Comparative Analysis of Tunnel Inflow Forecast
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Abstract. This paper summarizes the calculation method of tunnel water inflow and its applicable conditions, and enumerates the theoretical calculation formula of some tunnel water inflow. In order to reduce the error between the predicted value and the measured value of The La Yi Tunnel water inflow, based on the existing tunnel water inflow calculation formula, the tunnel engineering geological data are used for calculation, and the calculated values of the formulas are compared with the measured values to select the suitable tunnel. The theoretical calculation formula for the predicted value of water inflow. The research results provide a theoretical basis for the prediction of the tunnel water inflow and expansion, and provide reference to the prediction of the tunnel water inflow in this area.

Introduction
The tunnel will inevitably pass through the aquifer during the construction process. Once the tunnel has to water inrush during construction, the construction party will attach great importance to it. Excessive water inflow will inevitably influence the safety, schedule, investment, etc. during tunnel construction. Severe water inflow may do harm to the geological environment around the tunnel. The gushing water caused by the tunnel crossing the dark river and the filling type cave is usually mixed with a large amount of mud sand, which will not only affect the progress and investment of the project, but also threaten the safety of the construction workers in severe cases. For example, in 2016, the flooding mud accident in the Pingkan tunnel of the Hebai Expressway in Guangxi caused five workers to be trapped [1].

At present, the relevant theory of the prediction of the water inflow of the tunnel is not mature, and the deviation of the predicted value and the measured value is larger. According to the statistics of water inflow, the prediction error is only 15% within 20%; the error is 60% between 20% and 80%, the error value is 25% above 80%, and even some of the tunnel prediction water inflow error is more than ten times [2]. The deviation of forecast value of the tunnel water inflow will affect engineering feasibility evaluation, tunnel design line, construction investment cost and so on. Therefore, it is more urgent to study how to accurately predict the tunnel water inflow to ensure the safety of life and property during tunnel construction, which is also a practical engineering problem in the early stage of tunnel design and construction. The domestic and foreign scholars have studied the water discharge prediction for half a century. The main method of water discharge prediction is the calculation of the theoretical formula. In recent decades, scholars have revised the calculation formula of water discharge based on the measured data of water inflow. The prediction effect has been achieved, but it should be applied in practice. The effect of application needs further investigation and research. Up to now, there is still no accepted calculation method of water discharge at home and abroad. Most researchers are engaged in how to select a reasonable formula of water discharge calculation, so as to reduce the error between the predicted value and the measured value [3].

Current Calculation Method of Water Inflow and Its Applicable Conditions
The earliest methods of water inflow prediction are geophysical prospecting, drilling, hydrochemical methods, empirical prediction, water temperature measurement and so on. Early
prediction of water inflow is of poor accuracy, and the water discharge is mainly estimated by combining the direction of water flow experience. It is more difficult to predict the water inflow of tunnels in areas where groundwater is not well developed [4]. In recent years, scholars at home and abroad have made a lot of research achievements on the prediction of water discharge, mainly based on theoretical calculation. Theoretical calculation methods mainly include: water balance method, groundwater dynamics method, gynaecological analogy method, the main methods of theoretical calculation is: water balance method, groundwater dynamics method, gynaecological analogy method. Nonlinear theory (see table 1) [5,6]. With the emergence of fuzzy mathematics theory, scholars begin to use nonlinear theory to forecast tunnel water inflow. At present, the principal methods of nonlinear theory prediction are neural network and system identification method [7,8].

Table 1. Main calculation method of water inflow.

<table>
<thead>
<tr>
<th>Water inflow calculation method</th>
<th>Application Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water equality Balance law</td>
<td></td>
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<tr>
<td>Precipitation infiltration estimation method</td>
<td>It is suitable for the simple area of groundwater formation, such as uniform distribution of groundwater, stable groundwater source and clear recharge geological condition, which is suitable for predicting the whole water inflow of tunnel, and is not suitable for forecasting the inflow of water in tunnel interval.</td>
</tr>
<tr>
<td>Underground runoff modulus</td>
<td>It is mainly based on the shallow-buried mountain-ridge tunnel, and the recharge source of the groundwater is mainly seasonal rainfall.</td>
</tr>
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<td>Underground runoff depth method</td>
<td>It is suitable for tunneling through one or more surface watersheds.</td>
</tr>
<tr>
<td>Goodman's empirical equation</td>
<td>It is suitable for the simple area of groundwater formation, such as uniform distribution of groundwater, stable groundwater source and clear recharge geological condition, which is suitable for predicting the whole water inflow of tunnel, and is not suitable for forecasting the inflow of water in tunnel interval.</td>
</tr>
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<td>Sato Minami Unsteady flow</td>
<td>It is mainly based on the shallow-buried mountain-ridge tunnel, and the recharge source of the groundwater is mainly seasonal rainfall.</td>
</tr>
<tr>
<td>Job's Theoretic Formula</td>
<td>It is suitable for tunneling through one or more surface watersheds.</td>
</tr>
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<td>Sato Bangming empirical equation</td>
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<tr>
<td>Analytic</td>
<td>It is mainly based on the shallow-buried mountain-ridge tunnel, and the recharge source of the groundwater is mainly seasonal rainfall.</td>
</tr>
<tr>
<td>Railway standard empirical method, isotope method</td>
<td>It is suitable for tunneling through one or more surface watersheds.</td>
</tr>
<tr>
<td>Analytic</td>
<td>It is suitable for tunneling through one or more surface watersheds.</td>
</tr>
<tr>
<td>Hydrogeological analogy method</td>
<td>Applicable to areas where engineering geological conditions are relatively simple and aquifers do not change much.</td>
</tr>
<tr>
<td>Nonlinear theory</td>
<td></td>
</tr>
<tr>
<td>Neuron network</td>
<td>The calculation accuracy is high, but it is limited by the input data, which will affect the accuracy.</td>
</tr>
<tr>
<td>System identification</td>
<td>Suitable for karst tunnel water inrush prediction.</td>
</tr>
</tbody>
</table>

Common Formula for Calculating Water Inrush

According to the current prediction method of tunnel water inflow, this paper enumerates the more common theoretical calculation formulas of tunnel water inflow prediction.

Water Balance Method

(1) Precipitation infiltration estimation method

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In the formula: $Q_s$ — the normal inflow of tunnel (m$^3$/d); $a$ — rainfall infiltration coefficient; $W$ — annual average rainfall (mm); $A$ — tunnel water catchment area (km$^2$) across the surface of the water-bearing section.

(2) Subsurface runoff modulus method

$$Q_s = M \cdot A$$

$$M = Q'/F$$

In the formula: $M$ — subsurface runoff modulus (m$^3$/(d·km$^2$)); $Q'$ — The discharge of a river or descending spring (m$^3$/d) recharged by groundwater is generally based on the flow rate in the dry season; $F$ — Surface watershed area equivalent to $Q'$ (km$^2$).

(3) Depth method of underground runoff

$$Q_s = 2.74h \cdot A$$

$$h = W - H - E - SS$$

$$A = L \cdot B$$

In the formula: $h$ — annual groundwater runoff depth (mm); $H$ — annual surface runoff depth (mm); $E$ — tunnel passes through the annual evaporation amount in the basin, (mm); $SS$ — tunnel passes through the stagnant water depth (mm); $L$ — Length of tunnel passing through water (km); $B$ — inrush on both sides of the tunnel through the length of water (km).

**Groundwater Dynamics**

(1) Goodman's empirical formula

$$Q_0 = L \frac{2\pi \cdot K \cdot H}{\ln \frac{4H}{d}}$$

In the formula: $Q_0$ — maximum water inflow predicted by tunnel (m$^3$/d); $K$ — Water permeability coefficient; $H$ — water level line and equivalent center of tunnel section (m); $d$ — equivalent circle diameter of tunnel section (m).

(2) Unsteady flow of Sato

$$q_0 = \frac{2\pi \cdot m \cdot K \cdot h_2}{\ln \left[ \tan \left( \frac{\pi \cdot (2h_2 - r)}{4h_2} \right) \cot \left( \frac{\pi \cdot r}{4h_2} \right) \right]}$$

In the formula: $q_0$ — maximum water inflow per unit length [m$^3$/ (m·d)]; $m$ — conversion factor, generally 0.86; $h_2$ — equivalent Center distance from Water level to Tunnel Section (m); $r$ — equivalent Circular Radius (m) of Tunnel Section; $h_c$ — water thickness (m).

(3) Qiu Bui's theoretical formula

$$Q_s = L \cdot K \frac{H^2 - h^2}{R_y - r}$$

In the formula: $H$ — the thickness of submerged water body above the bottom of the cave (m); $h$ — hole gutter supposing the depth of the water (m); $R_y$ — recharge radius (m).

(4) Sato’s empirical formula
\[ q_s = q_0 - 0.584\bar{q} \cdot K \cdot r \]  
(10)

In the formula: \( q_s \) — normal water inflow per unit length \( [\text{m}^3/(\text{m} \cdot \text{d})] \); \( \bar{q} \) -- test coefficient, generally 12.8.

(5) Analytical formula

\[
Q = \frac{2\pi H k_1}{\ln \frac{r_2}{r_1} + k_g \ln \frac{r_2}{r_g} + k_1 \ln \frac{r_1}{r_0}}
\]

(11)

In the formula: \( h_1 \) — head of outer radius of lining (m); \( H \) — far-field stabilized head (m); \( r_0 \) — lining inner radius (m); \( r_1 \) — outer radius of lining (m); \( r_2 \) — far field distance equal to \( H \) (m); \( r_g \) — grouting ring radius (m); \( k_1 \) — permeability coefficient of lining (m/s); \( k_g \) — grouting ring permeability coefficient (m/s); \( k_r \) — permeability coefficient of surrounding rock (m/s).

Hydrogeologic Analogy

\[
Q = Q' \frac{F \cdot s}{F' \cdot s'}
\]

(12)

\[
F = B \cdot L
\]

(13)

\[
F' = B' \cdot L'
\]

(14)

In the formula: \( Q, Q' \) — new, existing tunnel discharge \( [\text{m}^3/\text{d}] \); \( F, F' \) — the area of water inrush of tunnel \( [\text{m}^2] \); \( s, s' \) — New, existing tunnel water level drop (m); \( B, B' \) — New, existing tunnel perimeter (m); \( L, L' \) — New existing tunnel through (m) with water length.

An Example of Calculating the Formula of Water Inrush

Yaoshan to Nandan Road Layi tunnel is located in Guangxi Hechi Nandan County Chengguan Town Layi village. The tunnel passes through the shaly siltstone and the limestone is comprised of a low mountain. The Layi tunnel is a two-way tunnel with a single hole, and the pile number is K35+123~K35+755 with a total length of 632 m. According to the Prophase exploration data of Layi tunnel, the permeability coefficient of surrounding rock of the tunnel is \( K = 2.05 \times 10^{-4} \) cm/s, permeability coefficient of grouting ring \( k_g = 1.03 \times 10^{-5} \) cm/s, secondary lining permeability coefficient \( k_1 = 8.3 \times 10^{-7} \) cm/s (almost impermeable), the maximum groundwater head height \( \text{max} = 148 \) m of the tunnel is located in K35+400~K35+500 section of grade V surrounding rock. The precipitation infiltration coefficient \( \alpha \) is taken as 0.2, and the catchment area is established according to the tunnel location, topography, lithology and burial depth. The water collection area of the Layi tunnel is 0.06 square kilometers. The average precipitation is 1400mm, the maximum annual precipitation is 1925.9mm, the modulus of underground runoff is 790.3 m³/d, the equivalent diameter of the tunnel is 13 m, the radius of the tunnel equivalent circle is 13 m. \( r = r_0 = 6.5 \) m.

Because the calculation formula used in the preliminary survey design of tunnel is the deviation between the water inflow value predicted by the method of estimating atmospheric precipitation and the measured value, the calculation formula of water inflow is adopted in this paper to compare and select, and the formula for predicting the water inflow suitable for Layi tunnel is screened out.

According to the geological data of the Layi Tunnel and the existing formulas for calculating the inflow of water, the method of estimating atmospheric precipitation, the modulus of underground runoff, the Goodman's empirical formula, and the unsteady flow of Sato Bong Ming are selected. The empirical formula of Sato Bangming is suitable for predicting the water inflow of Layi tunnel. The error analysis of the result of prediction of water inflow of Layi tunnel is shown in the following table 2, combined with the error analysis of the field measured water inflow value.
Table 2. The error analysis of forecast result of water inflow of Layi tunnel.

<table>
<thead>
<tr>
<th>Water inflow calculation method</th>
<th>predicted value (m³/(m·d))</th>
<th>measured value (m³/(m·d))</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation estimation method</td>
<td>0.27</td>
<td>5.97</td>
<td>21 times</td>
</tr>
<tr>
<td>Underground runoff modulus</td>
<td>0.08</td>
<td>5.97</td>
<td>73 times</td>
</tr>
<tr>
<td>Goodman's empirical formula</td>
<td>6.82</td>
<td>5.97</td>
<td>12.46%</td>
</tr>
<tr>
<td>Sato unsteady flow</td>
<td>21.38</td>
<td>5.97</td>
<td>72.08%</td>
</tr>
<tr>
<td>Sato's empirical style</td>
<td>12.77</td>
<td>5.97</td>
<td>53.25%</td>
</tr>
</tbody>
</table>

The result of error analysis in Table 2 shows that the predicted value calculated by the method of atmospheric precipitation estimation is small, and the measured value is about 21 times of the predicted value, which is seriously inconsistent with the actual situation, and the error of using Goodman's empirical method is the smallest 12.46 percent. The prediction of water inflow of Layi tunnel is suitable for Goodman's experience.

Conclusion

This paper enumerates the calculation methods of tunnel water inflow and its applicable conditions, and based on engineering geological data of Layi tunnel, compares the predicted values obtained by each water inflow formula with the field measured values. It is more suitable to predict the water inflow of Layi tunnel than the empirical formula of Goodman. The selection of water inflow prediction formula should compare with the applicable conditions of the tunnel engineering geological condition and the calculation formula, and the reasonable calculation result should be selected as the forecast value of the water inflow. The error between the predicted and measured values of water inflow is reduced as much as possible.

Reference


