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Back-analysis approach for the determination of hydraulic conductivity in rock caverns

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ABSTRACT

Water seepage related problem is often the major geological hazard in underground rock excavation. In order to reduce the risk associated with extensive seepage, a reliable hydro-geological model should be established based on the in-situ investigation data. One of the challenges for establishing a reliable hydro-geological model is on how to determine the hydraulic conductivities of the fractured rock masses using the limited in-situ investigation data. In this study, a back-analysis approach for the determination of the hydraulic conductivities along a rock cavern is presented. To take the advantages of both the analytical solutions and the numerical methods, this paper proposed a semi-analytical approach for prediction of the water inflow into caverns with the horseshoe section, and the semi-analytical solution is used for the back-analysis of the hydraulic conductivity around a rock cavern based on the in-situ monitoring data. The hydraulic conductivities are obtained by using the EXCEL spreadsheet's build-in optimization routine SOLVER to minimize the error function. The computed water inflow into the cavern is compared with the in-situ measured data. The results indicate that the derived hydraulic conductivity is acceptable.

1. Introduction

In the development of underground rock caverns for various uses, such as hydrocarbon storage (Kiyoyama, 1990) and hydropower projects (Li et al., 2008), the groundwater control during the excavation phase and in the operation phase plays a critical role in terms of construction cost and duration, and construction safety. As witnessed in many underground projects all over the world, water seepage related problems have been identified as the dominant geological hazards (Rebekka et al., 2003), which may potentially lead to: accidents during the construction, deterioration in working conditions which may threaten to worker's safety, rock-falls, settlement of aboveground buildings, extended construction duration and a high cost (Schwarz et al., 2006).

In order to reduce the risks associated with the seepage, a reliable hydro-geological model should be established based on the in-situ investigation data. For many projects, the hydro-geological model is established simply based on the arithmetic average or linear interpolation of the borehole data with laboratory and in-situ tests (Sun and Zhao, 2010), which is often not reliable. Actual hydro-geological field is anisotropic and heterogeneous, but information on the hydro-geological setting is sparse. Limited boreholes are often used to get a profile of hydraulic conductivity versus depth at specific locations. In addition, geophysical survey can provide the thickness of weathered zone, the depth of the fresh rock mass and the location of fault zone or water bearing zone. The key challenging issue during site investigation phase is how to integrate limited geological and hydro-geological data to establish a reliable hydro-geological model.

The neural network (NN) is a flexible data mining tool to establish an input–output mapping. It has been successfully applied in a wide range of civil engineering applications, such as in fault detection (Jakubek and Strasser, 2004), and preliminary hydro-geological modeling (Sun et al., 2011), which can be used to calculate the total water inflow into the underground caverns, a critical factor for construction planning and construction cost evaluation.

Numerical modeling using finite element and finite difference schemes can be used in various complicated geological conditions and is suitable for various shapes of the cavern section. However, it is tedious and time-consuming. On the other hand, many analytical solutions (Lei, 1999; El Tani, 2003; Park et al., 2008) on prediction of water flow into rock tunnel corresponding to specific conditions have been proposed which can be used easily to establish the relationship between the water inflow and the hydraulic conductivity around caverns. However, these analytical solutions are only applicable to caverns with simple geometrics, such as circular, elliptical or square cross-sections (El Tani, 1999).

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During the construction phase, there are more site data available around the excavation area, such as water pressure monitoring and seepage water measurement, but these data are often not fully utilized to analyze the mechanism of the seepage problem and to update the preliminary hydro-geological model. This paper continues our study on the determination of hydraulic conductivities of the rock masses (Sun and Zhao, 2010; Sun et al., 2011) for an underground rock cavern project. As the cavern is excavated, the data of water quantities into the underground rock cavern are collected together with the water pressure information at various locations measured through previously installed piezometers. This proposed model, named as "back-analysis approach", considers adequately the data collected from the site measurements during excavation. It consists of minimizing the error function, which is employed to refine the preliminary hydro-geological model and to build a reliable hydro-geological model. Then, it could be used for the back-analysis of the hydraulic conductivities. In this paper, the main hydrogeological features of a real project are described, the analytical and numerical models of groundwater flow are shown, and details of the implementation of back-analysis are also provided. Finally, the model calibration and testing as well as a discussion of the main achievements are presented.

2. Preliminary semi-analytical solution for water inflow estimation

In order to back calculate hydraulic conductivity, one of the most popular approaches is the comparison of the measured inflow data with modeled inflows, and then the relationship between water inflow and the hydraulic conductivity can be established. Several researchers presented analytical solutions to establish the relationship between the hydraulic conductivity and water inflow for the circular tunnel (Lei, 1999; EI Tani, 2003). Park et al. (2008) revised and compared existing analytical solutions using a common notation and reference datum for the hydraulic head. Zhang and Franklin (1993) presented an analytical solution for the circular tunnel assuming a hydraulic conductivity gradient, which can be regarded as an extension of the solution of Goodman (1965). Most of these models assume two-dimensional flow in a plane perpendicular to the tunnel axis and the tunnel has a circular geometry. When the water level is higher than the ground surface (or upper boundary) and 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).

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

where h is the tunnel depth, r is the tunnel radius, k is the hydraulic conductivity, H is the water depth at the upper boundary, α is a

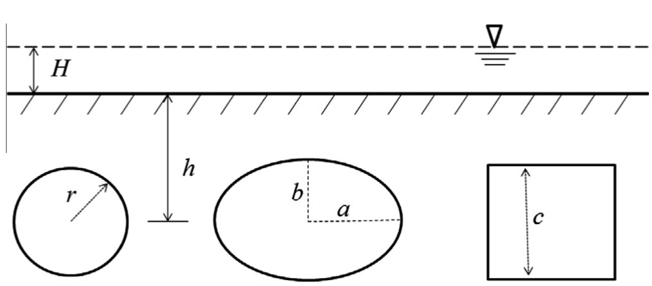

Fig. 1. Tunnels with different shapes in a semi-infinite aquifer (circle, ellipse and square).

parameter defined as $\alpha = (h-\sqrt{h^2-r^2})/r$, and A is the other parameter defined as $A = h(1-\alpha^2)/(1+\alpha^2)$.

In order to study more complicated scenarios, EI Tani (1999) derived formulae which permit the calculation of the water inflow into tunnels of elliptical or square cross-sections as

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

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

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

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

It should be noted that it is common to use the analytical solution to estimate the water inflow of a cross-section if it is close to one of the mentioned standard cross-sections, which is not reliable as the differences of estimated hydrogeological parameters among tunnels with different cross-sections are noticeable. For example, the maximum water inflow rate corresponds to a tunnel with the square cross-section, while the minimum water inflow is for a circular tunnel. The difference between the maximum value and the minimum value is up to 30% (Pengfei 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 suitable for prediction of water inflow due to the significant differences.

Over the last few decades, the numerical methods have been acknowledged as the most reasonable approach for estimating water flow related problems as many factors of geological conditions could be taken into account. However, a numerical method usually requires abundant skilled professional knowledge on geological and hydrogeological information and it is often considerable time-consuming. To take partial advantages of analytical solutions and numerical methods into account, this paper proposed a semi-analytical approach for preliminary hydrogeological modeling, which could be used to calculate the total water inflow around the cavern with horseshoe section.

Based on the existing analytical solutions 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 (i.e. Eqs. (1)–(3)) and other empirical formulas (Pengfei et al., 2010), it could be found that when the water level is higher than the upper boundary and atmospheric pressure is effective at the tunnel perimeter, the relationship between water inflow and the hydraulic conductivity for any cross-section can be expressed in the following general form:

$$\frac{Q}{k} = S + CH \tag{4}$$

where S and C are the two coefficients only related to the tunnel's shape and depth. For a specific cavern, the size of the cross-section and the location are fixed, so the values of S and C are also constants. Eq. (4) is very convenient to use, if the values of S and C are given. However, the parameters of S and C should be recalculated if the cross-section and depth of rock caverns are changed, even though the caverns locate in the same construction site.

In order to determine S and C for a specific case, the code FLAC is adopted to model the groundwater flow into the caverns. In FLAC code, one value of Q/k can be calculated if a certain water pressure H is given. A group of Q/k values will be obtained with changing the parameter of H which ranges from 0 m to 120 m water column at the upper boundary. The results of S and C can be determined by regression analysis. Then, the preliminary semi-analytical solution for water inflow prediction formula would be successfully built,