A numerical method for predicting groundwater inflow into mountain tunnel, taking into account rainfall recharge and lithological distribution over a large area

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Abstract: Groundwater inflow is related to the safety of the tunnels and the groundwater ecological environment around the tunnel site. Despite the tremendous effort invested in the area, there are few numerical methods for predicting groundwater inflow into a tunnel, taking into account the crossing faults and complex hydrogeology with different lithological distributions. This study presents a numerical method for predicting groundwater inflow into a tunnel using ModFlow software, which considers factors such as rainfall recharge, large area three-dimensional topography, faults, and lithological distribution. Based on groundwater inflow data, hydraulic conductivity inversion is performed to obtain the actual permeability of the surrounding rock. Then the proposed numerical method is verified against the results obtained on the site. Finally, the difference between groundwater inflow and the effect of tunnel excavation on groundwater drawdown is analyzed.

The results show that: (1) the errors of groundwater inflow between the proposed numerical method and the measured results between two measurement sites are in the range of 2.0%–28.6%, and the errors of the total groundwater inflow at each measurement point are within the range of 11.0%–28.3%; (2) The maximum drawdown of the tunnel site is 4.5 m. The proposed numerical method aims to provide a reasonable and efficient method for predicting groundwater inflow in a water-rich mountain tunnel in difficult geological conditions. The numerical method is then encapsulated in a groundwater inflow forecasting microservice and integrated into the infrastructure Smart Service System (iS3).

Keywords: numerical method; iS3; mountain tunnel; groundwater inflow; large area

1. Introduction
The inflow of groundwater into the tunnel can cause large drawdowns of the water table [1–2]. This can affect the energy-water balance of ecosystems, and vegetation can be destroyed due to a lack of water when the drawdown exceeds the ecological level of groundwater [3]. Thus, predicting groundwater inflow into water-rich mountain tunnels is a critical issue for accessing the impact of groundwater on the environment and limiting the tunnel discharge [4–5]. Various methods have been developed for estimating groundwater inflow into tunnels to provide a theoretical basis for the proper design of tunnel lining and to minimize its negative impact on the ecological environment. Examples
of such methods include analytical solutions [6–7], empirical methods [8–9], and numerical methods [10–11].

Numerical methods are successfully applied in many projects, as they can take into account complex geological conditions. Some researchers have used the finite element method [12–13] and the discrete element method [14–15] for simulation analysis of groundwater inflow. For example, Wang et al. [16] used a numerical method to analyze water inrush and its effect on the groundwater table in the Zhuzi tunnel in Japan using GIS and FLAC3D software. Li et al. [17] predicted the water inflow into the tunnel during the construction period of the subsea tunnel using numerical simulation. Zhang et al. [18] proposed a numerical dual permeability model for estimating groundwater inflow and calculating anisotropic flow behavior using finite element numerical simulations. Wang et al. [19] analyzed the relationship between the displacement of the drainage pipe and the water pressure behind the lining using 3D flow. However, these numerical methods are mainly focused on a local area with a single lithology without faults, and the modeling area is small. Few of the above studies address complex geological conditions such as faults and lithology distribution in actual engineering.

In this study, a three-dimensional numerical method was proposed for estimating groundwater inflow and drawdown, taking into account the influence of rainfall infiltration, lithological distribution, and three-dimensional topography of large-scale complex conditions. The numerical method can be encapsulated in a groundwater inflow forecasting microservice and integrated into the iS3 software [20], which implements an integrated groundwater information collection, analysis, and decision-making service and has a useful guiding role for the actual design of tunnels. iS3 is an intelligent service system designed to integrate the lifecycle data acquisition, processing, representation, analysis, and service of infrastructure. iS3 mainly serves infrastructure such as roads, bridges, tunnels, comprehensive pipe corridors, and foundation pits, covering the lifecycle of various information flow nodes at every stage–from planning, survey, design, construction to operation and maintenance.

2. Study site
The Laoying tunnel is located in Baoshan County, Yunnan Province, in southwestern China, as shown in Figure 1. The tunnel is 11.52 km long, and the rock mass along the tunnel axis consists mainly of limestone and sandstone with moderate weathering. The maximum buried depth of the tunnel is about 1255 m, and the maximum water head is more than 200 m. There are many drinking water intakes around the tunnel site, which affect a large number of residents.
3. Numerical method

Following Section 2, we plan to build a numerical model using ModFlow software to simulate the seepage in the study area, which aims to obtain groundwater inflow and drawdown.

3.1 Division of hydrogeological units

The study area includes the tunnel, the main fault zone, and the surrounding rectangular area affected by the tunnel excavation. The X-direction (EW) and Y-direction (SN) of the study area are 25200 × 13770 m, Z-direction (height) is 1200–3069.5 m. The total study area is about 347 km². This study uses two methods to separate hydrogeological units (HU) of the study area: 1) Small-scale model analysis uses ArcGIS software to separate hydrogeological units according to watershed and river outflow entrance; 2) Large-scale model analysis is based on the basis commonly used in current projects, as shown in Figure 2.

3.2 Grid generation and initial boundary conditions

When creating the grid model, the progressive grid generation method was used. In the area of the tunnel, a dense grid was adopted, the minimum distance between the rows of which was 0.1 m. On the contrary, a coarse grid of 50 × 50 m was used far from the tunnel. The vertical grid was divided into four layers as follows: the first layer was topsoil, which is the main soil layer for absorbing rainfall; the second layer was a transitional tunnel stratum; the third layer is where the tunnel was located; the fourth layer was the basement layer, as shown in Figure 3. The depth of the rock mass is in the range of 500–1869.5 m, which is deep enough to ignore bottom fluctuations. The ridge in the sub-catchment area was defined as the constant head boundary, the river was defined as the constant head drainage boundary, and the inner tunnel boundary was defined as the drainage boundary.
Figure 3. Grid generation and boundary conditions, a: tunnel plane; b: vertical section of the tunnel; c: cross-section of the tunnel

According to the results of groundwater measurements of geological boreholes, the initial conditions of the groundwater table were regressed and analyzed with the data on the surface elevation. The formula for the groundwater table was obtained:

\[ H_w = 0.9625H_g + 12.422 \]

where \( H_w \) is the groundwater table of the borehole and \( H_g \) is the surface elevation. Based on the terrain elevation parameters in 3D, the distribution of the initial groundwater table can be obtained as shown in Figure 4 below.

![Figure 4. Distribution of the initial groundwater table](image)

3.3 Model parameters

The surrounding rock consists mainly of sandstone and limestone mixed with several faults. The permeability of the rock in the model is continuous and isotropic, and the hydrogeological parameters of the surrounding rock are shown in Table 1.

| lithology  | Hydraulic conductivity (m/d) | Specific retention | Porosity |
|------------|-----------------------------|-------------------|----------|
| Sandstone  | 0.012                       | 0.02              | 0.05     |
| Limestone  | 0.05                        | 0.02              | 0.03     |
| Fault      | 0.05                        | 0.02              | 0.03     |

Rainfall recharge in the area of tunnels is an important factor influencing the inflow and drawdown of groundwater. The relationship between the rainfall infiltration coefficient and the rainfall can be expressed as:

\[ C = \mu \times \frac{\sum \Delta h}{P} \]  

(1)

where \( C \) is the recharge coefficient of rainfall infiltration; \( \mu \) is the water yield; \( \Delta h \) is the increase of groundwater table caused by monthly rainfall (mm); \( P \) is the annual rainfall (mm).

In this model, the average monthly rainfall in the Laoying tunnel is 140.06 mm and the average annual rainfall is 966.5 mm. According to Eq. (1), the rainfall infiltration is 0.0022 m/d.

3.4 Lithology distribution of tunnel site

Along the tunnel are various strata and surrounding rocks with different lithologies instead of a single rock mass. Therefore, the permeability of the rock mass differs significantly. Thus, it is necessary to assign values to different lithologies and rock strata in a single grid unit. Based on the lithological information found in the borehole, the variation function of lithological distribution was first
calculated. The distribution of limestone, sandstone, and fault fracture zone was then obtained using condition simulation analysis. Finally, the distribution information was imported into the numerical model.

During the study, the spherical model was adopted to fit the variation function, and the lithological distribution in the tunnel area was obtained by interpolation based on the variation function. The detailed steps were as follows: (1) interpolate and estimate all grid points using the indicative Kriging interpolation method; (2) select the measured values of any 100 boreholes as defined values to verify the results obtained by the indicative Kriging interpolation method using conditional modeling, and the 100 calculations of conditional modeling are completed by calling the prediction function in the R language; (3) 100 lithology values of all cells in the area of the site are obtained 100 times by conditional modeling, and the lithology value with a frequency of more than 50% is taken as the lithology value of the grid cell after the lithology value of each cell has been calculated. The resulting lithological distribution is shown in Figure 5.

![Figure 5. Lithology and distribution of fault in the tunnel site](image)

3.5 Initial model simulation and parameter inversion

The hydraulic conductivity of the rock mass was obtained by selecting a group of geological boreholes for on-site testing, and the result cannot reflect all the entire permeability of the rock over a large area due to the great variability. Therefore, it is necessary to adjust the hydraulic conductivity by inversion to improve the accuracy of the hydraulic conductivity. The inversion value can be achieved by adjusting the rock permeability value so that the numerically calculated groundwater inflow matches the measured results. Groundwater inflow per unit time in each direction was obtained using

\[
Q = k \times \Delta A \times \Delta h / \Delta l \]

where \( k \), \( \Delta h \), \( \Delta l \), and \( \Delta A \) are the average hydraulic conductivity, head difference, grid center distance, and grid cross-sectional between HU \((i, j, k)\) and adjacent grid units in each direction, respectively. The hydraulic conductivity of the surrounding rock after the inversion of the permeability of the rock is shown in Table 2.

| Inversion | Hydraulic | Hydraulic | Hydraulic | Groundwater | Measured | Errors of |
|-----------|-----------|-----------|-----------|-------------|----------|-----------|
|           |           |           |           |             |          |           |
Groundwater seepage in the numerical model was simulated after adjusting the rock permeability, and the groundwater inflow and drawdown are described in the next section.

4. Results analysis
This section analyzes the results of groundwater inflow using site measurements, the analytical solution, and the proposed numerical method. Site measurements are used to validate the numerical method, and Goodman’s solution is adopted to contrast with the numerical results to show the benefits and applicability of the numerical method.

4.1 Groundwater inflow
Goodman’s solution [21] is commonly used to estimate groundwater inflow. Thus, the applicability of the numerical method was evaluated. This analytical solution is expressed as follows:

\[
Q = 2\pi k \frac{h}{\ln(2h/r)}
\]

where \( Q \) is the amount of groundwater inflow, \( k \) is the hydraulic conductivity of the surrounding rock, \( h \) is the water table, and \( r \) is the radius of the tunnel.

The groundwater inflow at eight measurement locations (A1–A8) along the tunnel axis was measured in the tunnel site. The measurement locations are shown in Table 3.

Table 3. Locations of measurement sites

| Tunnel stake  | K1+435 | K2+300 | K2+900 | K5+200 |
|---------------|--------|--------|--------|--------|
| Location number | A1    | A2     | A3     | A4     |
| Tunnel stake  | K6+400 | K10+600| K12+000| K12+955|
| Location number | A5    | A6     | A7     | A7     |

The results of groundwater inflow using the numerical method, Goodman’s solution, and site measurements are shown in Figure 6. As can be seen from the figure, the groundwater inflow along each curve gradually increases from location A1 to location A8. The trend of the numerical method is consistent with the trend of the measurement results, showing good agreement. In addition, the curve of the numerical method is more like the curve of the measured result compared to Goodman's solution. For example, the results of the groundwater inflow of the analytical solution, the numerical method, and measurement at the site at the entrance to the tunnel (Location A1) are 10714 m$^3$/d, 7126 m$^3$/d, and 8260 m$^3$/d, respectively. The error between Goodman’s solution and the measured result is 23.2%, and the error between the numerical method and the measurement result is 13.7%. The errors between the two methods and the measurement results were further analyzed as shown in Figure 7.
Figure 6. Comparison of groundwater inflow obtained by two methods

As shown in Figure 7, the error in groundwater inflow between the numerical method and the measurement results range from 11.0% to 28.3%, and the corresponding errors in the average groundwater inflow between the two measurement locations range from 2.0% to 28.6%. The error between Goodman’s solution and measurement results range from 0.1% to 64.0%. In addition, it was found that the error curve of Goodman’s solution is steep with a large mutation, while the curve of the numerical method is flatter. This trend demonstrates that when Goodman’s solution is used to predict groundwater inflow, large errors can occur due to complex geological conditions, and the numerical method works better in such complex geological conditions.

4.2 Drawdown of groundwater

The resulting distribution of drawdown over the site area is shown in Figure 8.

Figure 8. Distribution of the drawdown in the Laoying tunnel

As seen from Figure 8, the maximum drawdown of the tunnel site area is 4.5 m, which is located near the entrance to the tunnel. Drawdowns at the four drinking water intake points (A-D) near the tunnel are about 0.6 m in Dongshanpo (A-point), 3.8 m in Wafang Township (B-point), 1.3 m in Laoying Township (C-point), and 0.8 m in Yangsanzhuang (D-point) when the excavation of the tunnel is finished. Therefore, the other three impacts can be ignored, except for the water intake point in Wafang Township. The results of the groundwater drawdown show that the groundwater table was affected by the excavation of the tunnel near the tunnel axis, while the area away from the tunnel axis...
is not apparent. It can be concluded that the numerical method can provide an opportunity to access the impact of the groundwater environment on the tunnel site.

5. Conclusions

(1) The proposed numerical method allows an estimation of groundwater inflow into a tunnel. This method can be applied to tunnels with natural three-dimensional terrain and large areas with complex geology.

(2) The results of groundwater drawdown show that the groundwater table is influenced by the excavation of the tunnel near the tunnel axis, while the area away from the tunnel axis is not obvious. The groundwater inflow is influenced by factors such as rainfall recharge, large area complex terrain, faults, and lithological distribution.

(3) The numerical method can be encapsulated into a groundwater inflow forecasting microservice and integrated into the iS3 software, which implements an integrated groundwater information collection, analysis, and decision-making service and has a useful guiding role for tunnel engineering.

Acknowledgments:
The research was supported by the National Natural Science Foundation of China (Grant No. 41877246). Dr. Yandong Li from Tongji University provided help in the numerical calculation of the research. The authors greatly appreciate the help provided.

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