text{d}$, and the designed antiwater pressure of the second lining structure is 0.3 MPa. The height of the static head is set at 200 m. According to the experience in the construction of other bidding sections of the project, the thickness of the grouting circle is 8 m.

5.3. Calculation of the Annulus Blind Tube Spacing. According to formula (15), the range of the annular blind pipe spacing is $44.72 \leq b^2 \leq 102.26$. To reduce the water pressure borne by the secondary liner structure, the annular blind pipe spacing is 8.0 m. At this point, the seepage water is $4.4 \text{ m}^3/\text{m}/\text{d}$. The water pressure borne by the second lining structure is shown in Figure 14.

Figure 14 shows that when the annular blind pipe spacing is 8 m, the secondary liner structure at the middle position of the two rows of annular blind pipes should bear the maximum water pressure of 0.192 MPa, which meets the requirement of the designed water resistance of 0.3 MPa.

5.4. Verification of Monitoring Data. The intelligent string-type digital osmometer is embedded on the inner surface of the initial support to monitor the water seepage pressure on the inner surface of the initial support. The field embedding is shown in Figure 15 (the distance from the nearest circumferential blind pipe is 2.6 m), and the monitoring result is 0.189 MPa. According to the calculation in Section 4, the water pressure is 0.168 MPa, with a difference of 12.5%; at the same time, using the hydrological velocity measuring instrument, as shown in Figure 16, the final stability of 120 m water seepage in this section is $496 \text{ m}^3/\text{d}$. According to the calculation in Section 4, the seepage volume is $528 \text{ m}^3/\text{d}$, with a difference of 6.45%.

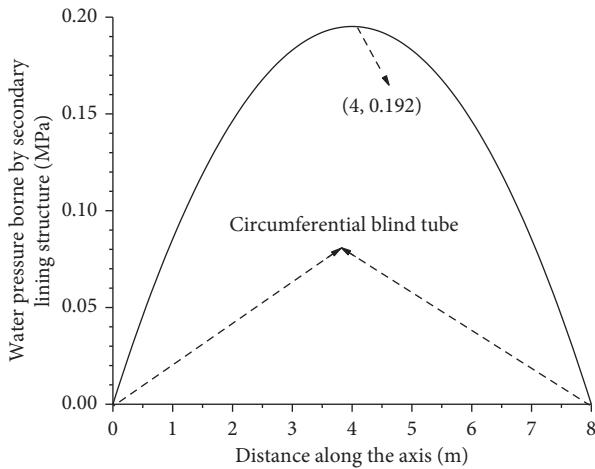


FIGURE 14: Seepage pressure borne by the secondary lining structure.



FIGURE 15: Site installation and burying.

The monitoring data can verify the accuracy of formulas (12)–(15) to a certain extent, and the requirements of the ecological environment and structural safety can be satisfied by setting the annular blind tube spacing reasonably. The deviation may be caused by the following reasons: the amount of water in the annular blind tube is not completely discharged from the tunnel through the longitudinal and transverse drainage pipes, and the water head assumed to be 0 at the position of the annular blind tube is also different from the actual situation.



FIGURE 16: Water inflow monitoring.

6. Conclusions

Based on Darcy's law and the law of conservation of mass, the design parameters of the grouting circle were optimised, and the formula for determining the annular blind pipe spacing was derived. The following conclusions are drawn:

- (1) Grouting reinforcement is an important means to reduce the amount of water seepage. The amount of water seepage in the tunnel and the water pressure to be borne by the second lining structure can be adjusted by changing the thickness and permeability coefficient of the grouting reinforcement circle.
- (2) According to the derived formula, the water head drops in a parabolic curve from the middle of the two rows of annular blind tubes to the annular blind tubes.
- (3) If the spacing between the annular blind pipes or the thickness of the geotextile is not properly set, it will have a significant effect on the supporting structure or cause damage to the local ecological environment.
- (4) Based on the derived formula, we determined that the annular blind pipe spacing in the test section of the Hongtu extra-long tunnel is 8 m.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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