Tunnelling and Underground Space Technology 80 (2018) 92–102

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Investigation of steady water inflow into a subsea grouted tunnel

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A R T I C L E I N F O

Keywords:
Subsea grouted tunnel
Steady seepage field
Analytical solution
Numerical simulation
Permeability of grouted zone

A B S T R A C T

This paper investigates analytical solutions for steady water inflow into a subsea grouted tunnel. The relevant parameters include the pore pressure distribution in the aquifer, external water pressure on the grouted zone and water inflow. Analytical solutions are obtained by the complex variable method (CVM), mirror image method (MIM) and axisymmetric modeling method (AMM). A series of numerical simulations are performed to validate the analytical solutions. The calculation accuracy and application conditions of each method are stated by comparisons of the pore pressure distribution and water inflow. Finally, the influencing factors, such as the boundary conditions, permeability of grouted zone and water depth, are discussed. It is suggested that the width of the lateral boundary should be at least nine times the tunnel diameter when conducting a numerical simulation for the steady seepage field. The relative permeability (i.e., k_r/k_g) has influences on comparisons between the analytical solutions and numerical solution, but the results remain in an acceptable range. It is also found that both the external water pressure on the grouted zone and water inflow increase linearly with the rising of the water table.

1. Introduction

Since the development of modern tunnel engineering, the subsea tunnel has become widely used for crossing rivers or seas. There are many advantages to a subsea tunnel, such as being unaffected by bad weather, requiring few land resources, and operating simultaneously with shipping operations that use the waterway (Fang et al., 2015). A subsea tunnel has a potentially infinite supply of water which cannot naturally drain off using a V-type longitudinal slope design. If full sealing is adopted to achieve a waterproof tunnel, the tunnel lining would have to sustain high water pressure for a long duration, which would result in water leakage and subsequent tunnel lining failure. If full drainage is implemented in the tunnel construction, a large-scale pumping system is needed, requiring a large amount of electric energy at high cost. Moreover, the water flowing into a subsea tunnel has strong corrosive capabilities, threatening the durability of the tunnel lining. If blocking with limited drainage is used, the water discharged into the tunnel is controlled and external water pressure on the tunnel lining is significantly reduced (Wang et al., 2008), an approach considered economical and safe.

The key to the design of blocking with limited discharge is to obtain the distribution characteristics of the seepage field, including the water inflow and pore pressure of the soil and external water pressure of tunnel lining, which can be analyzed by field monitoring, numerical simulation and theoretical analysis. Using monitoring data, Farhadian and Katibeh (2017) presented a new empirical model to evaluate groundwater flow into a circular tunnel using multiple regression analysis. The method of field monitoring is important for tunnels in construction, to avoid potential deformations and failures. Also, in designing tunnels in similar ground conditions and lining types, former monitoring data could be significant references for the new design in similar projects. Compared with field monitoring, numerical simulation can obtain the spatial distribution characteristics of the seepage field against the complex formation conditions in practical engineering. Many researchers have applied numerical simulation to calculate the external water pressure on a tunnel lining and predict the water inflow (Lee and Nam, 2001, 2004; Shin et al., 2002; Ivars, 2006; Lee et al., 2007; Arjnoi et al., 2009; Butscher, 2012). In addition, complexities such as highly pervious geological features and complex drainage systems, which affect groundwater flow into a tunnel, can be investigated using numerical simulation (Moon and Jeong, 2011; Chen et al., 2008).

Theoretical analysis is an efficient and convenient method for calculating the pore pressure distribution and predicting the water inflow into a tunnel. Harr (1962) presented the pore pressure distribution of a circular tunnel using the mirror image method. Goodman et al. (1965) predicted the analytical solutions of the water inflow for steady water inflow into undersea tunnels. Assuming a constant hydraulic head at the tunnel perimeter, Lei (1999) derived the analytical solutions to the hydraulic head distribution and water inflow for two-dimensional, steady water flow into a horizontal tunnel in a fully saturated,

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https://doi.org/10.1016/j.tust.2018.06.003
Received 12 December 2017; Received in revised form 16 April 2018; Accepted 6 June 2018

homogeneous, isotropic and semi-infinite aquifer. Based on the Mobius transformation and Fourier series, El Tani (2003) gave the exact analytical solutions to the water inflow, pressure, leakage and recharging infiltrations for a circular tunnel in a semi-infinite, homogeneous and isotropic aquifer. Kolymbas and Wagner (2007) obtained the analytical expressions of the steady state groundwater ingress into a circular tunnel using conformal mapping. The derived equations can be generally applied to deep and shallow tunnels. For deep tunnels, Wang et al. (2008) studied the influence of controlled drainage on the external water pressure on a tunnel lining by theoretical and experimental methods. The results drainage measures were necessary to reduce the external water pressure on the tunnel lining. Moreover, considering the constant hydraulic head and constant water pressure boundary conditions at the tunnel perimeter, some researchers (Park et al., 2008; Huangfu et al., 2010) derived the analytical solutions to the total hydraulic head (or pore pressure) distribution and water inflow for the steady seepage into a drained circular tunnel in a semi-infinite aquifer. Zhang et al. (2017) investigated the analytical solutions to the seepage field for a lined tunnel considering the grouting effect and validated the analytical solutions using a numerical simulation. Besides, other researches were performed to analyze the effects of the hydraulic conductivity gradient and nonlinear consolidation on the analytical solutions of the water inflow and pore pressure distribution (Zhang and Franklin, 1993; Cao et al., 2014).

As discussed, the design of tunnels below the water table has been systematically investigated by many researchers, many numerical simulations have been performed and several significant analytical solutions for the steady seepage field of tunnels have been obtained. However, most of these analytical solutions were obtained either neglecting the impact of the grouting permeability (without considering the grouted zone) or significantly simplifying the boundary conditions, and most of the numerical simulations didn't clarify the influences of the boundary conditions, either. This paper focuses on the analytical solutions for the steady seepage field of a subsea grouted tunnel, validated by a series of numerical simulations and discusses influencing factors, such as the boundary conditions, water depth and relative permeability between the grouted zone and natural ground.

2. Problem description

Fig. 1 shows the model for analyzing the steady seepage field in a subsea grouted tunnel. In this model, r_0 and r_g represent the internal and external radii of the grouted zone, respectively. The tunnel depth from the tunnel center to the ground surface is h. The water depth from the water table to the ground surface is h_w. The permeabilities of the aquifer and grouted zone are expressed as k_r and k_g, respectively.

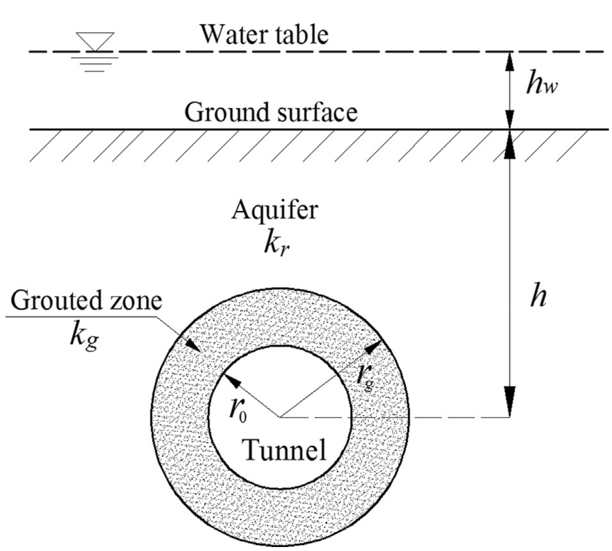

Fig. 1. Analytic model for the seepage field of a subsea grouted tunnel.

To obtain the analytical solutions for the steady seepage field of a subsea grouted tunnel, several simplifying assumptions were made:

(1) The tunnel has a circular cross-section and is located in a fully saturated, homogeneous, isotropic and semi-infinite aquifer;
(2) The grouting material is homogeneous and isotropic;
(3) A state of steady flow is assumed;
(4) The fluid is incompressible;
(5) The water table is horizontal and remains unchanged.

According to Darcy's law and conservation of mass, in fully saturated, homogeneous, isotropic media, the differential equation for two-dimensional steady-state groundwater flow is given by the Laplace equation:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \tag{1}$$

where H is the total hydraulic head and is equal to the sum of the pressure head and elevation head, that is

$$H = \frac{p}{\gamma_w} + y \tag{2}$$

where p is the water pressure, γ_w is the unit weight of water and y is the elevation head.

3. Analytical solutions

Considering the ground surface as the elevation reference datum in Fig. 1, the boundary conditions of the steady seepage field are given as follows: (1) The total hydraulic head at the ground surface remains constant and is defined as h_w; (2) A constant total hydraulic head h_{r_g} at the outer boundary of grouted zone is assumed; (3) Constant water pressure p_{r_0} at the inner boundary of grouted zone is assumed. Because of the complex boundary conditions, it is difficult to obtain analytical solutions to the steady seepage field by solving Eq. (1) directly. Consequently, the complex variable method (CVM), mirror image method (MIM) and axisymmetric modelling method (AMM) are introduced to obtain the analytical solutions for the steady seepage field of a subsea grouted tunnel.

3.1. Analytical solutions by the complex variable method (CVM)

The complex boundary conditions can be mapped conformally to simple boundary conditions by adopting the conformal mapping technique (Fang et al., 2015; Huangfu et al., 2010; Zhang et al., 2017; Bobet and Yu, 2015; Bobet, 2016), which allows one to obtain the analytical solutions to the steady seepage field. The subsea grouted tunnel is located in a semi-infinite aquifer. The previous analytic model in Fig. 1 is separated into two sections: the aquifer region (Fig. 2(a)) and the grouted zone (Fig. 2(b)). An x-y coordinate system is applied, as shown in Fig. 2.

3.1.1. Steady seepage field analysis in the aquifer region.

For the aquifer region, the appropriate conformal mapping function (Fang et al., 2015; Verruijt and Booker, 2000) is given by

$$z = \omega(\zeta) = -ih\frac{1-\alpha^2}{1+\alpha^2}\frac{1+\zeta}{1-\zeta} \tag{3}$$

where α is a ratio determined by r_g and h, namely

$$\frac{r_g}{h} = \frac{2\alpha}{1+\alpha^2} \text{ or } \alpha = h/r_g - \sqrt{(h/r_g)^2 - 1} \tag{4}$$

With the conformal mapping technique, the ground surface and outer boundary of the grouted zone in the z-plane can be mapped