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Reasonable overburden thickness for underwater shield tunnel

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A R T I C L E I N F O

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A B S T R A C T

A reasonable overburden thickness is of importance for the stability of underwater shield tunnels. Based on the analysis of existing theoretical methods, this paper presents a modified method for the estimation of the minimum overburden thickness during underwater shield tunnelling. As the existing methods neglect the effects of grouting pressure, the modified method takes into account the grouting pressure and the hardening of grouting mortar. The modified method is compared with existing methods based on a practical underwater tunnelling project of Beijing Subway Line 14. Parametric analysis of the proposed method considering the dimension of the tunnel, the geological condition and the grouting behavior is performed. The results show that tunnel diameter, friction angle and cohesion of soil, and grouting pressure have significant impacts on the results of modified methods. The results of this study can provide a reference for similar projects.

1. Introduction

As water pressure reduces the effective stress in the soil, the arching effect of an underwater tunnel is thus weakened. When a shallowly buried underwater tunnel is excavated in soil, water inrush and ground failure may occur if measures are not appropriately adopted. For a shallow-buried underwater shield tunnel, there are two typical failure modes. One is the water inrush and roof collapse caused by the rupture of shallow overburden due to excessive water pressure or grouting pressure (Wang and Huang, 2005; Wang, 2014). The other is the floating of the segmental lining caused by the buoyancy forces (Jiang et al., 2007; Song and Wang, 2009). To safeguard an underwater tunnel excavated in soil, the proper determination of minimum overburden thickness is of great importance.

The multiple factors influencing the estimation of the minimum overburden thickness, such as the tunnel scale, the engineering geology and the hydrogeological characteristics, have been studied by many scholars (Wang et al., 2003; Sun, 2006; Ye et al., 2008). Model tests and theoretical analysis have been carried out to reveal the uplifting mechanism of pipelines (Palmer et al., 2003; White et al., 2008; Cheuk et al., 2008), which serves as a meaningful reference for the underwater shield tunnel. The floating mechanism of the underwater shield tunnel lining was also studied by Ye et al. (2008), and the influence of the grouting pressure on the anti-buoyancy security of tunnel lining was emphasized.

To estimate the minimum overburden thickness of an underwater tunnel, experiences from Norway underwater tunnel construction have been summarized and presented (Nilsen, 1993; Eisenstein, 1994; Nilsen, 2005). Some simplified methods for calculating the minimum overburden thickness of a shallow-buried underwater shield tunnel have also been proposed by Maidl et al. (1996) and Verruijt (2001), which estimate the minimum overburden thickness based on the equilibrium between buoyancy and overburden weight (Fig. 1). To take into accounts the resistance of soil around the overburden layer, another method was presented by Dai et al. (2006). Based on the equilibrium between the tunnel face and shield chamber, Zhang et al. (2004) proposed a formula which can be used to determine the safety overburden thickness of a shallow-buried underwater shield tunnel. The combination of engineering analysis and numerical simulation is also widely used for the estimation of the overburden thickness of an underwater tunnel (Jiang et al., 2007; Wang et al., 2007; Song et al., 2008). Sun and Tan (2009) suggested the minimum overburden thickness of an underwater tunnel could be estimated through engineering analysis and stability analysis.

The previous research on the reasonable thickness of an underwater tunnel mainly focuses on the buoyancy of tunnel lining due to grouting mortar and water. In this research, the effects of grouting pressure on uplifting the segmental lining are considered. Related formulas are put forward to calculate the minimum overburden thickness of an underwater tunnel. Parametric analyses of the formulas are also performed.

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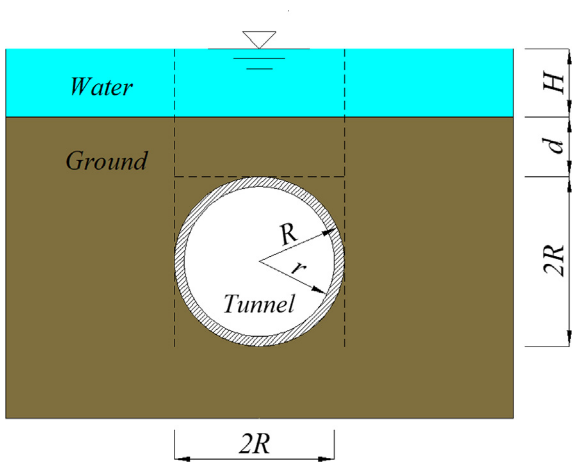

Fig. 1. Sketch of problem.

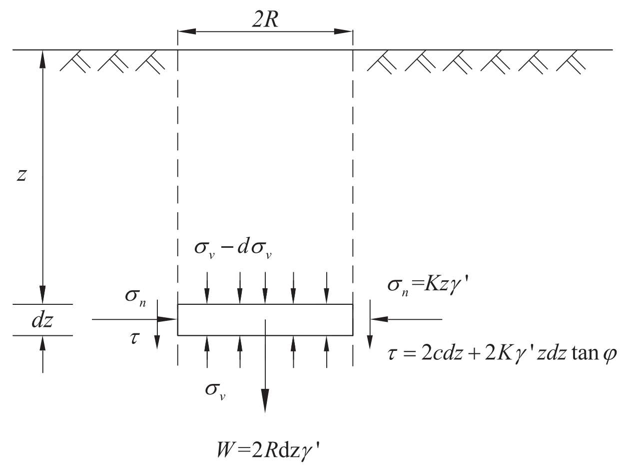

Fig. 3. Model considering soil shear force (Dai et al., 2006).

2. Method of calculating the minimum overburden thickness

Currently, there are two typical theoretical methods for calculating the minimum overburden thickness, namely the simplified calculation method and the method considering soil shear force.

2.1. Simplified method

The simplified method assumes the overlaying soil slides vertically and ignores the friction or shear force alone the slip line (Fig. 1). The relationship between the weight of overlaying soil (W), the gravity of lining (G) and the buoyancy (F_b) are shown in Fig. 2 and could be calculated using Eqs. (1)–(3):

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

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

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

where R is the outer diameter of the tunnel; r is the inner diameter of the tunnel; γ_c is the unit weight of tunnel lining; γ_s is the unit weight of overlaying soil; γ_g is the unit weight of grouting mortar; and γ_w is the unit weight of water.

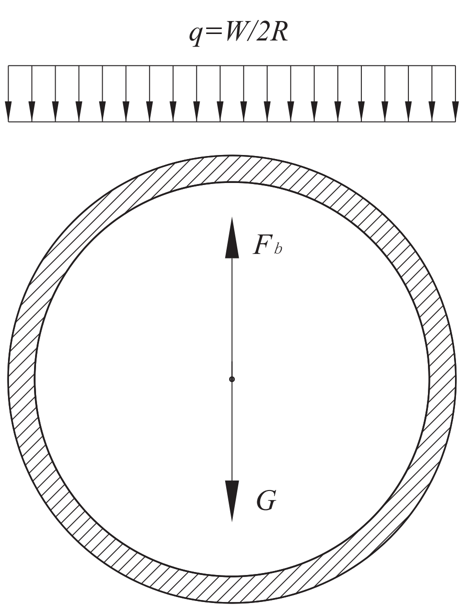

Fig. 2. Equilibrium of forces (Dai et al., 2006).

For the limit equilibrium state, the relationship between W, G and F_b is:

$$W + G = F_b \tag{4}$$

By substituting Eqs. (1)–(3) into Eq. (4), the formula for the minimum overburden thickness is:

$$d = \frac{\pi r^2\gamma_c - \left(2 - \frac{\pi}{2}\right)R^2(\gamma_s - \gamma_w) - \pi R^2(\gamma_c - \gamma_g)}{2R(\gamma_s - \gamma_w)} \tag{5}$$

2.2. Method considering soil shear force

In this case, the slide lines of overlaying soil are assumed to develop vertically with a distance of $2R$ and the calculation model is shown in Fig. 3.

The lateral earth pressure on the slide face is set as static earth pressure and can be expressed as:

$$\sigma_h = \gamma' z K_0 \tag{6}$$

For each infinitesimal horizontal layer of overlaying soil, when considering the resistance of surrounding soil, the shear stress along the slide line consists of cohesive stress and frictional stress, which could be calculated as:

$$\tau = 2cdz + 2K\gamma' zdz \tan\varphi \tag{7}$$

The equilibrium of each infinitesimal layer of soil and its boundary condition could be described as:

$$2R\sigma_v = 2R\gamma' dz + 2R(\sigma_v - d\sigma_v) + 2cdz + 2K_0\gamma' \tan\varphi zdz \tag{8}$$

$$z = z_0 \quad \sigma_z = P_0$$

$$z = 0 \quad \sigma_v = 0$$

The pressure of soil at any thickness can be expressed as:

$$\sigma_v = p_0 + \frac{R\gamma' + c}{R}(z - z_0) + \frac{K_0\gamma' \tan\varphi}{R}\left(\frac{z^2}{2} - \frac{{z_0}^2}{2}\right) \tag{9}$$

where c is the cohesion of soil; $\varphi$is the friction angle of soil; γ' is the submerged unit weight of soil, K_0 is the lateral pressure coefficient of soil; and p_0 is the pressure on the bottom of the soil column applied by tunnel lining, which is calculated by:

$$p_0 = \frac{F_f - G - \left(2 - \frac{\pi}{2}\right)R^2\gamma'}{2R} \tag{10}$$

The minimum overburden thickness can be calculated as followed: