

Article

An Analytical Model of Seepage Field for Symmetrical Underwater Tunnels

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Received: 15 June 2018; Accepted: 9 July 2018; Published: 11 July 2018



Abstract: Based on the mirror image method and superposition principle, an analytical model of seepage field for symmetrical underwater tunnels is proposed. The condition is assumed as two-dimensional steady water inflow into symmetrical and horizontal underwater tunnels in a fully saturated, homogeneous, isotropic, and semi-infinite aquifer. Analytical solutions of pore water distribution and water inflow into tunnels are obtained. Two different boundary conditions at the perimeter of symmetrical tunnels are considered, constant total hydraulic head and constant water pressure. Taking the subsea tunnels of Xiamen Xiang'an in China as an example, comparisons between analytical solutions and numerical solutions are analyzed in the case of zero water pressure at the perimeter of symmetrical tunnels. The results show that the analytical solutions for pore pressure distribution and water inflow match well with the numerical solutions and that the relative deviations are all in an acceptable range. The solutions derived from the analytical model in this paper can analyze the steady seepage field of symmetrical underwater tunnels accurately and reasonably.

Keywords: symmetrical underwater tunnels; steady seepage field; mirror image method; superposition principle; comparative analysis

1. Introduction

Along with advances in transportation infrastructure, more and more underwater tunnels have been under construction. During the construction process, the initial equilibrium of groundwater is broken. Water ingress may seriously influence the behavior of tunnels in the construction stage as well as in the operation stage. The safety of underwater tunnels during the construction and operation stages is threatened by the groundwater flow. Therefore, it is important and meaningful to investigate the seepage field of underwater tunnels [1–3] and predict the water ingress into tunnels in advance [4,5].

Nowadays, the commonly used methods to obtain analytical solutions of seepage fields for underwater tunnels are the complex variable method, mirror image method, and axisymmetric modeling method [6]. Based on the complex variable method, Kolymbas and Wagner [7] used the conformal mapping technique and obtained exact analytical solutions of groundwater ingress into a circular tunnel with deep or shallow buried depth. Considering the different boundary conditions at the tunnel perimeter, constant total hydraulic head and constant water pressure, Park et al. [8] and Huangfu et al. [9] derived analytical solutions of seepage field for steady water inflow into a drained circular tunnel in a semi-infinite aquifer. Zhang et al. [10] investigated analytical solutions for tunnel leakage-induced ground and tunnel responses considering the grouting effect. Ying et al. [11] derived a semi-analytical solution for groundwater ingress into lined tunnels using a conformal mapping technique. Using the mirror image method, Harr [12] presented the pore pressure distribution of a circular tunnel. Using the axisymmetric modeling method, Wang et al. [13] conducted a theoretical

and experimental study to analyze the influence of controlled drainage on the external water pressure of lining for deep tunnels. In addition, Li et al. [14] investigated analytical solutions for steady water inflow into a subsea grouted tunnel using the complex variable method, mirror image method, and axisymmetric modeling method. However, all the research mentioned above focused on single underwater tunnels. The analytical solutions of seepage field for symmetrical underwater tunnels have had little research. For symmetrical underwater tunnels, the boundary conditions are more complex than they are for single underwater tunnels. It is too hard to find an appropriate conformal mapping function, which makes it difficult to apply the complex variable method to analyze the seepage field for symmetrical underwater tunnels. When it comes to the axisymmetric modeling method, it is often used to analyze the analytical solutions of seepage field for single underwater tunnels because of the simple boundary conditions. However, due to the property of superposition for the potential function, the mirror image method can be used to analyze the seepage field for symmetrical underwater tunnels with complex boundary conditions.

This paper focuses on the analytical solutions of steady seepage field for symmetrical underwater tunnels. An analytical model of seepage field is proposed. The analytical solutions are obtained based on the mirror image method and superposition principle. A series of numerical simulations are conducted to validate the analytical solutions.

2. Problem Description

Figure 1 shows the model for analyzing the steady seepage field of symmetrical underwater tunnels in a semi-infinite aquifer. In this model, r_0 represents the radius of the tunnels. The distance between the two tunnel centers is $2b$. The tunnel depth from the center to the ground surface is h . The water table is above the ground surface. The water depth from the water table to the ground surface is h_w . The permeability of the aquifer is expressed as k .

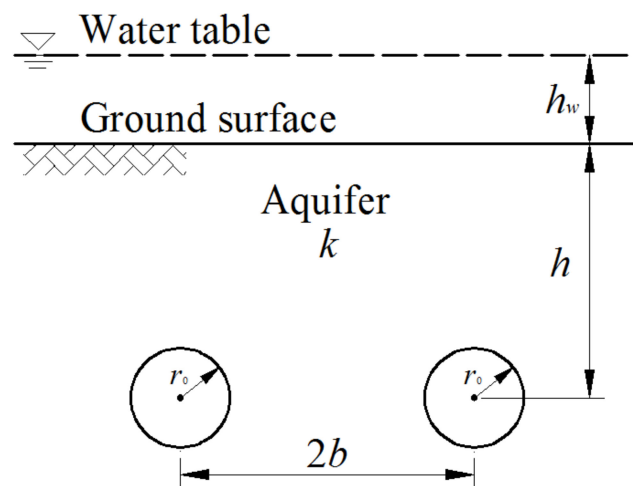


Figure 1. Model of steady seepage field for symmetrical underwater tunnels.

In order to obtain the analytical solutions of steady seepage field, several simplified assumptions are made, as follows:

- (1) Symmetrical underwater tunnels are circular and are located in a fully saturated, homogeneous, isotropic, and semi-infinite aquifer.
- (2) A state of steady flow is assumed.
- (3) The fluid is incompressible.
- (4) The water table above the ground surface 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:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \quad (1)$$

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

$$H = \frac{p}{\gamma_w} + y \quad (2)$$

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

3. Analytical Solutions

Equation (1) cannot be solved directly to obtain the analytical solutions of seepage field due to the complex boundary conditions. The mirror image method is widely used in analyzing steady seepage field. By mirroring the prototype semi-infinite seepage field into a virtual one, the problem of obtaining analytical solutions of steady seepage field in a semi-infinite aquifer is converted into a problem of obtaining such solutions in an infinite aquifer. Figure 2 describes the model to obtain the analytical solutions of steady seepage field for symmetrical underwater tunnels using the mirror image method. The ground surface is considered as the mirror face. The prototype semi-infinite steady seepage field is equivalent to a steady seepage field formed by two pumping wells, while the virtual steady seepage field is equivalent to a steady seepage field generated by two injection wells. Furthermore, the seepage velocity and water inflow of the prototype seepage field are equal to those of the virtual seepage field. The steady seepage field in an infinite aquifer composed of four tunnels is formed.

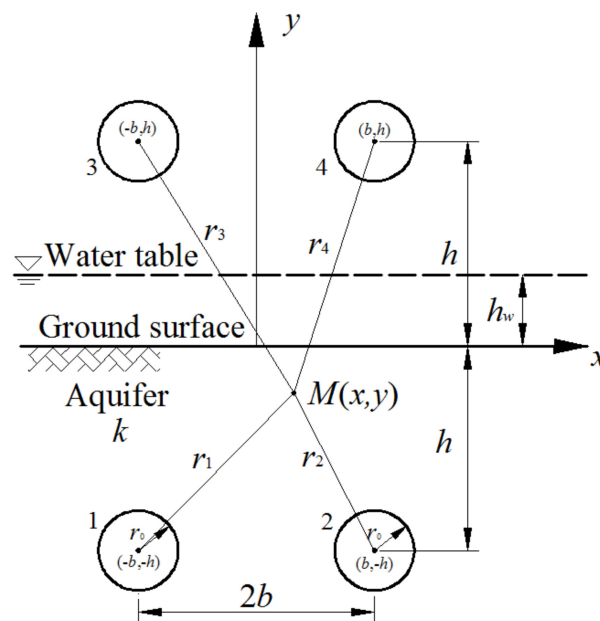


Figure 2. Analytical model using the mirror image method.

In Figure 2, tunnel 3 is the mirror image of tunnel 1, while tunnel 4 is the mirror image of tunnel 2. Because of symmetry, the water inflow for both tunnel 1 and tunnel 2 is assumed to be Q . Supposing that water inflow is positive and water outflow is negative, the water inflow for both tunnel 3 and tunnel 4 is $-Q$. A Cartesian coordinate system is applied (see Figure 2). $M(x, y)$ is a certain point in the semi-infinite aquifer; r_1, r_2 represent the distance from the point $M(x, y)$ to the centers of tunnels 1 and

2, respectively; and r_3, r_4 represent the distance from the point $M(x,y)$ to the centers of tunnels 3 and 4, respectively. According to geometric properties, r_1, r_2, r_3 , and r_4 can be denoted as:

$$r_1 = \sqrt{(x+b)^2 + (y+h)^2} \quad (3)$$

$$r_2 = \sqrt{(x-b)^2 + (y+h)^2} \quad (4)$$

$$r_3 = \sqrt{(x+b)^2 + (y-h)^2} \quad (5)$$

$$r_4 = \sqrt{(x-b)^2 + (y-h)^2} \quad (6)$$

According to Bear [15], Equation (1) can be converted into an equation in the polar coordinate system, as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial H}{\partial r} \right) = 0 \quad (7)$$

where r is the seepage radius and H is the total hydraulic head.

According to Darcy's law, the water inflow per meter of a circular tunnel can be denoted as

$$Q = 2\pi k r \frac{\partial H}{\partial r} \quad (8)$$

By integrating, H can be expressed as

$$H = \frac{Q}{2\pi k} \ln r + C \quad (9)$$

where C is the integral constant.

According to the superposition principle [15], the total hydraulic head H_M of point $M(x,y)$ in the infinite aquifer composed of four tunnels can be written as

$$\begin{aligned} H_M = \sum_{i=1}^4 H_i &= \frac{Q}{2\pi k} \ln r_1 + \frac{Q}{2\pi k} \ln r_2 + \frac{-Q}{2\pi k} \ln r_3 + \frac{-Q}{2\pi k} \ln r_4 + C \\ &= \frac{Q}{2\pi k} \ln \frac{r_1 r_2}{r_3 r_4} + C \end{aligned} \quad (10)$$

When the point $M(x,y)$ is on the ground surface (i.e., $r_1 = r_3$ and $r_2 = r_4$), the total hydraulic head is equal to h_w . Substituting this boundary condition into Equation (10), the integral constant C can be obtained as $C = h_w$.

When the point $M(x,y)$ is at the perimeter of tunnel 1 (i.e., $r_1 = r_0$), r_2, r_3 , and r_4 can be denoted as $r_2 = \sqrt{r_0^2 - 4bx}$, $r_3 = \sqrt{r_0^2 - 4hy}$, and $r_4 = \sqrt{r_0^2 - 4bx - 4hy}$. Here, x and y represent the abscissa and ordinate values at the perimeter of tunnel 1. Thus, x and y follow the relationships $-b - r_0 \leq x \leq -b + r_0$ and $-h - r_0 \leq y \leq -h + r_0$. If r_0 is small enough relative to b and r_0 is small enough relative to h , x and y can be approximately denoted as $x = -b$ and $y = -h$. r_2, r_3 , and r_4 can be approximately rewritten as $r_2 = \sqrt{r_0^2 + 4b^2}$, $r_3 = \sqrt{r_0^2 + 4h^2}$, and $r_4 = \sqrt{r_0^2 + 4b^2 + 4h^2}$.

When the point $M(x,y)$ is at the perimeter of tunnel 2 (i.e., $r_2 = r_0$), r_1, r_3 , and r_4 can be denoted as $r_1 = \sqrt{r_0^2 + 4bx}$, $r_3 = \sqrt{r_0^2 + 4bx - 4hy}$, and $r_4 = \sqrt{r_0^2 - 4hy}$. Here, x and y represent the abscissa and ordinate values at the perimeter of tunnel 2. Thus, x and y follow the relationships $b - r_0 \leq x \leq b + r_0$ and $-h - r_0 \leq y \leq -h + r_0$. If r_0 is small enough relative to b and r_0 is small enough relative to h , x and y can be approximately denoted as $x = b$ and $y = -h$. r_1, r_3 , and r_4 can be approximately rewritten as $r_1 = \sqrt{r_0^2 + 4b^2}$, $r_3 = \sqrt{r_0^2 + 4b^2 + 4h^2}$, and $r_4 = \sqrt{r_0^2 + 4h^2}$.

In the next sections, two kinds of boundary conditions are discussed to obtain the analytical solutions of steady seepage field for symmetrical underwater tunnels: (1) constant total hydraulic head H_0 at the perimeter of the tunnel and (2) constant water pressure p_0 at the perimeter of the tunnel.

3.1. Considering Constant Total Hydraulic Head H_0 at the Perimeter of a Symmetrical Tunnel

Substituting the boundary conditions into Equation (10), the total hydraulic head H_0 can be written as

$$H_0 = \frac{Q}{2\pi k} \ln \sqrt{\frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} + h_w \quad (11)$$

The water inflow of a symmetrical tunnel can be obtained as

$$Q = \frac{2\pi k(H_0 - h_w)}{\ln \sqrt{\frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}}} \quad (12)$$

Substituting Equation (12) into Equation (10), the total hydraulic head H_M of point $M(x,y)$ in the semi-infinite aquifer is denoted as

$$H_M = \frac{H_0 - h_w}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{\left[\frac{(x+b)^2 + (y+h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y+h)^2}{(x-b)^2 + (y-h)^2} \right]}{\left[\frac{(x+b)^2 + (y-h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y-h)^2}{(x-b)^2 + (y-h)^2} \right]} + h_w \quad (13)$$

According to Equation (2), the pore pressure p_M in the semi-infinite aquifer can be written as

$$p_M = \frac{\gamma_w(H_0 - h_w)}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{\left[\frac{(x+b)^2 + (y+h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y+h)^2}{(x-b)^2 + (y-h)^2} \right]}{\left[\frac{(x+b)^2 + (y-h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y-h)^2}{(x-b)^2 + (y-h)^2} \right]} + (h_w - y)\gamma_w \quad (14)$$

3.2. Considering Constant Water Pressure p_0 at the Perimeter of a Symmetrical Tunnel

When gravity is neglected and the elevation head is not taken into account, the water pressure p_0 at the perimeter of a symmetrical tunnel is described as $p_0 = \gamma_w H_0$, and the total hydraulic head at the perimeter of the tunnel is constant. Therefore, according to the derived equation in Section 3.1, the pore pressure p_M of point $M(x,y)$ in the semi-infinite aquifer can be written as

$$p_M = \frac{p_0 - \gamma_w h_w}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{\left[\frac{(x+b)^2 + (y+h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y+h)^2}{(x-b)^2 + (y-h)^2} \right]}{\left[\frac{(x+b)^2 + (y-h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y-h)^2}{(x-b)^2 + (y-h)^2} \right]} + \gamma_w h_w \quad (15)$$

Actually, the pore pressure is related to the unit weight and elevation head. Thus, referring to Huang et al. [9], the real expression of the pore pressure p_M should be assumed as

$$p_M = \frac{p_0 - \gamma_w h_w + Y(x,y)}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{\left[\frac{(x+b)^2 + (y+h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y+h)^2}{(x-b)^2 + (y-h)^2} \right]}{\left[\frac{(x+b)^2 + (y-h)^2}{(x+b)^2 + (y-h)^2} \right] \left[\frac{(x-b)^2 + (y-h)^2}{(x-b)^2 + (y-h)^2} \right]} + \gamma_w h_w + X(x,y) \quad (16)$$

where $X(x,y)$ and $Y(x,y)$ are determined by the boundary conditions.

Considering the unit weight and elevation head, the boundary conditions are described as follows: when the point $M(x,y)$ is at the perimeter of a symmetrical tunnel, $p_M = p_0$; when the point $M(x,y)$ is on the ground surface, $p_M = \gamma_w h_w - \gamma_w y$. Substituting the boundary conditions above into Equation (16), the solutions to $X(x,y)$ and $Y(x,y)$ can be found with

$$X(x,y) = -y\gamma_w \quad (17)$$

and

$$Y(x,y) = -\gamma_w h \quad (18)$$

Substituting Equations (17) and (18) into Equation (16), the pore pressure p_M of point $M(x,y)$ in the semi-infinite aquifer can be written as

$$p_M = \frac{p_0 - \gamma_w h_w - \gamma_w h}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{[(x+b)^2 + (y+h)^2][(x-b)^2 + (y+h)^2]}{[(x+b)^2 + (y-h)^2][(x-b)^2 + (y-h)^2]} + \gamma_w(h_w - y) \quad (19)$$

According to Equation (2), the total hydraulic head H_M of point $M(x,y)$ in the semi-infinite aquifer is denoted as

$$H_M = \frac{\frac{p_0}{\gamma_w} - h_w - h}{\ln \frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}} \ln \frac{[(x+b)^2 + (y+h)^2][(x-b)^2 + (y+h)^2]}{[(x+b)^2 + (y-h)^2][(x-b)^2 + (y-h)^2]} + h_w \quad (20)$$

Substituting Equation (20) into Equation (10) and considering the boundary conditions at the perimeter of a symmetrical tunnel, the water inflow of a symmetrical tunnel is calculated as

$$Q = \frac{2\pi k \left(\frac{p_0}{r_w} - h - h_w \right)}{\ln \sqrt{\frac{r_0^2(r_0^2 + 4b^2)}{(r_0^2 + 4h^2)(r_0^2 + 4b^2 + 4h^2)}}} \quad (21)$$

4. Comparison of Analytical Solutions and Numerical Solutions

4.1. Numerical Model

For the case of constant water pressure at the perimeter of a symmetrical tunnel, the analytical solutions presented in this paper are compared with the numerical solutions obtained by the program FLAC^{3D} (3.00-261, Itasca, Minneapolis, MN, USA). Taking the F4 weathered slot of the Xiamen Xiang'an subsea tunnel in China as an example, the calculating parameters are shown in Table 1. According to the research results by Li et al. [14], the lateral boundary should be at least nine times the tunnel diameter when analyzing seepage field by numerical simulation. Figure 3 shows a schematic diagram of the numerical model. The numerical model measures 377.6 m in width, 1 m in length, and 207.8 m in height. The lateral displacement boundaries are fixed in the normal direction and the displacement boundaries at the bottom are fixed in both the horizontal and vertical directions. The ground surface boundaries are free and permeable.

Table 1. Calculating parameters.

r_0 (m)	b (m)	h (m)	h_w (m)	k_r (m/s)	H_0 (m)	p_0 (Pa)
7.4	33.4	52.4	20	5.0×10^{-6}	5	0

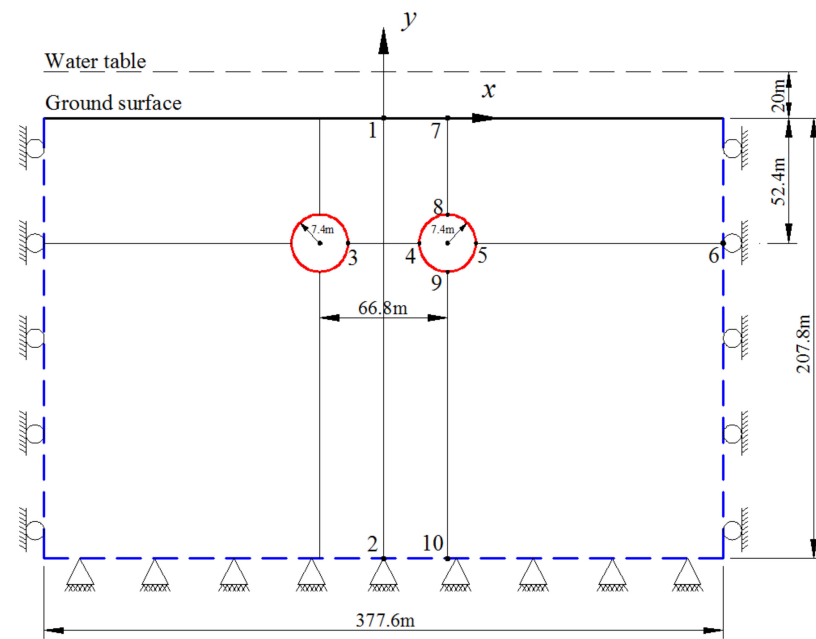


Figure 3. Schematic diagram of the numerical model.

4.2. Pore Pressure Distribution

Figure 4 shows comparisons of pore pressure distribution between analytical solutions and numerical solutions. Overall, the analytical solutions match well with the numerical solutions by the program $\text{FLAC}^{3\text{D}}$ (3.00-261, Itasca, Minneapolis, MN, USA), which indicates that the analytical solutions derived in this paper can accurately predict the pore pressure distribution of symmetrical underwater tunnels in semi-infinite aquifers. Note that in Figure 4b,d, the most significant deviations between analytical solutions and numerical solutions occur at the perimeter of symmetrical tunnels. In addition, the analytical solutions of pore pressure at the perimeter of symmetrical tunnels are not equal to the assumed constant water pressure p_0 . This is the result that approximate solutions adopt when substituting the boundary conditions at the perimeter of symmetrical tunnels into Equation (10). However, the deviations are small and in an acceptable range, especially when the tunnel radius r_0 is small enough relative to the distance b and h . Figure 4f describes a comparison of pore pressure contours between analytical solutions and numerical solutions. It is clear that the analytical solutions match well with the numerical solutions for points near the tunnels. The most significant deviation occurs at the value of 0.16 MPa, but in an acceptable range.

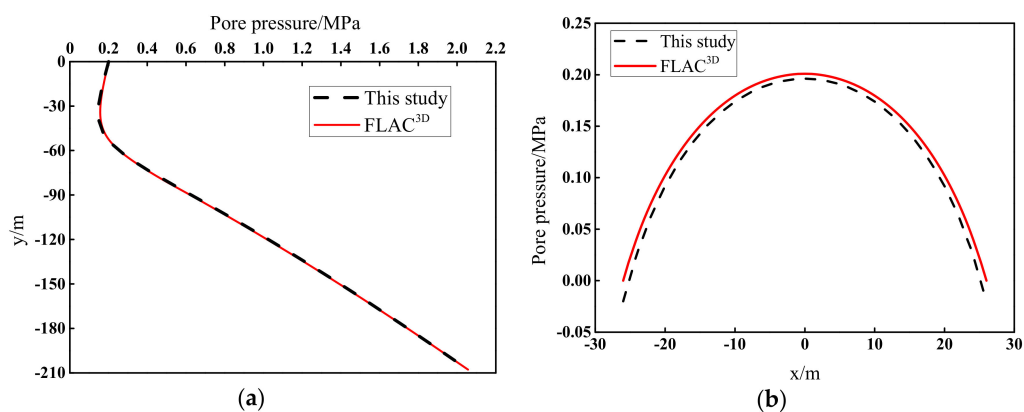


Figure 4. Cont.

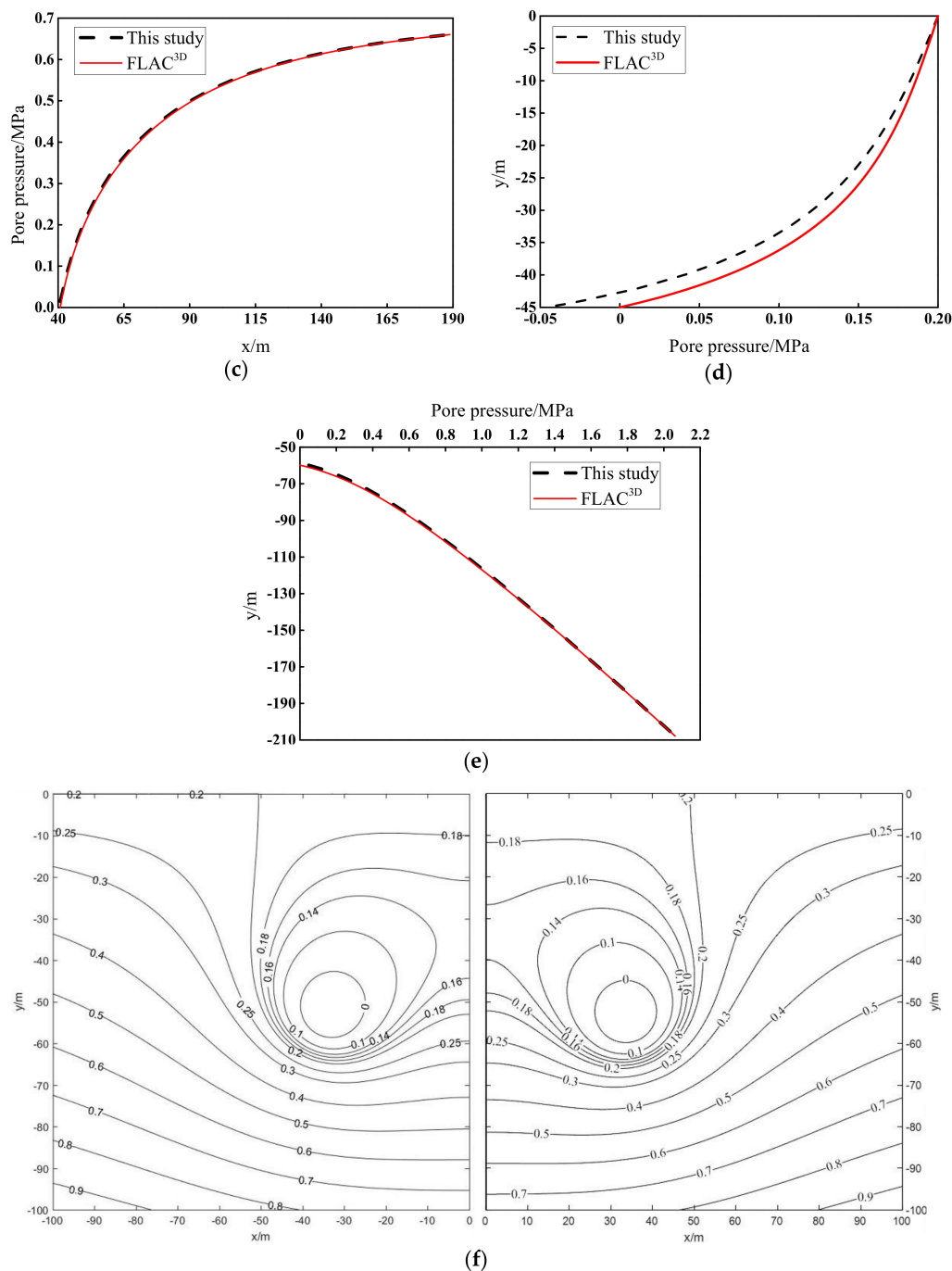


Figure 4. Comparisons of pore pressure distribution between analytical solutions and numerical solutions: (a) 1–2; (b) 3–4; (c) 5–6; (d) 7–8; (e) 9–10; (f) pore pressure (MPa) contours near the tunnel by this study (left-hand side) and FLAC^{3D} (right-hand side).

4.3. Water Inflow

Figure 5 shows a comparison of water inflow between analytical solution and numerical solution. The analytical solution of water inflow is very close to the numerical solution, just 0.43% more as predicted by the program FLAC^{3D} (3.00-261, Itasca, Minneapolis, MN, USA). It provides a safe prediction for an engineering application. Therefore, the analytical solution derived in this paper can accurately predict the water inflow of symmetrical underwater tunnels.

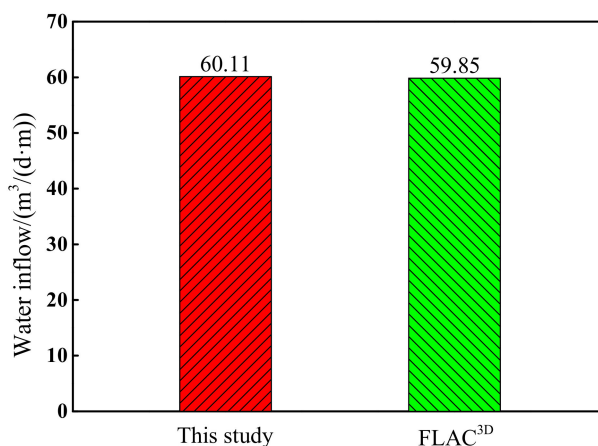


Figure 5. Comparison of water inflow between analytical solution and numerical solution.

5. Conclusions

The mirror image method is an effective method for the analysis of steady seepage field. An analytical model is proposed to obtain analytical solutions of steady seepage field for symmetrical underwater tunnels based on the mirror image method and the superposition principle. The analytical solutions of pore pressure distribution and water inflow are derived and compared with the numerical solutions obtained by the program FLAC^{3D} (3.00-261, Itasca, Minneapolis, MN, USA). The results show that the analytical solutions derived in this paper can accurately predict pore pressure distribution and water inflow for symmetrical underwater tunnels.

Author Contributions: Conceptualization, F.W. and P.L.; methodology, F.W. and P.L.; investigation, F.W. and P.L.

Acknowledgments: This research was supported by the National Natural Science Foundation of China, grant number 51778025.

Conflicts of Interest: The authors declare no conflict of interest.

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