Investigation of Overburden Thickness in Close Underpass River Tunnels Considering Grouting Effects

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Abstract. This study investigates the impact of grouting measures on the overburden thickness of the Yuxi River Tunnel. Using theoretical analysis, engineering analogy, and numerical simulations, the research determines the minimum safe overburden thickness. Results show corrected thicknesses of 9.6m without grouting force and 9.2m with it. The Japanese minimum seepage method indicates an overburden thickness of 13.9m, while minimum thicknesses for grouting ranges of 2m, 4m, and 6m are 11.12m, 10.75m, and 10.42m, respectively. It can be seen that the larger the grouting range, the smaller the minimum cover thickness becomes, but its value changes less. In the actual construction, the economic rationality of the grouting layer thickness and the minimum cover thickness should be considered comprehensively.

Keywords: Underwater tunnel; Cover thickness; Grouting measures

1 Introduction

With the rapid development of metro construction, the challenges are increasing. It is inevitable that underpassing rivers will be encountered during tunnel construction, requiring tunnels to traverse more complex stratigraphic conditions [1] and face technical challenges such as riverbed collapse, water influx, and seepage [2]. Determining a safe and economical tunnel cover thickness poses a major challenge for this type of project. Currently, Sun et al. [3] designed the overburden thickness by considering the stability of the excavation surface; Guo et al. [4] corrected the overburden thickness by taking into account grouting pressure and the hardening of the grouting mortar; Sun et al. [5] derived the minimum overburden thickness for different tunnel section forms; and Zhang et al. [6] developed a calculation method for determining the minimum depth of the tunnel under varying surface water levels during construction. However, research on the effect of grouting reinforcement on the minimum overburden thickness is limited. Based on specific engineering examples, this study aims to investigate the influence of grouting measures on the overburden thickness of tunnels passing beneath rivers through theoretical analysis, numerical simulation, and other methods.

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2 Project Overview

Proposed Trade City North Station to Guangyangwan Station subway tunnel length 2851.4m, depth of about 9.8 ~ 67.3m in the mileage SK41 +900 to SK42 +100 section under the yuxi river. The topography of the proposed site varies greatly, and it is a river valley geomorphology. Under the river tunnel project location plan see Fig. 1.

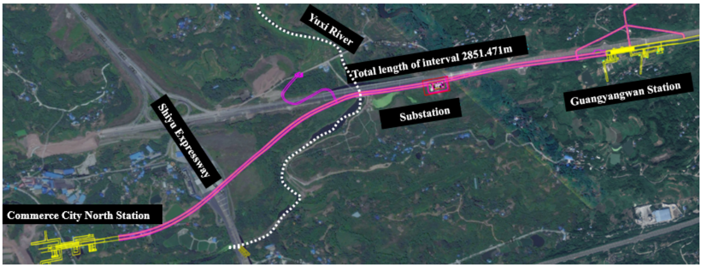

Fig. 1. Schematic location of the tunnel under the river section

The surrounding rocks of the tunnel are sandstone (J2s-Ss) and sandy mudstone (J2s-Sm) in the Middle Jurassic Shaximiao Formation, consisting of unequal thicknesses of rhythmic rock strata, with weathering fissures developed, strongly weathered cores in the form of fragmented blocks, and moderately weathered rocks with good integrity. And the overall lowest point of the interval is located in Yuxi river. The geological longitudinal section is illustrated in Fig. 2, and the physical and mechanical parameters of the surrounding rock are presented in Table 1.

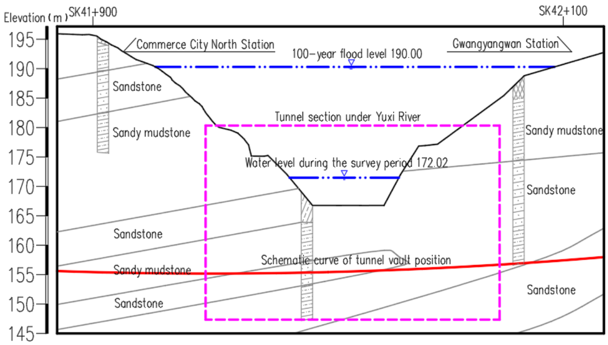

Fig. 2. Geological longitudinal section

Table 1. Physical and mechanical parameters of surrounding rock

Rock samples	unit weight(kN·m^{-3})	modulus of compressibility(GPa)	cohesion (MPa)	internal friction angle(°)	Poisson's ratio
sandstone	24.9	4.6	1.9	41	0.11
Sandy mudstone	25.6	1.3	0.66	33	0.37

3 Calculating the Overburden Thickness in River-Underpassing Tunnels

3.1 Simplified Minimum Burial Depth Method

This method assumes that the overlying soil layer slides vertically, ignoring friction or shear forces on the slip line. The method is analyzed by comparing the weight of the soil above the tunnel with the buoyancy of the water on the tunnel, and the minimum critical cover thickness is the one when the weight of the overlying soil and the buoyancy have reached a state of limiting equilibrium. The overburden weight W, tunnel gravity G, and buoyancy F_b are defined in Eq. (1) to (3), and the specific calculation schematic is illustrated in Fig. 3.

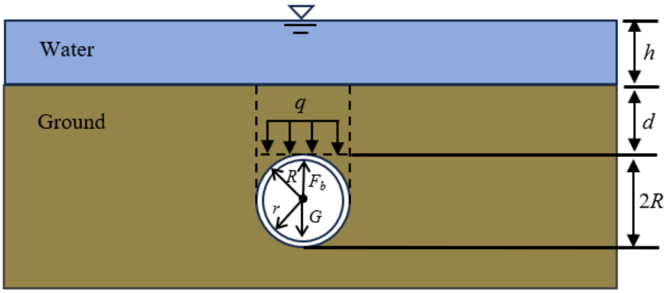

Fig. 3. Simplified Minimum Burial Depth Method Calculation Schematic

$$W = (\gamma_s - \gamma_w)\left[2Rd + \left(2 - \frac{\pi}{2}\right)R^2\right] \tag{1}$$

$$G = \pi(R^2 - r^2)\gamma_c \tag{2}$$

$$F_b = \pi R^2 \gamma_g \tag{3}$$

Where R is the outer diameter of the tunnel; r is the inner diameter of the tunnel; γ_c is the unit weight of the tunnel lining; γ_s is the unit weight of the overburden; γ_g is the unit weight of the grouting material; and γ_w is the unit weight of the water.

The tunnel is subjected to a limiting force equilibrium analysis, which results in W+G=Fb. The minimum overburden thickness d can be obtained using Eq. (4).

$$d = \frac{\pi r^2\gamma_c - \left(2 - \frac{\pi}{2}\right)R^2(\gamma_s - \gamma_w) - \pi R^2(\gamma_c - \gamma_g)}{2R(\gamma_s - \gamma_w)} \tag{4}$$

3.2 Modified Calculation Method Considering Grouting Forces

The method assumes that the overlying soil layer moves vertically, the grout layer is homogeneous and incompressible, and the density of the grout material remains constant before and after grouting. By simplifying the distribution of grouting pressure to a sector, the vertical component of the total grouting force is calculated in Eq. (5):

$$F_g = 2\int_0^{\theta} P\cos\alpha \bullet R\sin\alpha \, d\alpha = \frac{1}{2}PR(1-\cos 2\alpha) \quad 0<\theta<\frac{\pi}{2} \tag{5}$$

Simplifications are made by considering the most unfavorable case: $\theta=\pi/2$, F_g=PR, and $F_b=\pi R^2\gamma_g/2$. The calculation schematic is illustrated in Fig. 4, while the equilibrium and boundary conditions for each layer of infinitesimal soil are presented in Eq. (6) and Eq. (7):

$$2R\sigma_v = 2R\gamma' \, dz + 2R(\sigma_v - d\sigma_v) + 2c\, dz + 2K_0 \tan\varphi \, \gamma' z \, dz \tag{6}$$

$$z = z_0 \;\; \sigma_v = P_0 \;\;, \;\; z = 0 \; \sigma_v = P_w \tag{7}$$

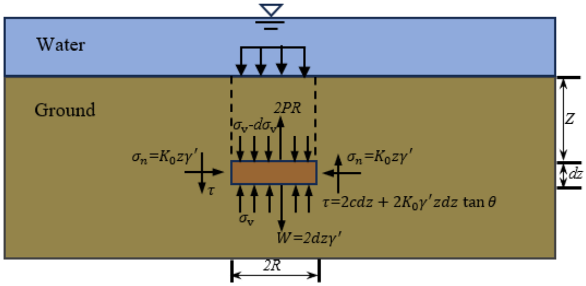

Fig. 4. Schematic diagram of the modified calculation considering the grouting pressure

At this stage, the soil is subjected to grouting pressure, as expressed in Eq. (8):

$$P_0 = \frac{F_b + PR - G - \left(2-\frac{\pi}{2}\right)R^2\gamma'}{2R} \tag{8}$$

Therefore, the value of earth pressure at any depth is expressed in Eq. (9):

$$\sigma_v = P_0 + \frac{R\gamma' + c}{R}(z - z_0) + \frac{K_0 \tan\varphi\gamma'}{R}\left(\frac{z^2}{2} - \frac{z_0^2}{2}\right) \tag{9}$$

From Eq. (9), the minimum cover thickness d considering the effect of grouting pressure can be obtained, and the result is shown in Eq. (10).

$$d = \frac{\sqrt{(R\gamma'+c)^2 + 2R(P_0 - P_w)K_0\gamma'\tan\varphi} - (R\gamma'+c)}{K_0\gamma'\tan\varphi} \tag{10}$$

Where: c is the soil cohesion; φ is the friction angle ; γ′ is the submerged unit weight of soil; K_0 is the lateral pressure coefficient . The two methods described above are theoretical calculations. Based on the hydrogeological conditions of the tunnel under the Yuxi River, substituting geological parameters into Eq. (4) yields a minimum overburden thickness of 9.6 m when grouting pressure is not considered, while substituting the parameters into Eq. (10) results in a minimum overburden thickness of 9.2 m when grouting pressure is taken into account. This suggests that considering grouting pressure reduces the minimum overburden thickness. However, the above theoretical approach does not consider the effect of water depth over the overburden.

3.3 Japanese Minimum Seepage Method

Japanese scholars have predicted the seepage of underwater tunnels, and proposed the minimum surge method, which is an empirical formula in a given water depth and determine the shape of the tunnel excavation section, the minimum surge of the tunnel corresponds to the thickness of the cover layer for the economic safety of the minimum thickness of the cover layer, which is assumed to be an infinite-length circular tunnel for the excavation, and Eq. (11) can be derived from Darcy's law.

$$Q = 2\pi k \frac{H+h}{\ln\frac{2h}{r}} \tag{11}$$

When $\partial Q/\partial h = 0$, Q reaches its minimum value. The corresponding minimum overburden thickness is presented in Eq. (12).

$$h = \frac{r}{2} e^{(1+\frac{H}{h})} \tag{12}$$

Where: Q is the tunnel water influx (m^3/d); h is the thickness of the rock layer covered by the tunnel (m); k is the permeability coefficient of the surrounding rock (m/d); r is the effective excavation radius of the tunnel (m); H is the depth of water (m).

This method takes into account the influence of water depth and has been widely used in engineering practice in Japan. Based on the aforementioned tunnel hydrogeological conditions, the deepest section of the river within the interval is selected for analysis. The 100-year flood level is considered to be H=15m, and the effective excavation radius of the tunnel is r=3.5m. By substituting this data into Eq. (12), a minimum overburden thickness of 13.9 m is obtained.

3.4 Minimum Overburden Thickness Correction Considering Grouting

For the stratum after grouting treatment, the theoretical method is difficult to calculate effectively. Based on the Japanese minimum seepage method and considering the influence of the range of grouting reinforcement, the author uses numerical simulation to comparatively analyze the influence of grouting measures on the seepage volume of the tunnel, so as to determine the minimum thickness of the cover layer.

3.4.1 Confirmation and Establishment of Model Parameters.

To minimize errors in the simulation results caused by boundary condition constraints, the final model dimensions were determined to be 120 m × 120 m × 80 m (length × width × height). The specific calculation model is illustrated in Fig. 5.

3.4.2 Analysis of overburden thickness without considering the effects of grouting.

The seepage volume of the tunnel without grouting in relation to the overburden layer is shown in Fig. 6.

From Fig. 5, when the cover layer thickness is less than 12 m, the tunnel's seepage volume is larger. The curve depicting the relationship between seepage flow and cover layer thickness decreases and then increases, reaching a minimum near 13 m. Thus, the minimum thickness of the cover layer without grouting measures is determined to be 13 m. This value is lower than the Japanese minimum seepage method, which does not account for the weight and permeability of the rock body. The difference is 0.9 m (approximately 6.4%), which is considered reasonable.

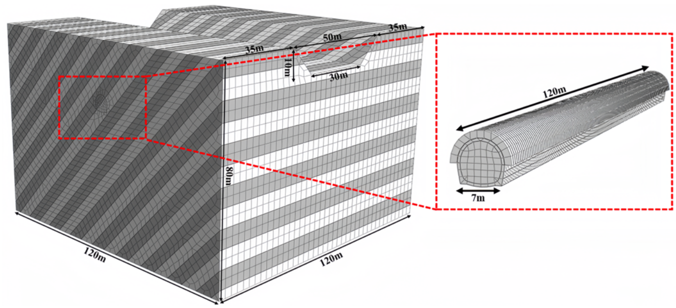

Fig. 5. Finite element calculation model

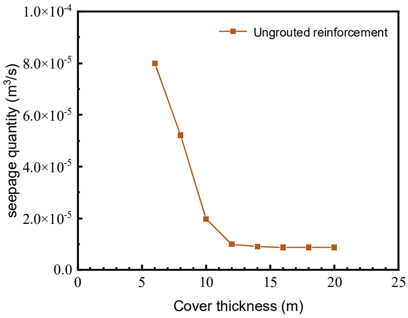

Fig. 6. Curve of seepage versus overburden thickness without considering the effect of grouting

3.4.3 Analysis of Overburden Thickness Considering the Effects of Grouting. The relationship between seepage and cover thickness for the tunnel considering grouting is shown in Fig. 7.

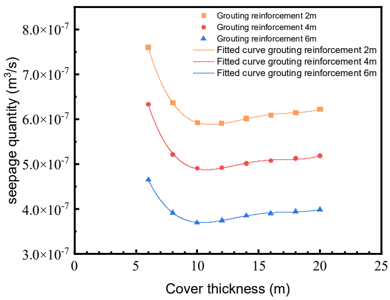

Fig. 7. Curve of tunnel seepage versus overburden thickness considering grouting effect

The seepage volume of the tunnel significantly decreases after implementing grouting reinforcement measures, and it further diminishes with an increase in the grouting range. For instance, with a cover layer thickness of 10 m, the seepage flow within the 2 to 6 m grouting range was reduced from 5.92×10^{-7} m^3/s to 3.70×10^{-7} m^3/s, which is negligible compared to the volume without grouting.

To determine the minimum overburden thickness considering grouting, the author fitted the data, with parameters shown in Table 2.

Table 2. Parameter table of the fitting function

Fit function / Grouting range	$y = A + B_1x + B_2x^2 + B_3x^3 + B_4x^4$				
	A	B_1	B_2	B_3	B_4
2m	2.19×10^{-6}	-4.43×10^{-7}	4.47×10^{-8}	-1.95×10^{-9}	3.13×10^{-11}
4m	1.99×10^{-6}	-4.29×10^{-7}	4.46×10^{-8}	-2.00×10^{-9}	3.30×10^{-11}
6m	1.41×10^{-6}	-2.99×10^{-7}	3.12×10^{-8}	-1.39×10^{-9}	2.28×10^{-11}

The fitting function typically uses the fit index coefficient R^2 as a reference. The R^2 values for the three curves are 0.9998, 0.9990, and 0.9995, all of which are close to 1, indicating a high degree of fit. The horizontal coordinates of the polynomial extreme points represent the minimum overburden thicknesses for the corresponding grouting reinforcement ranges. The calculated minimum overburden thicknesses for grouting ranges of 2m, 4m, and 6m are 11.12m, 10.75m, and 10.42m, respectively.

4 Conclusions

Based on the example of the tunnel project under the Yuxi river, the effect of grouting measures on the minimum overburden thickness was investigated by combining the estimation method with numerical analysis, and the conclusions of this study are summarized as follows:

- The overburden thicknesses of 9.6 m and 9.2 m, obtained from the simplified minimum embedment method and the grouting pressure correction method, are less than the 13.9 m from the Japanese minimum seepage method. This difference is due to the theoretical calculations not accounting for water depth.
- Based on the Japanese minimum seepage method, the minimum cover thickness is 13m without considering grouting. For grouting reinforcement ranges of 2 m, 4 m, and 6 m, the corresponding minimum overburden thicknesses are 11.12 m, 10.75 m, and 10.42 m, respectively. As the grouting range increases, the minimum overburden thickness decreases.
- It can be seen that the larger the grouting range, the smaller the minimum cover thickness becomes, but its value changes less. In the actual construction, the economic rationality of the grouting layer thickness and the minimum cover thickness should be considered comprehensively.

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