Evaluation of Negative Effect on Groundwater Environment Caused by Weathered Granite Tunnel Construction with Mining Method Based on GIS

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Abstract. In order to figure out the negative effect on groundwater environment caused by weathered granite tunnel construction with mining method, the influence factors were considered comprehensively to establish the evaluation index system and classification standard for negative effect on groundwater environment. The fuzzy comprehensive evaluation and analytic hierarchy process were used to quantify the evaluation indexes and determine the weight of indexes. The system to evaluate the negative effect caused by tunnel construction with mining method on groundwater environment was developed based on GIS and was applied to a tunnel section of Guangzhou Metro line 21. The research results show that: the permeability of rock, the grouting effect and the waterproof and drainage are the major influence factors. The negative effects of DK25+984.0~DK26+000.0 and DK26+000.0~DK26+434.0 mileage sections are strong and medium, respectively, which coincided with the actual situation. This research can provide a scientific approach to evaluate the negative effect caused by tunnel construction with mining method on groundwater environment.

1. Introduction
The negative effect on groundwater environment caused by tunnel construction are mainly manifested in the decline of groundwater level, land subsidence, tunnel water inrush, groundwater pollution and ecological environment degradation[1]. How to scientifically evaluate the negative effect on groundwater environment produced by tunnel construction is one of the technical problems that have puzzled the constructors of tunnel engineering for a long time[2]. In recent years, scholars at home and abroad have carried out a lot of researches on this problem. Vincenzi et al[3] have studied the negative effect of Firezuola extra-long tunnel construction in Italy. The results show that tunnel drainage has caused serious damage to the surrounding ecological environment. Liu Jian et al[4,5] constructed the evaluation index system of the negative effect of the groundwater environment for the karst growth tunnel, and provided the basis for the evaluation of the negative effect of the groundwater environment in the karst tunnel.

The existing research results take the whole section of tunnel as the evaluation object, which are suitable for extra-long tunnel, and the applicability to granite tunnel with obvious difference and weathered is poor. In addition, there are still obvious shortcomings in the traditional evaluation methods
in the information management of evaluation indicators and the visualization of evaluation results, and the above problems can be effectively solved with the help of geographic information system (GIS). In this paper, a weathered granite tunnel of Guangzhou Metro Line 21 was taken as the research object and the comprehensive evaluation index system was constructed. Then the secondary development based on GIS platform was carried on and the weathered granite tunnel mine mountain method construction groundwater environment was realized.

2. Evaluation of Negative Effect of Groundwater Environment in Mining Method Construction

2.1. Comprehensive evaluation method and process

The evaluation system has the characteristics of multi-level and multi-index, and the evaluation object and evaluation index have certain fuzziness. In this paper, the negative effect of groundwater environment in granite tunnel mining method is evaluated by the combination of analytic hierarchy process (AHP) and fuzzy comprehensive evaluation method, and the evaluation index system is constructed according to the characteristics of multi-level and multi-index. By constructing the membership function, the grade to which the quantitative evaluation index of membership degree belongs.

The fuzzy comprehensive evaluation method[6-8] first establishes the factor set $U = \{u_1, u_2, \ldots, u_n\}$ composed of $n$ evaluation indicators. Each evaluation index has an evaluation set $V = \{v_1, v_2, \ldots, v_m\}$ composed of $m$ evaluation results. Then the weight of each evaluation index is determined and constitutes a weight set $W = \{w_1, w_2, \ldots, w_n\}$. Then a single factor evaluation of the $i$-th evaluation index in $U$ is evaluated and a single factor $(v_{i1}, v_{i2}, \ldots, v_{im})$ pair evaluation set is determined. The $v_j (j = 1, 2, \ldots, m)$ membership degree $r_{ij}$, the fuzzy subset $r_i = (r_{i1}, r_{i2}, \ldots, r_{im})$ are obtained, and a $n \times m$ fuzzy evaluation matrix $R$ is formed:

$$R = \begin{bmatrix}
  r_{11} & r_{12} & \cdots & r_{1m} \\
r_{21} & r_{22} & \cdots & r_{2m} \\
  \vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & \cdots & r_{nm}
\end{bmatrix}$$

Finally, the fuzzy transformation about $W$ is performed on the rectangle $R$, and the model comprehensive evaluation result $B$ is obtained:

$$B = W \times R = \{b_1, b_2, \ldots, b_n\}$$

The fuzzy comprehensive evaluation result uses the weighted average method to calculate the score $a$ of the final evaluation result:

$$a = \frac{\sum_{j=1}^{m} b_j v_j}{\sum_{j=1}^{m} b_j}$$

2.2. Evaluation index system and evaluation criteria

The main impact of tunnel construction on groundwater environment is the loss of groundwater caused by water seepage and water inrush in the tunnel. Therefore, the relevant factors of tunnel water inrush are mainly considered to be the evaluation indicators[9]. Based on the research results of the literature[4,5], combined with the engineering characteristics of the study area, the evaluation level of negative effect on groundwater environment is divided into five levels, which are poor (I), weak (II), medium (III), strong (IV), extremely strong (V), as show in Table 1. According to the evaluation level of Table 1, the evaluation index system and evaluation criteria are listed, as shown in Table 2. There are 15 quantitative indicators and 2 qualitative indicators in the negative effect index system, which is determined as the evaluation index set. According to the grading standard of the evaluation index, for
the quantitative index, the interpolation method is used for the score, and for the qualitative index, the interval median score is used.

Table 1. Classification standard of negative effect

| Evaluation level | Score | Negative effect on groundwater environment |
|------------------|-------|---------------------------------------------|
| Poor(I)          | 0~20  | There is no outlet water or only a small amount of effluent in the tunnel, and the decrease of groundwater level is not obvious, which has no effect on the surface vegetation and human settlement environment. |
| Weak(II)         | 20~40 | There is a small amount of effluent in the tunnel, and the groundwater level on both sides of the tunnel decreases in a certain range, which has a slight impact on the surface vegetation and human settlement environment. |
| Medium(III)      | 40~60 | Water inrush occurs in the tunnel, and the groundwater level on both sides of the tunnel drops in a large range, which has a certain impact on the surface vegetation and human settlement environment. The land subsidence in some areas, the surface water flow has been reduced and a certain number of wells and springs have been exhausted. |
| Strong(IV)       | 60~80 | There is obvious water inrush in the tunnel, the groundwater level on both sides of the tunnel drops, the land subsidence occurs in a certain range, the surface water flow decreases obviously and a large number of wells and springs dry up, which has obvious influence on the surface vegetation and human settlement environment. |
| Extremely Strong(V) | 80~100 | Large-scale water inrush occurred in the tunnel, the groundwater level on both sides of the tunnel decreased, and with the large-scale land subsidence, a large number of surface water and well springs dried up, the surface vegetation dried up, and the human settlement environment deteriorated sharply. |

2.3. Quantification of evaluation indicators

2.3.1. Quantitative index quantification. In the index system, the semi-ladder or triangular fuzzy distribution function is used to determine the membership degree of the quantitative index. For the higher the numerical value, the stronger the negative effect of groundwater environment, the stronger the positive correlation quantitative index (C<sub>11</sub>, C<sub>12</sub>, C<sub>13</sub>, C<sub>15</sub>, C<sub>22</sub>, C<sub>23</sub>, C<sub>31</sub>, C<sub>32</sub>, C<sub>33</sub>), and the fuzzy distribution curve of positive correlated index is as follows:

![Figure 1. Fuzzy distribution curve of positive correlated index](image)

The negative correlation quantitative index (C<sub>14</sub>, C<sub>21</sub>, C<sub>41</sub>, C<sub>42</sub>, C<sub>43</sub>, C<sub>44</sub>) with less impact on the negative effect of the groundwater environment is as follows:

![Figure 2. Fuzzy distribution curve of negative correlated index](image)

2.3.2. Quantitative index quantification

The quantification of qualitative indicators often depends to a large extent on the evaluator's engineering experience and subjective judgment. Qualitative indicators of groundwater chemical type (C<sub>24</sub>) and anti-
drainage measures (C\textsubscript{35}) in the indicator system, combined with survey data and construction data records, quantified according to professional experience.

| Table 2. Evaluation index system and evaluation standard of negative effect |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Criterion layer | Index layer | Poor(I) | Weak(II) | Medium(III) | Strong(IV) | Extremely Strong(V) |
| [B\textsubscript{1}] Natural environment | [C\textsubscript{1}] Monthly average rainfall/mm | <15 | 15~30 | 30~90 | 90~150 | >150 |
| | [C\textsubscript{2}] Rainfall infiltration coefficient | <0.05 | 0.05~0.15 | 0.15~0.25 | 0.25~0.35 | >0.35 |
| | [C\textsubscript{3}] Scale of adjacent reservoirs and lakes/m\textsuperscript{3} | <10\textsuperscript{4} | 10\textsuperscript{4}~10\textsuperscript{5} | 10\textsuperscript{5}~10\textsuperscript{6} | 10\textsuperscript{6}~10\textsuperscript{7} | >10\textsuperscript{7} |
| | [C\textsubscript{4}] Distance between reservoir, lake and tunnel/m | >3000 | 1000~3000 | 500~1000 | 200~500 | <200 |
| | [C\textsubscript{5}] Surface confluence area/km\textsuperscript{2} | <5 | 5~10 | 10~30 | 30~50 | >50 |
| | [C\textsubscript{6}] Rock mass integrity coefficient | >0.75 | 0.55~0.75 | 0.35~0.55 | 0.15~0.35 | <0.15 |
| [B\textsubscript{2}] Engineering geology and hydrogeology | [C\textsubscript{7}] Permeability coefficient of surrounding rock/(m\textsuperscript{d}) | <0.04 | 0.04~0.2 | 0.2~1 | 1~5 | >5 |
| | [C\textsubscript{8}] The buried depth below the water level/m | <10 | 10~40 | 40~70 | 70~100 | >100 |
| | [C\textsubscript{9}] Groundwater chemical type | HCO\textsubscript{3} type | HCO\textsubscript{3}~SO\textsubscript{4} type | SO\textsubscript{4} type | Cl~SO\textsubscript{4} type | Cl type |
| | [C\textsubscript{10}] Excavation area/m\textsuperscript{2} | <25 | 25~60 | 60~110 | 110~160 | >160 |
| | [C\textsubscript{11}] permeability of excavation damage area | 1 | 1~4 | 4~7 | 7~10 | >10 |
| | [C\textsubscript{12}] Thickness of damaged area of excavation/m | <0.5 | 0.5~1 | 1~1.5 | 1.5~2 | >2 |
| [B\textsubscript{3}] Tunnel excavation | [C\textsubscript{13}] Impermeability of grouting body | >100 | 50~100 | 10~50 | 1~10 | 1 |
| | [C\textsubscript{14}] Grouting thickness/m | >6 | 4~6 | 2~4 | 1~2 | <1 |
| | [C\textsubscript{15}] Impermeability of initial support | >1000 | 100~1000 | 10~100 | 1~10 | 1 |
| | [C\textsubscript{16}] Initial support thickness/cm | >30 | 20~30 | 10~20 | 5~10 | <5 |
| [B\textsubscript{4}] Tunnel waterproofing and drainage system | [C\textsubscript{17}] Waterproof and drainage measures | Pre-grouting + full package waterproofing | Post grouting + full package waterproofing | Full package waterproofing | Water shutoff and limited discharge | Full row of water |

2.4. Evaluation index weight calculation
The relative importance of the evaluation indicators needs to be distinguished by the weight of the indicators. The analytic hierarchy process (AHP) [10] can be used to process the complex evaluation process. The evaluation object is regarded as a system, and the relationship between the factors is decomposed at a level by level, and is presented in the form of a hierarchical structure, and then the evaluation are carried out layer by layer. The calculation of the analytic hierarchy process is as follows:

(1) The structural judgment matrix \( A = (a_{ij})_{m \times n} \), \( a_{ij} \) indicates the importance of the \( i \)-th evaluation index relative to the \( j \)-th evaluation index. The 1-9 scale method is used to compare the same-level indicators.
evaluation indicators in pairs, and the ratio of relative weights is obtained. (2) The method comprises the following steps of: calculating a maximum characteristic value and a characteristic vector of a judgment matrix by using a geometric mean and a normalization method[10]:

① Normalizing each column vector of the judgment matrix $A$:
$$\tilde{w}_j = a_j / \sum_{i=1}^{n} a_j \quad (j = 1, 2, \ldots, n)$$

(4)

② Calculating the sum of the elements of each row of the matrix after normalization
$$\tilde{w}_i = \sum_{j=1}^{n} \tilde{w}_j \quad (i = 1, 2, \ldots, n)$$

(5)

③ Normalizing $\tilde{w}_i$
$$w_i = \tilde{w}_i / \sum_{i=1}^{n} \tilde{w}_i$$

(6)

In the form, where $w_i$ is the $i$-th component of the eigenvector found, then there is an eigenvector, the weight vector is
$$w = (w_1, w_2, \ldots, w_n)^T$$

(7)

④ Calculating the maximum eigenvalue $\lambda_{max}$ of the judgment matrix $A$
$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} (Aw)_i$$

(8)

(3) The consistency test of judgment matrix $A$ is carried out:
$$CI = \frac{\lambda_{max} - n}{n - 1}$$

(9)

In the formula, $CI$ is the consistency index of the judgment matrix, and the larger the $CI$ value is, the more deviated the judgment matrix is from the complete consistency, and the closer it is to the complete consistency.

(4) An average random consistency test for judgment matrices
$$CR = CI / RI$$

(10)

In the formula, $RI$ is the average random consistency index and $CR$ is the random consistency ratio of the judgment matrix. When $CR$ is less than 0.10, it can be considered that the judgment matrix satisfies the consistency, otherwise it is necessary to adjust and analyze the judgment matrix.

2.5. Evaluation system based on GIS

Based on the above research work, the negative effect assessment system of groundwater environment is obtained by secondary development of tool GIS. The system includes four modules: index system, index weight, index quantification and evaluation results.

The operation steps of the evaluation system are as follows: ① the complete index information of each index layer, such as natural environment, engineering geology and hydrogeology, tunnel excavation and tunnel waterproof and drainage system, is extracted, and the evaluation index database is established; ② the grid function is used to select the research section to obtain the attribute values of all the evaluation indexes in the research section;③ the expert scores are input into the evaluation system and consistent. Through the function of index weight module, the weight of each evaluation index is obtained. ④ the evaluation index of tunnel research section is quantitatively calculated by the function of index quantification module. ⑤ using the function of evaluation result module to obtain the final result of comprehensive evaluation of negative effect on groundwater environment.

3. Engineering case analysis

3.1. Project overview

The mountain tunnel section of Changping Station to Jinkeng Station of Guangzhou Metro Line 21 includes the first section with a length of 1278 m and the second section with a length of 2503 m. Survey
data show that the surface water system of construction site is greatly affected by seasonal rainfall, and the surface water system is relatively developed. Influenced by topography, groundwater level is 1.2-28.70 m, with an average of 15.08m. It mainly occurs in bedrock fissures. The bedrock fissure water mainly occurs in strong weathering zone and weathering zone of Proterozoic granitic gneiss. Some parts of the construction site have developed fissures, broken rocks, medium permeability, good water-rich, and serious local leakage. The weathered fissure water of some strong-to-moderate weathered bedrocks has the characteristics of confined water, whose head is affected by seasonal variation.

Groundwater is mainly recharged by artificial filling layer of Quaternary, pore water infiltration of Alluvial-diluvial sand layer and atmospheric precipitation, and discharged by atmospheric evaporation. Groundwater table is obviously affected by season. The fissure water in the foundation rock of the construction site mainly circulates vertically. Groundwater runoff path is relatively short, and runoff direction and slope direction are generally the same. Groundwater is mostly discharged to the nearby low-lying areas in the form of diversion.

3.2. Evaluation index weight calculation
Ten experts from different research institutes and institutions are invited to score the importance matrix of each level under the evaluation index system according to the 1-9 scale method. The experts’ scores are entered into the evaluation system and the consistency is checked.

3.3. Evaluation index
According to the evaluation index grading standard in Table 2, the DK25+984.0~DK26+434.0 mileage segment of the tunnel is selected by the function of the index quantification module with the evaluation index quantitatively calculated, and the quantitative results of each evaluation index are saved.

3.4. Evaluation result output
The evaluation result module is used to obtain the final evaluation result of the negative effect of groundwater environment in the construction of the granite tunnel in the study section, as shown in figure 3.

Figure 3. The evaluation chart of groundwater environment negative effect in tunnel research area

Figure 3 shows that the negative effect of groundwater environment in the construction of DK25+984.0~DK26+000.0 mileage section is strong, and the negative effect of groundwater environment in the construction of DK26+000.0~DK26+434.0 mileage section is medium. Effective groundwater environmental protection measures shall be taken during the construction of the mining section to reduce the impact of tunnel construction on the groundwater environment.

3.5. Evaluation result analysis and verification
According to the field investigation, it is found that the inrush water disasters occur mostly in the area with relative strong or strong groundwater environmental effect evaluation grade, which verifies the reliability of the evaluation results to a certain extent.

4. Conclusion

(1) According to the engineering characteristics of weathered granite tunnels, an index system of negative effect on groundwater environment is constructed, which includes four subsystems of natural environment, engineering geology and hydrogeology, tunnel excavation, tunnel waterproof and drainage system and 17 evaluation indicators. Fuzzy comprehensive evaluation method is used to quantify the evaluation index, and the weight of evaluation index is obtained by analytic hierarchy process. The weight calculation shows that the permeability coefficient of surrounding rock, grouting effect and the selection of tunnel waterproof and drainage measures are the main factors.

(2) Based on the GIS platform, an evaluation system for negative effect on groundwater environment caused by weathered granite tunnel construction with mining method is developed, the zoning evaluation of a granite tunnel section of Guangzhou Metro Line 21 is realized. The results show that the negative effect of groundwater environment produced by mining method construction in DK25+984.0-DK26+000.0 mileage section is relatively strong, while that produced by mining method construction in DK26+000.0-DK26+434.0 mileage section is medium.

(3) The rationality of the evaluation results of the system is verified by field investigation. The inrush water disasters mostly occur in the area where the evaluation grade of groundwater environmental effect is strong or relatively strong, and the evaluation results are consistent with the actual situation.

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