Determination of hydraulic conductivity of fractured rock masses: A case study for a rock cavern project in Singapore

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Abstract

In order to reduce the risk associated with water seepage in an underground rock cavern project in Singapore, a reliable hydro-geological model should be established based on the in situ investigation data. The key challenging issue in the hydro-geological model building is how to integrate limited geological and hydro-geological data to determine the hydraulic conductivity of the fractured rock masses. Based on the data obtained from different stages (feasibility investigation stage, construction stage, and post-construction stage), suitable models and methods are proposed to determine the hydraulic conductivities at different locations and depths, which will be used at other locations in the future.

1. Introduction

The rock cavern project located at an offshore island in Singapore is an underground liquid hydrocarbon storage facility. The underground storage rock caverns have many advantages over the aboveground storages, in terms of protection against fire, earthquake and explosion, and can save substantial aboveground land for other better uses. The underground rock caverns are also superior in terms of environmental conservation, because the sealing effects of groundwater ensure that there is less danger for the stored oil to leak out to the ground surface (Kiyoyama, 1990).

The rock caverns are located at a depth of 130 m beneath a basin, and their crowns are located at about 100 m below the sea bottom. Each rock cavern is excavated by drill-and-blast method, and then lined by a high-pressure spray "shotcrete". This project includes a number of caverns/tunnels at two levels: the water curtain tunnels are at upper level, and oil storage caverns are at lower level. Groundwater seeps through rock joints, exerting a pressure known as hydrostatic pressure to keep oil from leaking out of the rock mass. The water curtain helps to provide a stable pressure distributed around the caverns. Pressure gauges are installed in the water curtains, and water from the operational and access tunnels is injected continuously into the curtains to maintain the pressure.

The water that seeps into the cavern is collected using sumps within the caverns, and then treated and discharged into the sea.

As witnessed in many underground projects all over the world, water seepage related problem is considered as one of the main geological hazards which may potentially cause: accidents, deteriorated working conditions and threat to workers' safety, rock falls, settlement of aboveground buildings, extended construction duration, and a high cost. The groundwater control during the construction (i.e. excavation) phase and the operation phase plays a critical role in terms of construction/operation cost and construction safety. In order to reduce the risk associated with the groundwater seepage, a reliable hydro-geological model should be established based on the in situ investigation data. The key challenging issue is how to integrate limited geological and hydro-geological data to determine the hydraulic conductivity of the fractured rock masses. For this project, various data are collected at different stages: feasibility investigation stage, construction stage, and post-construction stage. This paper tries to propose suitable models and methods to determine the hydraulic conductivity of the fractured rock masses based on different monitored data.

2. Determination of the hydraulic conductivity at the site investigation stage

At the site investigation stage, six vertical boreholes were drilled to investigate the hydraulic properties of the fractured rock masses. The locations of six vertical boreholes B1 to B6 are shown in Fig. 1. The basic information of the six boreholes is listed in Table 1. The fracture orientation data and dip/dip angle were obtained from the borehole survey. In total, 72 hydraulic conductivity measurements as listed in Table 1 were conducted in the six boreholes, by the
Fig. 2 presents the measured hydraulic conductivity data at the six boreholes at the depth between $-40$ mACD and $-200$ mACD, where ACD stands for admiralty chart datum. The results show that the hydraulic conductivity varies between $10^{-11}$ m/s and $10^{-4}$ m/s. It should be noted that the hydraulic conductivities obtained from the correlation curve of injected water pressure and flow quantity of the injected water (Spane and Wurstner, 1993; Chakrabarty and Enachescu, 1997) are based on the assumptions that the fractured rock masses are homogenous, isotropic and porous media, and the flow geometry is cylindrical, which do not reflect the anisotropic property of the fractured rock masses. In order to derive the local stress regime at the proposed development area, 10 hydrofrac/hydraulic injection tests were conducted in the uncased section of borehole B5 between $-96$ mACD and $-181.4$ mACD. A typical test record illustrating the test procedure is shown in Fig. 3, and the results of the stress field inversion calculations are shown in Fig. 4.

In order to obtain anisotropic permeability $k_{ij}$ along the boreholes, the following assumptions are made:

1. Each fracture is idealized by a set of parallel plates with a uniform aperture $t$.
2. The solid matrix is impermeable.
3. The hydraulic gradient is uniformly distributed over the whole body.
4. Seepage flow through a fracture can be treated as laminar flow between parallel plates with a uniform aperture.
5. There is no water head loss at intersections between fractures.

Table 1
Basic information of six boreholes.

<table>
<thead>
<tr>
<th>Borehole no.</th>
<th>Length (m)</th>
<th>Depth (mACD)</th>
<th>Fracture data</th>
<th>Number of hydraulic conductivity measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>143</td>
<td>$[-50, -193]$</td>
<td>1175</td>
<td>10</td>
</tr>
<tr>
<td>B2</td>
<td>122</td>
<td>$[-71, -193]$</td>
<td>943</td>
<td>10</td>
</tr>
<tr>
<td>B3</td>
<td>148</td>
<td>$[-45, -193]$</td>
<td>682</td>
<td>11</td>
</tr>
<tr>
<td>B4</td>
<td>158</td>
<td>$[-46, -204]$</td>
<td>978</td>
<td>14</td>
</tr>
<tr>
<td>B5</td>
<td>167</td>
<td>$[-44, -211]$</td>
<td>648</td>
<td>14</td>
</tr>
<tr>
<td>B6</td>
<td>160</td>
<td>$[-50, -210]$</td>
<td>936</td>
<td>13</td>
</tr>
</tbody>
</table>
Based on the above assumptions, the fractured rock masses can be treated as equivalent continuous media, and Oda (1985) proposed hydraulic conductivity components as follows:

\[
k_{ij} = \frac{\lambda g}{v} \left( P_{kk} \delta_{ij} - P_{ij} \right)
\]

where

\[
P_{ij} = \frac{\pi \rho}{4} \int_0^\infty \int_0^\infty \int_\Omega r^2 t^3 n_i n_j E(n, r, t) d\Omega dr dt
\]

\[
P_{kk} = P_{11} + P_{22} + P_{33}
\]

where \( g \) is the gravitational acceleration; \( v \) is the kinematic viscosity; \( \lambda \) is a dimensionless scalar dependent on the connectivity among joints and can be set to 1/12 for practical applications (Oda et al., 1987); \( \delta_{ij} \) is the Kronecker delta; \( \rho \) is the number of joints per unit volume; \( n_i \) is the component of \( n \) projected on the orthogonal reference axis system \( (x_i = 1, 2, 3) \); \( E(n, r, t) \) is the density function; \( r \) is the fracture length; \( k_{ij} \) and \( P_{ij} \) are both symmetric second-rank tensors, and have the principal values in the principal directions.

The aperture \( t \) can be obtained as follows (Cheng, 2006):

\[
t = r \left( \frac{1}{c} - \frac{\sigma_y n_j n_j}{h + c \sigma_y n_j} \right)
\]

then

\[
P_{ij} = \frac{\pi \rho}{4} \int_0^\infty \int_0^\infty \int_\Omega \left( \frac{1}{c} - \frac{\sigma_y n_j n_j}{h + c \sigma_y n_j} \right)^3 r^5 n_i n_j E(n, r) d\Omega dr dt
\]

The number of joints per unit volume \( \rho \) can be obtained as follows (Cheng, 2006):

\[
\rho = \frac{N_{jk}}{l}
\]

where \( N_{jk} / l \) is the number of fractures crossed by unit length of a scan line in the direction \( q \). With the assumption that the statistical

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**Fig. 2.** Hydraulic conductivity with increasing depth at the six boreholes.

**Fig. 3.** A typical set of injection pressure and flow rate records of hydraulic fracturing test.

**Fig. 4.** Stress profile for borehole B5. \( S_h \) and \( S_v \) are the minimum and maximum horizontal principal stresses, respectively; and \( S_t \) is the vertical principal stress. The direction of the maximum horizontal stress \( S_h \) is N10°/C14° (NNE–SSW).
variables \( n \) and \( r \) are mutually independent, the density function \( E(n, r) \) is given by Oda (1985) as follows:

\[
E(n, r) = E(n)f(r)
\]

where \( E(n) \) and \( f(r) \) are the probability density functions of \( n \) and \( r \), respectively. The density function \( E(n) \) can be obtained from the in situ fracture orientation survey. The distributed forms of fracture length, i.e. \( f(r) \), can be considered as negative exponential or lognormal form (Dershowitz and Einstein, 1988). A lognormal distribution function \( f(r) \) is adopted:

\[
f(r) = \frac{1}{r \sigma_{\log} \sqrt{2\pi}} \exp \left[ -\frac{(\log r - \mu_{\log})^2}{2 \sigma_{\log}^2} \right]
\]

where

\[
\sigma_{\log} = \sqrt{\log_{10} \left[ 1 + \left( \frac{\sigma}{\mu} \right)^2 \right]}
\]

\[
\mu_{\log} = \log_{10} \left( \frac{1}{2} \left( \log_{10} \left[ 1 + \left( \frac{\sigma}{\mu} \right)^2 \right] \right) \right)
\]

where \( \mu \) and \( \sigma \) are the mean and standard deviations, respectively. Based on above equations, the hydraulic conductivity can be estimated if in situ stress \( \sigma_{\text{in}} \), the fracture orientation information \( E(n) \), scan line direction \( q \) and fracture magnitude along the scan line and parameters \( c, h, \mu \) and \( \sigma \) are known. More details can be found in Cheng (2006) and Sun and Zhao (2010).

Based on the parameter sensitivity analysis, the ratios of anisotropic hydraulic conductivity, defined as \( k_1/k_3 \) and \( k_1/k_2 \), are mainly controlled by the fracture orientation distribution and in situ geostatic stress. The influence of joint size, normal stiffness constant and aspect ratio on anisotropy is negligible (Cheng, 2006). The fracture orientation information in each borehole and in situ stress in borehole B5 are used to determine the anisotropic hydraulic conductivity along the six boreholes. The analysis results show that \( k_1 \) and \( k_2 \) are almost in horizontal directions, and \( k_3 \) is close to vertical direction. As \( k_1 \) and \( k_2 \) are almost the same and along horizontal direction, the hydraulic conductivity measured from the injection test can be considered approximately as the average value of \( k_1 \) and \( k_2 \). Because the influence of joint size, normal stiffness constant and aspect ratio on anisotropic hydraulic conductivity is very little, any parameter can be changed until the average value of \( k_1 \) and \( k_2 \) equals the hydraulic conductivity measured from injection test, then the hydraulic conductivity components can be considered as the real anisotropic hydraulic conductivities along these boreholes. Table 2 lists the six anisotropic hydraulic conductivity components and three calculated principal hydraulic conductivities.

### Table 2

<table>
<thead>
<tr>
<th>Components of hydraulic conductivity</th>
<th>Principal hydraulic conductivities</th>
<th>In situ measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_x )</td>
<td>( k_y )</td>
<td>( k_z )</td>
</tr>
<tr>
<td>( 1.49 \times 10^{-10} )</td>
<td>( 1.43 \times 10^{-10} )</td>
<td>( 8.1 \times 10^{-11} )</td>
</tr>
</tbody>
</table>

3. Determination of the hydraulic conductivity at the construction stage

An important part of the project during the construction stage is the characterization of the hydraulic properties of the rock mass through probe holes during the excavation. The work involves the drilling of a number of probe holes from the tunnel front. The water flow rate and water pressure are measured near the water-bearing zone with 79 measured data at five sections, to estimate the hydraulic properties of the rock mass. Based on the measured data, the hydraulic conductivity can be derived based on the following equation (Goodman et al., 1965; Fernandez, 1994):

\[
k = \frac{2.33Q}{2\pi L} \log_{10} \frac{L}{H}
\]

where \( Q \) is the measured water flow rate at the site \((m^3/s)\), \( L \) is the drill hole length \((m)\), \( r' \) is the drill hole radius \((m)\), and \( H \) is the hydraulic head \((m)\). Fig. 5 shows the cumulative distribution plot of the 79 hydraulic conductivity data. It shows that the hydraulic conductivity at the water-bearing zone is in the order of \( 10^{-6} \) m/s and the average value is \( 1.73 \times 10^{-6} \) m/s. In this case, grouting is used to reduce the hydraulic conductivity in the water-bearing zone and some check holes are used to measure the water flow and the water pressure after grouting. When reducing the seepage flow rate or improving the rock mass conditions is needed, grouting will be carried out prior to the excavation:

(1) If the measured flow rate \( Q \) is greater than the predefined threshold value \( Q_1 \) for the total water ingress in a certain probe hole.

(2) And/or if the local increment of the water ingress \( Q' \) on a 3 m interval is greater than the threshold value \( q' \).

The predefined threshold values of \( Q_1 \) and \( q' \) can be calculated by Eq. (12), and \( k \) is the acceptable hydraulic conductivity (i.e.

![Fig. 5. Cumulative distribution of hydraulic conductivity at the water-bearing zone.](Image)
In this study, we use $k = 1 \times 10^{-7}$ m/s for $Q_1$ and $k = 5 \times 10^{-7}$ m/s for $q_0$.

The hydraulic conductivity after grouting is evaluated again based on Eq. (12). The results show that the hydraulic conductivity after grouting is in the order of $10^{-7}$ m/s as shown in Fig. 6. It means that the reduction of permeability of the grouted rock mass is successful.

4. Determination of the hydraulic conductivity at the post-construction stage

The practical range of hydraulic conductivity in fractured rock is typically having a large range. It is very hard to determine the hydraulic conductivity along the cavern length. In order to have an in-depth understanding in the hydro-geological behavior, the water flow data, including water pressure, groundwater table and rainfall, were monitored and collected. In this study, only the hydraulic conductivities around Cavern A at lower level (Fig. 7) are studied. The hydraulic heads at eight control points in Tunnel A at upper level (Fig. 7) were monitored and the water flow into Cavern A was collected. Data monitored during the 65 d after the Cavern A and Tunnel A were totally excavated are used for model calibration and validation, as shown in Figs. 8 and 9.

In order to back calculate hydraulic conductivity, one of the most popular approaches is to compare the measured inflow data with modeled inflows, and the relationship between water inflow and 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 (e.g., Lei, 1999; El Tani, 2003). In order to study more complicated scenarios, El Tani (1999) derived formulas which permit the calculation of the water inflow into tunnels in elliptical or square cross-section. Until now, there is no analytical solution available in general for the water inflow of tunnels in horseshoe cross-section. In order to derive the relationship, the code FLAC is adopted to...
model the groundwater flow into the caverns, with 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 that at the invert.
(4) The upper boundary is located at −93 mACD, coinciding with the location of the water pressure monitoring holes. And the lateral and the bottom boundaries are no-flow boundary.
(5) For the upper boundary, water pressure obtained from the probe holes in gallery tunnel varies from 0 m to 120 m water column (Fig. 8), i.e. the parameter of $H$.
(6) According to geological survey data, the vertical effective hydraulic conductivity is considered to be $10^{-10}$ m/s in this case study.

Groundwater is assumed to obey Darcy’s law and is incompressible. The shape of the cavern is horseshoe, with the height of 27 m and the width of 20 m. Based on the numerical results, the relationship between the water inflow and the hydraulic conductivity around Cavern A can be determined as

$$Q = k(118.85 + 3.21H)$$  \hfill (13)

In this project, only eight control points were installed to monitor the water pressure along Tunnel A, so the rock mass around the Cavern A is assumed to have eight hydro-geological units, and each unit has a constant hydraulic conductivity. Data monitored during the first 50 d were used for model calibration. Measured data after 50 d were used to test the validity of the model. The back analysis consists of minimizing an error function $E$ that represents the discrepancy between the water inflow into the Cavern A in the field and the corresponding computed results, which in turn depend on eight unknown coefficients of hydraulic conductivity $k_j$:

$$E = \sum_{i=1}^{80} \left| Q_i^m - \sum_{j=1}^{8} Q_j L_j \right|$$ \hfill (14)

where $Q_i^m$ is the measured water inflow into Cavern A, $Q_j$ is the computed water inflow at the different units, and $L_j$ is the length of each unit. The error defined by Eq. (14) is a nonlinear function of the unknown parameters $k_j$ and its gradient cannot be determined analytically. The eight unknown coefficients of hydraulic conductivity are obtained by using the EXCEL spreadsheet’s build-in optimization routine SOLVER to minimize the error function in Eq. (14) by changing the $k_j$ values, under the constraint that all the hydraulic conductivities are larger than $10^{-10}$ m/s and less than $10^{-6}$ m/s and the hydraulic conductivity around the water-bearing zone is larger than that at other locations. Prior to invoking the SOLVER search algorithm, the eight unknown coefficients of hydraulic conductivity are randomly set between $10^{-10}$ m/s and $10^{-6}$ m/s. Iterative numerical derivatives and directional search for the eight unknown coefficients of hydraulic conductivity are automatically carried out in the spreadsheet environment. More details on the implementation of the EXCEL spreadsheet can be found in Zhang and Goh (2012). Fig. 9 shows the time evolution of the water inflow into the Cavern A. The result shows that the back-analysis model reproduces the trend of measured flow rates.

The hydraulic conductivity distribution along the length of the Cavern A is shown in Fig. 10. The result illustrates that the hydraulic conductivities are mainly in the order of $10^{-10}$ m/s except two locations where the water-bearing zones are intersected with the Cavern A. For this project, the target hydraulic conductivity after grouting is in the order of $10^{-7}$ m/s. The result shows that the computed hydraulic conductivities at the two water-bearing zones are in the order of $10^{-7}$ m/s, which means that the computed results are close to the real condition and can be acceptable to represent the hydro-geological condition around the Cavern A.

5. Conclusions

In order to reduce the risk associated with the groundwater seepage, reliable hydro-geological model should be established based on the in situ investigation data. The key challenging issue is how to integrate limited geological and hydro-geological data to determine the hydraulic conductivity of the fractured rock masses. For this project, different data are collected at different stages: site investigation stage, construction stage, and post-construction stage. This paper proposes suitable models and methods to determine the hydraulic conductivity at specific locations based on monitored data. The semi-analytical method for anisotropic permeability estimation provides background knowledge for site measurement based estimation models in Sections 3 and 4. At this stage, only the data of water pressure and water flow rate are
utilized. We will add the fracture orientation information in our further study to capture the anisotropic characteristics.

When the hydraulic conductivities are known at some specific locations, determination of hydraulic conductivities at other locations is another challenging issue, because the fractured rock masses are heterogenous media. The artificial neural network, which is a computational model for information processing based on the biological neural networks, can be used to determine the hydraulic conductivities at other locations (Sun et al., 2011). Based on the obtained hydraulic conductivity at different locations and depths, the reliable hydro-geological model can be established. At the same time, the reliability of the proposed model can be updated if more boreholes or more monitoring data are provided.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References


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