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Determination of water flow rate into subsea deep rock cavern with horseshoe cross-section

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ABSTRACT: To reduce the risk related to water seepage during tunnel/cavern excavation, some analytical solutions for water inflow prediction corresponding to specific geological conditions have been established over the last decades. Unfortunately, these analytical solutions are only applicable for tunnels/caverns with regular cross-sections, such as circular, elliptical or square. In reality, the cross-sections for most of real tunnels/caverns are always asymmetric, such as in a horseshoe shape. Therefore, the existing analytical solutions are not very suitable for water inflow prediction.

Based on the monitoring data from a deep subsea rock cavern with horseshoe-shaped cross-section, and taking the advantages of both the analytical solutions and the numerical method, this paper proposed a semi-analytical approach for determining the water inflow rate. In this paper, the two-dimensional water inflow is described by a simplified linear equation with assumptions of Darcy's law and mass conservation. According to the monitoring data collected from the site, FLAC 2D is used to validate the correctness of the simplified linear equation, and to determine the constants in the empirical equation. Then, water flow could be estimated by the established semi-analytical solution. The approach presented in this paper offers an effective alternative to predict the water inflow rate for caverns excavated with similar hydrogeological conditions, and provides an back analysis procedure for estimating the hydraulic conductivities for rock cavern projects.

1 INTRODUCTION

For many underground projects, groundwater seepage related problems are often the most potential hydrogeological hazard, which may cause some fatalities during tunneling (e.g. rock fall, water burst), deteriorate the working conditions (e.g. unstable wall rock, unacceptable humidity), extend the construction duration, and result in an overrun budget. For example, during the construction of Seikan Tunnel in Japan, the sudden water inflow led to catastrophic face collapsing, tunnel flood, and advance stop, which had greatly postponed construction duration. In order to create underground structures safely, cost-effectively and environmental friendly, as one of the key technical challenges, groundwater control should be addressed.

A successful and effective groundwater control mainly depends on reliable hydrogeological modeling. In the past few decades, under the guidance of groundwater dynamics especially Thiem equation and Theis equation, some analytical models for estimating water inflow rate have been established, which could be utilized to build the relationship between the water inflow and the hydraulic conductivities around caverns (Lei, 1999; El Tani, 2003; Park et al., 2008). It should be pointed out that these existing analytical solutions are used only for tunnels/caverns with circular, elliptical or square cross-sections (El Tani, 1999). However, in reality the geometric shape of cross-section is often asymmetric, such as horseshoe-shaped. According to the equivalent area criterion of the flow cross sections, the traditional modeling methods usually treat asymmetric cross-section of tunnels as a circular shape for estimating the hydrogeological parameters, which is not reliable as the difference of estimated hydrogeological parameters among tunnels with different cross-sections are noticeable. For example, the maximum water inflow rate corresponds to a square cross-section, while the minimum water inflow is in circular tunnel. The difference between the maximum value and the minimum value is up to 30% (Li et al., 2010), and the difference increases with the increase of the cross-section size. Thus, for a horseshoe-shaped rock cavern with a large diameter (i.e. more than 20 m), the existing analytical solutions are not be able to predict the water inflow due to the noticeable differences.

Admittedly, numerical method is acknowledged as the most reasonable approach for estimating water flow related problems, because many factors of geological conditions could be taken into account. However, a numerical method usually requires abundant skilled professional knowledge and it is often considerably time-consuming. To take the advantages of analytical solutions and numerical method, this paper proposed a semi-analytical approach for estimating the water flow rate into a large rock cavern with horseshoe cross-section.

2 SEMI-ANALYTICAL SOLUTION FOR PREDICTION OF WATER FLOW RATE INTO A LARGE CAVERN WITH HORSESHOE SECTION

According to Darcy's law and mass conservation equation, some researchers have presented several analytical solutions to build the relationship between the hydraulic conductivity and water inflow for the circular tunnel (e.g. Lei, 1999; El Tani, 2003). Li et al. (2010) made a comparison study on various exsting groundwater flow prediction methods. Park et al. (2008) revised existing analytical solutions using a common notation and reference datum for the hydraulic head. Zhang and Franklin (1993) published an analytical solution for circular tunnel assuming a hydraulic conductivity gradient, which can be considered as an extension of Goodman's solution (1965). Most of these solutions are established under assumptions of two-dimensional flow in a plane perpendicular to the tunnel axis and circular cross-section .

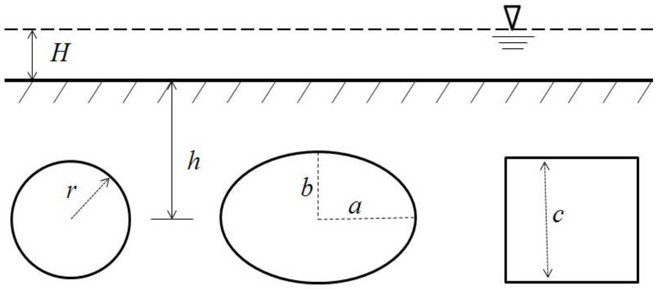

Fig.1 Tunnels with circle, ellipse and square sections in semi-infinite aquifer

When the water level is higher than the surface (or upper boundary) and the atmospheric pressure is effective inside the tunnel and at the tunnel perimeter (Fig. 1), the solution for the groundwater inflow Q, which is the volume of water per unit tunnel length, into an unlined circular tunnel can be obtained as (Park et al. 2008)

$$Q = \frac{2\pi k}{\ln\left(\frac{h}{r} + \sqrt{\frac{h^2}{r^2} - 1}\right)}\left(A + H\right) \qquad (1)$$

where h is the tunnel depth (i.e. from surface to geometric center of the cross-section), r is the tunnel radius, k is the hydraulic conductivity, H is the water head at upper boundary, and A is a parameter defined as $A = \frac{h\left(1-\alpha^2\right)}{1+\alpha^2}$, α is another parameter defined as $\alpha = \frac{h - \sqrt{h^2 - r^2}}{r}$.

In order to study more complicated scenarios, El Tani (1999) derived formula which permit the calculation of the water flow into tunnels with elliptical cross-section as

$$Q = \frac{2\pi k}{\ln \frac{4h}{a+b}\sqrt{1 + \frac{a^2 - b^2}{4h^2}}}\left(h + H\right) \qquad (2)$$

where a and b are horizontal and vertical semi-axis lengths of the elliptical cross-section, respectively (Fig. 1).

As for the sqaured cross-section, the formula is described as

$$Q = \frac{2\pi k}{\frac{6-\pi}{4} + \ln \frac{2^{\frac{3}{4}} h}{c}}\left(h + H\right) \qquad (3)$$

where c is the side length of the square (Fig. 1).

In order to estimate the water flow into tunnel with horseshoe cross-section, based on the exsting analytical solution and numerical method, we attempt to establish a relationship between water inflow and the corresponding boundary conditions. Interestingly, by making a comparison of existing analytical solutions and other empirical formulas (Li et al., 2010), it could be found that all solutions can be expressed in the following general form:

$$Q = k(S + C)H \qquad (4)$$

where S is a coefficient only related to the tunnel's shape and depth, C is another coefficient only related to the shape and depth. For a specific tunnel, the size of the cross-section and the location are fixed, so the values of S and C are also constants. The equation (4) is convenient to use in practice, if the values of S and C are given.

FLAC 2D is used to validate whether the simplified linear relationship of equation (4) is reasonable for the horseshoed cross-section, and to calculate the constants of S and C. Then, the semi-analytical solution for water inflow prediction formula would be successfully built. Thus, for future excavations of this type of cavern with similar sections, sizes and locations in the region, by using this semi-analytical solution, the water inflow Q would be effectively estimated if the water pressure data collected at the boundary (e.g. from the gallery probe holes) is available.

In addtion, according to monitored water inflow, the hydraulic conductivities at different loactions could be more accurately evaluated by back analysis method, while more geology structures are taken into consideration. Therefore, more reliable estimation of water inflow could be obtained during the continued excavation phases in future.

3 CASE STUDY: WATER INFLOW ESTIMATION FOR ROCK CAVERN WITH HORSESHOE-SHAPED SECTION

The subsea deep rock cavern cited in this paper is one cavern of the underground oil/gas storage facilities, which locates in heterogeneous sedimentary bedrock of an offshore island (Fig.2). The length is 360 m, and depth of cavern crown is -119 mACD, where ACD is the abbreviation of “Admiralty Chart Datum”. Its cross-section is horseshoe-shaped, within 20 m in width and 27 m in height. In order to provent oil leakage, there is a water curtain gallery with depth of -93 mACD above the cavern. A set of horizontal and vertical water injection holes drilled from the gallery tunnel will establish continuous horizontal and vertical water curtains for keeping oil/gas inside the cavern. During the site geological investigation and first phase excavation, the properties of the bedrock, actual water flow into the cavern, water pressure in probe holes of the water curtain gallery, groundwater table and other relevant information are monitored and collected.

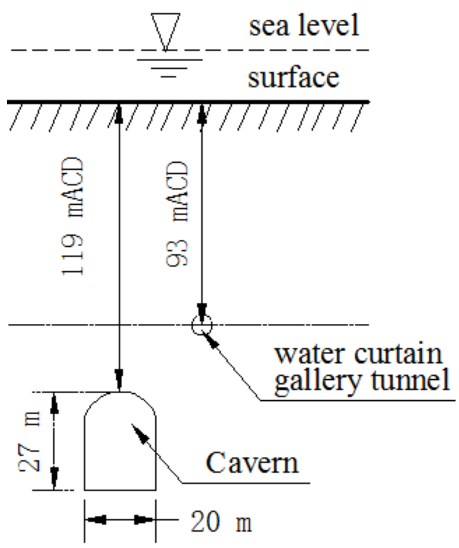

Fig. 2 The subsea rock cavern for oil/gas storage

The numerical modeling with FLAC 2D obeys following assumptions:

(1) The dimensions of the model domain are chosen large enough to ensure that the boundaries will have little effect on the calculated results.
(2) Atmospheric pressure is effective inside the cavern and at its perimeter.
(3) Groundwater flow is assumed to be steady, and hydraulic head is not uniform but higher at the cavern crown than at the invert.
(4) Upper boundary is located at -93 mACD, where is the location of water pressure monitoring holes. And lateral and downward boundaries are no-flow boundary.
(5) For the upper boundary, water pressure collected from the probe holes in gallery tunnel varies from 0 m to 120 m water column (Fig. 3 and 4), i.e the parameter of *H*.
(6) According to geologcal survey data, the vertical effective hydraulic conductivity is considered as 10^{-10} m/s in this case study.

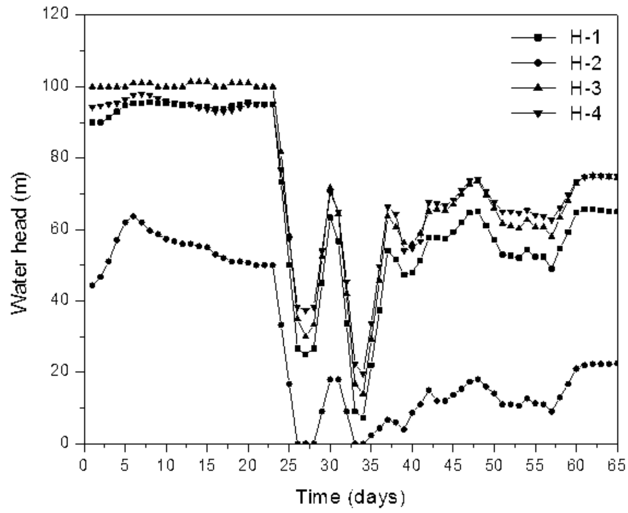

Fig. 3 Measured water heads at vertical holes (H1 - H4)

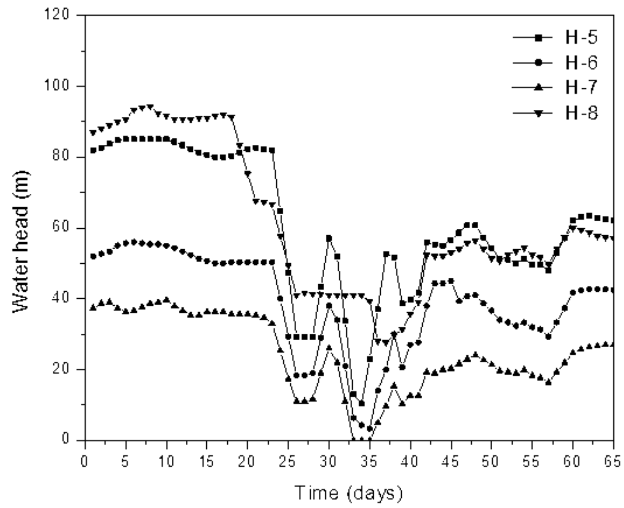

Fig. 4 Measured water heads at vertical holes (H5 - H8)

A set of values of $\frac{Q}{k}$ are obtained with changing the parameter of *H* which ranges from 0 m to 120 m water column. The results with regression analysis by EXCEL software are shown in Fig. 5. It could be find that the relationship between the water inflow and the hydraulic conductivity is linear for this specific case, which means that the assumption of Eq. (4) is at least suitable for this project, and values of S and C are 118.86 and 3.21, respectively.

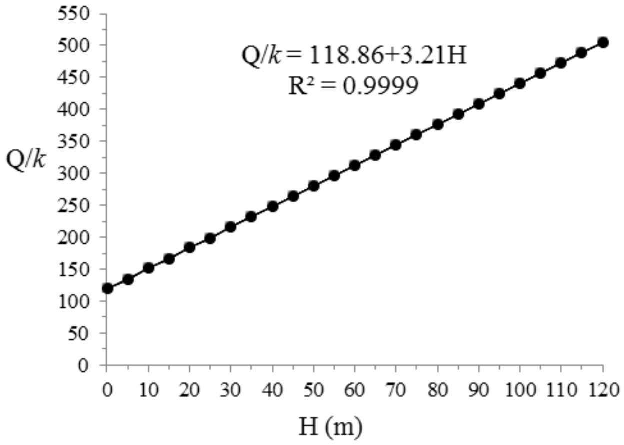

Fig. 5 Determination of the two parameters S and C

Thus, for this specific project, the semi-analytical solution for water inflow prediction in a subsea rock cavern with horseshoe-shaped section is established as equation (5), which will be easily and conveniently used to predict the water inflow into cavern during further excavation of this cavern or nearby caverns with similar sections and sizes and locations in the future.

$$\frac{Q}{k} = 118.86 + 3.21H \tag{5}$$

According to equation (5), water inflow rate data monitored during the 65 days after the whole cavern and gallery are fully excavated are used for model calibration and validation, as shown in Fig. 6. It could be found that the calculated water inflow rate approximately equates to the monitored water inflow rate, which means the results got from the semi-analytical solution are acceptable and reliable.

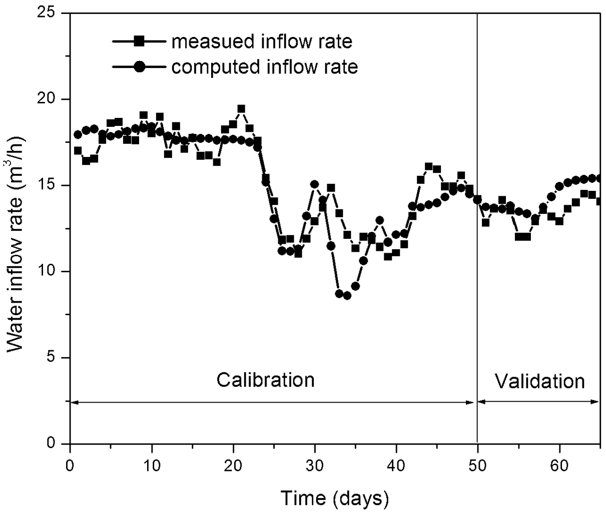

Fig. 6 Monitored and calculated water flow rates

4 CONCLUSIONS

In the field of underground space development, how to evaluate the hydrogeological conditions is often a challenging and significant task, which is vital to cost-effective underground structures design and construction. In this paper, based on exsting analytical solutions for water inflow approximation, the two-dimensional water inflow around the cavern/tunnel with horseshoe-shaped section is described by a simplified linear equation. Then, according to the hydrogeological investigation and water pressure data collected from a real project site, FLAC 2D is adopted to validate the simplified linear equation, and to determine the semi-analytical solution. Thus, the semi-analytical solution for a specific project is sucessfully built, which offers another effective approach to predict the water inflow rate for future excavation of this cavern or neary caverns with similar conditions. Moreover, the established semi-analytical solution could be employed to back analyze hydraulic conductivities along the length of the cavern while more geological factors such as joints and faults are cosidered.

It should be pointed out that the presented approach offers an alternative for estimating the water inflow rate and other hydraulic parameters. At the early stage of the project, on the basis of limited geological survey data, the semi-analytical solution can offer a preliminary evaluation of water inflow. With more data collected during the continued construction, the semi-analytical solution could be utilized to further back analyze the hydrogeological parameters such as hydraulic conductivities, which will provide a more accurate estimation of water inflow in future.

The proposed semi-analytical method in this paper is just suitable for predicting the average of total water inflow due to the assumptions of homogeneous and isotropic properties of the ground. However, actual geology properties are always inhomogeneous and anisotropic and discontinuous, and geological structures such as faults and fissures usually play a crucial and controlling role in the process of water flow. Thus, for a more accurate evaluation of hydrogeological parameters, advanced analysis should be further studied in the future, where the discrete properties of strata are taken into consideration.

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