Fuzzy Comprehensive Assessment for Impact on Ecology Environment of Construction of Extra-long Highway Tunnels in Mountain Area

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Abstract: Construction of highway tunnels affect the original hydrogeological environment in tunnel zone, may even cause the unbalance of ecological environment, study on the influence on ecology environment of tunnels construction is therefore of great significance by adopting effective evaluation measures. Problem commonly encountered with comprehensive assessment of impact on environment is as follows, the multiple indexes, the narrow scope of application, the quantification of index with high difficult. With the support of Erlang Moutain Tunnel, six factors associated with assessment of impact on ecological environmental during tunnel construction are weighted according to the characteristic of tunnel. Determine both the subordinated function and weight of factors on the basis of fuzzy hierarchy estimation, evaluation systems on ecology environment of construction of extra-long highway tunnels in mountain area are established. Through confirmatory analysis of Erlang Moutain Tunnel, the evaluation systems obtained has good application and operability, which may provide reference to similar tunnels or underground engineering.

1. Introduction

Compared with other transportation, tunnel has some advantages such as cutting vehicle mileage, optimizing road alignment, reduction of land expropriation and ensuring operating security, therefore tunnel has been more and more widely adopted during highway construction in mountain area with the development of transportation infrastructure[1–3]. The influence of tunnel construction on ecological environment is increasingly arousing the concern of society in recent years. As tunnel is most built under the surface of the land, tunnel excavation may considerably change the route of underground water supply, runoff and drainage, constantly deteriorate the hydrogeological environment, even cause the decrease of groundwater level, the wilt or death of plants, survival environment worsening for wildlife in tunnel zone[4–6].

About the environmental impact assessment of highway construction, there are some scholars who have made some achievements[7–9]. Shenggao Cheng et al systematically studied the method of eco-
logical environmental assessment, who summarized the usual methods, such as analogy, ecological mechanism analysis, system analysis, landscape ecology, eco-map, comprehensive index analysis, mathematical evaluation[10]. Thomas et al estimated ecological safety of the river of Columbia by adopting different analysis index, including subsystem such as forest, grassland[11]. By studying on the characteristics of karst tunnel, Jian Liu et al established the evaluation system of negative effect of discharge of groundwater[12–13]. By employing fuzzy synthetic evaluation method, they rationally estimated the negative influence caused by construction of highway tunnel. It is indicated that the evaluation system established is reasonable by comparing with the field survey. Based on long-term monitoring data of groundwater of Geleshan Tunnel, Naixia Li et al systematically analyzed both the dynamic feature and chemistry of groundwater in tunnel zone[14]. In addition, impacts caused by construction of tunnel on groundwater environment were discussed by adopting some effective methods such as pollution index method, fuzzy synthetic evaluation method. They gave the corresponding solving measures according to the analysis results. Wei Zheng et al put forward the assessment index system of impact on ecological environment caused by highway tunnel in mountainous area[15]. For the problems of constructing the evaluation system, they achieve some significant results such as impact factors, evaluating objects, extent of impact on surrounding environment, evaluation methods, countermeasures. Considering the important factors of impact on groundwater system of extra-long tunnel, Hongzhi Yao graded the degree of effect of each factors[16].

The research on ecology environmental impact assessment of tunnel construction covers a broad area, the establishment of the appraisal target system is complex currently because the factor is both multitudinous and fuzzy. Therefore the selection of the evaluating index system should be targeted and representative combining the factual characteristics of highway tunnels to be evaluated. Recently, most studies focus on a summary of existing evaluating systems or the assessment index, and the evaluative criteria established is inapplicable to the tunnel to be evaluated. The manuscript firstly selects six representative indexex on ecology environmental impact assessment of tunnel construction according to characteristics of the project to be evaluated, and determines the assessment matrix and judgment matrix based on the fuzzy analytic hierarchy process(FAHP), then the evaluate system is gained and applies to the extra-long highway tunnel. Finally, on the basis of the evaluation result, some suitable engineering measures are proposed, which could offer guidance to the similar projects on protecting groundwater environment and maintaining ecological balance in the future.

2. Project profile of a extra-long mountain tunnel
The tunnel is the dominant engineering of a highway in the mountain area, about thirteen kilometers, passing through both a natural heritage protected area and a national forest park. It is visible that the surrounding area is environmentally sensitive. Topographically, the tunnel passes through a mountain, which forms the watershed between two big rivers. Temperature of the west region and east region differ hugely due to the different geographical conditions. The east area’s annual rainfall is 1900 millimeters, and the west area’s annual rainfall is 900 millimeters. Similarly, the east region has clear mountain vegetation vertical belt structure and the characteristics of communities in each belt is very remarkable, the perennial vegetation cover is 80%–90%. The major vegetation types in west region are shrubs and ground vegetation, and the perennial vegetation cover is 60%–70%. According to the research on the hydrogeologic characteristics of the region, the groundwater is divided into fracture water, karst fracture water, fault pore-fRACTURE water and pore phreatic water in loose rock mass.

3. Fuzzy analytical hierarchy process
Fuzzy analytic hierarchy process[17–19] has been put forward on the basis of AHP theory[20] by introducing the fuzzy idea and method. The following steps are required to build a rational mathematics model with the theory system.

(1) Setting up the evaluation factors set
The evaluation factors set is composed of elements influencing the evaluated objects, it is supposed that the set has n elements.
The impact on evaluated objects of each factor is divided into several ($m$) levels, forming a new set as follows.

$$U = \{u_1, u_2, \ldots, u_n\}$$

(1)

$$u_i = \{u_{i1}, u_{i2}, \ldots, u_{im}\} \quad (i = 1, 2, \ldots, n)$$

(2)

(2) Setting up the assessment grade set

The assessment grade set composed of the all evaluation results is divided into several ($k$) levels according to the demands in the assessment system.

$$V = \{v_1, v_2, \ldots, v_k\}$$

(3)

Where the $v$ expresses the evaluation criterion, and the $V$ represents the evaluation set.

(3) Establishing the fuzzy relational matrix $R$

Based on the fuzzy synthesis evaluation, the membership function of each evaluation factor is build, and the fuzzy correlation matrix is determined.

$$R = \begin{bmatrix}
R & u_1 \\
R & u_2 \\
\vdots & \vdots \\
R & u_n
\end{bmatrix} = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1k} \\
r_{21} & r_{22} & \cdots & r_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & \cdots & r_{nk}
\end{bmatrix}$$

(4)

The element $r_{ij}$ in the matrix represents the membership of the evaluation factor $u_i$ to the corresponding fuzzy assessment grade $v_j$, which is revealed through the fuzzy vector, namely $(R|u_i) = (r_{i1}, r_{i2}, \ldots, r_{ik})$. In other evaluation system, the vector always is replaced by one determined value. Therefore, constructing the fuzzy comprehensive evaluation system needs more information.

(4) Confirming the weight of each evaluation element

The element $a_i$ in the vector ($A = (a_1, a_2, \ldots, a_n)$) essentially is the membership of the evaluation factor $u_i$ to the fuzzy subset. In this manuscript, the weight coefficient is determined based on analytic hierarchy process (AHP), then the vector would be normalized before the synthetic operation as follows.

$$\sum_{i=1}^{n} a_i = 1, \quad a_i \geq 0, \quad i = 1, 2, \ldots, n$$

(5)

(5) The vector of fuzzy comprehensive evaluation

$$AxR = (a_1, a_2, \ldots, a_n) = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1k} \\
r_{21} & r_{22} & \cdots & r_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & \cdots & r_{nk}
\end{bmatrix}(b_1, b_2, \ldots, b_k) = B$$

(6)

The element $b_j$ represents the membership of the object to be evaluated to the element $v_j$ in fuzzy subset.

(6) Results analysis

The evaluation result is gain according to the principle of maximum membership degree.

$$V = \left\{v_j, \frac{\max_{v_j}^* b_j}{v_j} \right\}$$

(7)

4. Fuzzy comprehensive evaluation of the impact on ecological environment of extra-long tunnel

4.1. Study on grade of the influence factors

The most important question about researching on ecological impact assessment of tunnel project is the selection of evaluation index. The evaluation index in this manuscript are established mainly following the principles below. Firstly, the primary selected index are compared with each other, simultaneously be optimized with combining some experts’ suggestion to ensure that the evaluation system
has a better engineering applicability. According to the above method, several main factors in the assessment system of impact on the ecological environment of extra-long tunnel construction are obtained as follows, surge water amount, length of tunnel, vegetation coverage, distribution of surface water, distribution of rare animals and development degree of karst. The evaluation factor set (U) is established, as follows.

\[ U = \{ u_1, u_2, u_3, u_4, u_5, u_6 \} \]  (8)

Where \( u_1 \) expresses surge water amount, \( u_2 \) expresses length of tunnel, \( u_3 \) expresses vegetation coverage, \( u_4 \) expresses distribution of surface water, \( u_5 \) expresses distribution of rare animals, \( u_6 \) expresses development degree of karst. Each factor is graded into several rates according to its degree of influence on the ecological environment.

(1) Surge water amount

Based on the completing documents of some tunnels in roads, railways and mines, there are all water burst varying different degrees in the process of construction. For example, the surge water amount from the drainage hole of Dabanshan tunnel is 20 t/h in the summer, 10 t/h in the winter. The maximum flow is up to 132000 t/d of Basishiyan tunnel, while 19550 t/d of Shalamu tunnel, 53000 t/d of Zhongliangshan tunnel, 27000 t/d of Dabashan tunnel. On the basis of the data above, the surge water amount is graded as follows.

Table 1. Grading standards for surge water amount of tunnel

| Grading standards | fewest | fewer | generally | more | most |
|-------------------|-------|-------|-----------|------|------|
| Surge water amount m³/d | <10^2 | 10^2~10^3 | 10^3~10^4 | 10^4~10^5 | >10^5 |

(2) Length of tunnel

According to Code For Design of Road Tunnel and other technology standards, the evaluation factor of length of tunnel is graded as follows.

Table 2. Grading standards for length of tunnel

| Grading standards | fewest | fewer | generally | more | most |
|-------------------|-------|-------|-----------|------|------|
| Length of tunnel (km) | <0.5 | 0.5~1 | 1~3 | 3~10 | >10 |

(3) Vegetation coverage

The larger vegetation coverage, the smaller effect on surrounding ecological environment of the construction of tunnels. The vegetation coverage is graded as follows.

Table 3. Grading standards for vegetation coverage

| Grading standards | fewest | fewer | generally | more | most |
|-------------------|-------|-------|-----------|------|------|
| Vegetation coverage (%) | >90 | 70~90 | 50~70 | 30~50 | <30 |

(4) Distribution of surface water

This factor shows the distribution of surface water, such as reservoir, pond and stream near the tunnel. If the surface water is widely distributed around the tunnel, it will cause some serious problems on the leakage of surface water while excavating the tunnels. This factor is graded as follows.

Table 4. Grading standards for distribution of surface water

| Grading standards | fewest | fewer | generally | more | most |
|-------------------|-------|-------|-----------|------|------|
| Distribution of surface water | rarely | little | generally | rich | very rich |

(5) Distribution of rare animals

If there are rare animals surviving near the tunnel showing that the surrounding environment is important and ecology-sensitive. Therefore this manuscript grading the factor of distribution of rare animals as follows with fuzzy mathematics.

Table 5. Grading standards for distribution of rare animals

| Grading standards | fewest | fewer | generally | more | most |
|-------------------|-------|-------|-----------|------|------|
| Distribution of rare animals | rarely | little | generally | rich | very rich |
characteristics of the development of karst

The tunnel excavated tend to be a new discharge channel of groundwater, influencing the quality of surrounding environment if the karst is intensively developed near the tunnel. According to the fuzzy mathematics, the characteristics of the development of karst is graded as follows.

| Grading standards | characteristics of the development of karst |
|-------------------|---------------------------------------------|
| rarely            | rarely                                      |
| little            | little                                      |
| generally         | generally                                   |
| rich              | rich                                        |
| very rich         | very rich                                   |

4.2. Establishing the set of judgement

The degree of influence on the ecological environment of tunnels make up the set of judgement. It is also described based on fuzzy mathematics as follows.

$$V = \{v_1, v_2, v_3, v_4, v_5\}$$ (9)

Where $v_1$ expresses weaker, $v_2$ expresses weak, $v_3$ expresses generally, $v_4$ expresses strong and $v_5$ expresses stronger.

4.3. Defining membership grade and subjection matrix

Subjection matrix is established according to influence factors and judgement fuzzy set and its grade of membership. For the three factors, surge water amount, length of tunnel and vegetation coverage, the degree of influencing on the surrounding ecological environment has a positive relationship with its value. Therefore, the membership functions are considered as trapezium ones for the three factors, as follows.

\[
\begin{align*}
  u_{v_1} & = \begin{cases} 
  1 & x \leq a \\
  \frac{b - x}{b - a} & a < x \leq b \\
  0 & x > b
  \end{cases} \\
  u_{v_2} & = \begin{cases} 
  0 & x \leq a \\
  1 & a < x \leq b \\
  \frac{c - x}{c - b} & b < x \leq c \\
  0 & x > b
  \end{cases} \\
  u_{v_3} & = \begin{cases} 
  0 & x \leq a \\
  \frac{x - a}{b - a} & a < x \leq b \\
  1 & b < x \leq c \\
  \frac{x - d}{d - c} & c < x \leq d \\
  0 & x > d
  \end{cases}
\end{align*}
\]

(a) fewest \hspace{1cm} (b) fewer \hspace{1cm} (c) generally

For the three factors, distribution of surface water, distribution of rare animals and characteristics of the development of karst, quantitative gradation is extremely difficult. The fuzzy membership function(see Table 7) proposed by Kaiwowski is usually applied in the filed of civil engineering.

| fuzzy language variable | Membership function |
|-------------------------|---------------------|
| little                  | 1.0 0.9 0.7 0.3 0.1 0 0 |
| More or less            | 0 0 0.3 0.5 0.85 0.95 1 |
| medium                  | 0 0.2 0.7 1.0 0.7 0.2 0 |
| great                   | 0 0 0.1 0.3 0.7 0.9 1 |
| greater                 | 0 0 0 0.1 0.5 0.8 1 |

The judgement matrix of membership grade for the factors, distribution of surface water, distribution of rare animals and characteristics of the development of karst is established as follows.
Table 8. The judgement matrix of membership grade based on fuzzy mathematics

| $R$ | $v_1$ | $v_2$ | $v_3$ | $v_4$ | $v_5$ |
|-----|-------|-------|-------|-------|-------|
| fewest | rarely | 1 | 0 | 0 | 0 | 0 |
| fewer | 0.7 | 0.3 | 0.7 | 0.1 | 0 |
| generally | 0.3 | 0.5 | 1.0 | 0.3 | 0.1 |
| more | 0.1 | 0.85 | 0.7 | 0.7 | 0.5 |
| most | 0 | 0.95 | 0.2 | 0.9 | 0.8 |

The basic geological condition of the tunnel to be evaluated is shown in Table 9.

Table 9. Basic geological condition of the tunnel to be evaluated

| factors | relevant parameters | grade |
|---------|---------------------|-------|
| surge water amount | 59000m³/d | more |
| length of tunnel | 13000m | most |
| vegetation coverage | 80% | fewer |
| distribution of surface water | little | fewer |
| distribution of rare animals | rich | more |
| characteristics of the development of karst | generally | generally |

According to the membership function, the assessment matrix for the impact on the ecological environment of the construction of tunnel is set up.

$$R = \begin{bmatrix}
0.41 & 0.414 & 0.455 & 1 & 0.589 \\
0 & 0 & 0 & 0 & 1 \\
0.833 & 0.25 & 0.5 & 1 & 0.167 \\
0.7 & 0.3 & 0.7 & 0.1 & 0 \\
0.1 & 0.85 & 0.7 & 0.7 & 0.5 \\
0.3 & 0.5 & 1 & 0.3 & 0.1
\end{bmatrix}$$  \hspace{1cm} (10)

4.4. Defining factor weight set

Through the consult to experts (Table 10), the judgement matrix of factors is structured, as follows (Table 11).

Table 10. Distribution of experts invested in different majors

| sequence number | major | number |
|-----------------|-------|--------|
| 1               | environmental engineering | 13     |
| 2               | zoology       | 5      |
| 3               | ecology       | 9      |
| 4               | transportation | 4      |
| 5               | Tunnel, hydrogeology, geotechnical engineering | 17     |
| total           |            | 48     |

Table 11. Judgment matrix of factors

| $u_1$ | $u_2$ | $u_3$ | $u_4$ | $u_5$ | $u_6$ |
|--------|-------|-------|-------|-------|-------|
| $u_1$  | 1     | 3     | 3     | 3     | 1     | 2     |
| $u_2$  | 1/3   | 1     | 1     | 3/3   | 1     | 1     |
| $u_3$  | 1/3   | 1/3   | 1     | 1     | 1/5   | 1/3   |
| $u_4$  | 1/3   | 1/3   | 1     | 1     | 1/5   | 1/2   |
| $u_5$  | 1     | 3     | 5     | 5     | 1     | 2     |
| $u_6$  | 1/2   | 1     | 3     | 2     | 1/2   | 1     |

The maximal eigenvalue and corresponding eigenvector of the judgement matrix is given, and carrying out the consistency checking to prove the matrix is reasonable.
\[ CI = \frac{\lambda_{\text{max}} - n}{n-1} = \frac{6.1393 - 6}{6-1} = 0.02786 \]  

Random consistency indicators can be get from the Table 12.

Then
\[ CR = \frac{CI}{RI} = \frac{0.02786}{1.26} = 0.022 < 0.1 \]  

Table 12. Average random consistency index (RI)

| n  | RI |
|----|----|
| 1  | 0  |
| 2  | 0  |
| 3  | 0.52 |
| 4  | 0.89 |
| 5  | 1.12 |
| 6  | 1.26 |
| 7  | 1.36 |
| 8  | 1.41 |
| 9  | 1.45 |

Normalizing the eigenvector of the maximum eigenvalue.

\[ W = \{w_1, w_2, w_3, w_4, w_5, w_6\} = (0.3505, 0.0896, 0.0206, 0.0140, 0.4379, 0.0874) \]

4.5. Result

The evaluate result for the impact on the ecological environment of construction of the tunnel is as follows.

\[ B = W \times R = (0.2407, 0.5704, 0.5735, 0.7053, 0.5272) \]

According to the principle of maximum membership degree, the grade of the impact on the surrounding ecological environment is more. During the construction of the tunnel, some environmentally engineering measures should be adopted to protect the ecological balance.

5. Conclusions

Through employing fuzzy mathematics, the assessment system was put forward for the influence on the ecological environment of construction of the extra-long highway tunnel. The following conclusions can be drawn.

(1) According to the characteristics of the tunnel, six factors and its grade were proposed for establishing the evaluation system for the impact on ecological environment of construction of the extra-long highway tunnel, which are surge water amount, length of tunnel, vegetation coverage, distribution of surface water, distribution of rare animals and characteristics of the development of karst.

(2) Establish the fuzzy comprehensive evaluation model for the impact on ecological environment of construction of the highway extra-long tunnel, based on defining the membership function of factors and factor weight set.

(3) Applying the built evaluation system to a extra-long highway tunnel, result is that the grade of the impact on the surrounding ecological environment is more, indicating the established system is reasonable.

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