Fuzzy comprehensive evaluation of humanistic characteristics of smart tunnels

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Abstract. The smart tunnel concept has emerged to optimize the construction and operation of resources and functions. However, difficulties remain in comprehensively evaluating the degree of wisdom in this area and in scientifically guiding top-level design. To emphasize the humanistic spirit and concept of human-oriented smart tunnels, this study adopts the analytic hierarchy process (AHP)-based fuzzy comprehensive evaluation method is used to comprehensively evaluate the humanistic characteristics of tunnels, which have been previously ignored in the literature. The satisfaction of human needs is selected as the objective performance indicator, while the social value of tunnels is selected as the subjective guiding indicator. A three-level evaluation index system containing 3 first-level indexes, 6 second-level indexes, and 22 third-level indexes is built. The judgment matrix is established using the improved AHP, while the membership function is constructed on the basis of fuzzy theory. This study ultimately realizes the comprehensive evaluation of the humanistic attributes of smart tunnels. Taking the Bo’ao tunnel in Hangzhou as a typical case, this work demonstrates the reliability and practicability of the proposed evaluation system, which is expected to benefit the construction of tunnels from a humanistic perspective.

Keywords. smart tunnel, humanistic characteristics, AHP, fuzzy comprehensive evaluation

1. Introduction

The development of smart tunnels involves two common problems. First, a precise interpretation of the concept of tunnels’ “wisdom” is lacking, thus hindering the formation of unified and clear construction goals within the industry. Second, a suitable evaluation standard has yet to be established. Therefore, the process of smart tunnel construction cannot be evaluated objectively and scientifically. At the 13th National Conference on Soil Mechanics and Geotechnical Engineering, the “prospects of China’s geotechnical engineering” were discussed and formed after extensive and in-depth exchanges between more than 2,500 local and foreign delegates. According to the discussion, future geotechnical engineering should have four qualities, namely, “resilience,” “intelligence,” “green,” and “humanity.” This study interprets the wisdom of tunnels as a function, with resilience, intelligence, green, and humanity as the primary variables. These variables are used as basis in evaluating smart tunnels. The results should serve as a reference in constructing comprehensive evaluation systems for smart tunnels.

2. Evaluation index for humanistic attribute of smart tunnels

Humanism originated from the traditional culture of ancient Greece. Its core ideas are caring about people, especially about their spiritual life; and respect for the value of human existence, especially...
spiritual existence. The humanistic attribute of smart tunnels is mainly reflected in the concept of “human orientation” and its social value[1]. As different tunnel projects bear different social values, this study regards social value as a guiding evaluation index for the humanistic attribute of smart tunnels. It considers the embodiment of humanism in tunnel engineering as the primary evaluation index.

2.1. Primary evaluation indexes
The humanistic value of tunnel engineering is mainly reflected in the satisfaction of people’s needs. According to Maslow’s hierarchy of needs, human necessities can be divided into physiological needs, safety needs, needs of belongingness and love, need for esteem, and self-actualization needs[2]. Combined with the characteristics of tunnels, people’s needs for smart tunnels can be divided into safety needs, comfort needs, and spiritual civilization pursuit. According to the perspective of the human life cycle, the need for safety and comfort is mainly reflected in the construction and operation of tunnels. People’s pursuit of spiritual civilization is primarily reflected in tunnels’ aesthetic function and cultural connotation, which are mainly observed in the entrances and landscape of tunnels. The primary evaluation indexes for the human attributes of smart tunnels are shown in Figure 1.

![Figure 1. Primary evaluation indexes of the humanistic attributes of smart tunnels](image)

2.2. Guiding evaluation indexes
The social value of tunnels mainly includes contributions to regional development, characteristics of embodiment of the times, and protection and inheritance of historical and cultural heritage. Given the varying construction backgrounds and functions of different tunnel projects, their social values also differ. Therefore, when evaluating the humanistic attributes of smart tunnels, the model adopted herein regards social value as a bonus item, with the maximum bonus not exceeding 10 points. The specific bonus rules are shown in Table 1.

| Target layer          | Rule layer                                      | Index layer                             | Bonus rules                                                                 |
|-----------------------|------------------------------------------------|-----------------------------------------|----------------------------------------------------------------------------|
| Social values         | Contributions to the region                     | Convenient Transportation               | Improve traffic order and meet travel demand: +1                           |
|                       |                                                 | Tourism Development                     | Improve the urban road network planning: +0.5                             |
|                       |                                                 | Economic Growth                         | Promote the development of local tourism: +1                              |
|                       |                                                 | Others                                  | The connection between the business district and surrounding areas has been strengthened: +1 |
|                       |                                                 |                                        | Scored by experts according to the actual situation.                      |

Table 1. Guiding evaluation indexes’ bonus rules
3. Fuzzy comprehensive evaluation model based on multiple indexes

This study divides the humanistic performance of smart tunnels into four grades: excellent, good, moderate, and poor. Given the absence of a clear boundary of the humanistic attributes of tunnels under multifactor indexes, this study uses the analytic hierarchy process (AHP)-based fuzzy comprehensive evaluation method to build the primary evaluation model.

3.1. Factor set of primary evaluation

This study refers to relevant norms[3–7] and research results[8–12] to evaluate the humanistic attributes of smart tunnels objectively and efficiently. It selects 22 third-level indicators based on the second-level indicators shown in Figure 1 and ultimately forms a three-level evaluation index system. The factor set is shown in Table 2.

| Target layer | Rule layer | Index layer |
|--------------|------------|-------------|
| Safety needs | $U_{11}$: Safety of construction personnel | $U_{111}$: Safety awareness of employees $U_{112}$: Safety and completeness of facilities and equipment $U_{113}$: Safety of construction environment $U_{114}$: Safe and orderly management |
| | $U_{12}$: Safe operation in the tunnel | $U_{121}$: Design of traffic $U_{122}$: Operation of electromechanical systems $U_{123}$: Traffic conditions $U_{124}$: Management of tunnel operation $U_{125}$: Traffic safety facilities |
| Comfort needs | $U_{21}$: Civilized construction | $U_{211}$: Civilized and orderly construction site $U_{212}$: Complete and adequate civilized management $U_{213}$: Civilization consciousness and health of construction personnel |
| | $U_{22}$: Comfortable environment in the tunnel | $U_{221}$: Lighting environment $U_{222}$: Air quality $U_{223}$: Noise control |
| | $U_{31}$: Landscape of the tunnel entrance | $U_{311}$: Practicability of the function $U_{312}$: Ecological integration $U_{313}$: Aesthetic value $U_{314}$: Embodiment of culture |
| | $U_{32}$: Landscape inside the tunnel | $U_{321}$: Comfort of the visual environment $U_{322}$: Aesthetic value |
3.2. Comment set and membership function

The evaluation of the humanistic attributes of tunnels consists of two parts: primary evaluation and guiding evaluation. According to the actual situations of tunnels, experts score two types of indicators:

1. Comprehensive scores of primary evaluation indexes (maximum score: 90);
2. Bonus scores of guiding evaluation indexes (maximum score: 10).

The evaluation result \( V \) is divided into four grades according to the total score \( x \) of the humanistic attributes of smart tunnels. The comment set is established as

\[
V = \{ v_1(Excellent), v_2(Good), v_3(Medium), v_4(Poor) \} \quad (1)
\]

The membership function of the “Excellent” fuzzy set \( A \) is as follows:

\[
\mu_A(x) = \begin{cases} 
0, & 0 \leq x \leq 85 \\
\frac{x-85}{5}, & 85 < x \leq 90 \\
1.90, & 90 < x \leq 100
\end{cases} \quad (2)
\]

The membership function of the “Good” fuzzy set \( B \) is as follows:

\[
\mu_B(x) = \begin{cases} 
0, & 0 \leq x \leq 70 \\
\frac{x-70}{5}, & 70 < x \leq 75 \\
1.75, & 75 < x \leq 85 \\
\frac{90-x}{5}, & 85 < x \leq 90 \\
0.90, & 90 < x \leq 100
\end{cases} \quad (3)
\]

The membership function of the “Medium” fuzzy set \( C \) is as follows:

\[
\mu_C(x) = \begin{cases} 
0, & 0 \leq x \leq 55 \\
\frac{x-55}{5}, & 55 < x \leq 60 \\
1.60, & 60 < x \leq 70 \\
\frac{75-x}{5}, & 70 < x \leq 75 \\
0.75, & 75 < x \leq 85
\end{cases} \quad (4)
\]

The membership function of the “Poor” fuzzy set \( D \) is as follows:

\[
\mu_D(x) = \begin{cases} 
1.0, & 0 \leq x \leq 55 \\
\frac{60-x}{5}, & 55 < x \leq 60 \\
0.60, & 60 < x \leq 100
\end{cases} \quad (5)
\]

3.3. Determination of weight coefficient based on AHP

The AHP is a simple quantitative analysis method for non-quantitative events in system engineering. It is also an effective way to describe people’s subjective judgment objectively. It determines the weight set by comparing the importance of indicators[13].

1. The judgment matrix is constructed according to the factor set in Table 2. Here, \( A \) represents the goal, \( u_i \) represents the evaluation factor, \( u_{ij} \) represents the relative importance value of factor \( u_i \) to factor \( u_j \), and the scale of \( u_{ij} \) is shown in Table 3.
The A-U judgment matrix can be obtained as
\[
P = \begin{bmatrix}
u_{11} & u_{12} & \cdots & u_{1n} \\
u_{21} & u_{22} & \cdots & u_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
u_{n1} & u_{n2} & \cdots & u_{nn}
\end{bmatrix} \quad (6)
\]

(2) According to the A-U judgment matrix, the eigenvector corresponding to the maximum eigenvalue is obtained. Then, after normalizing the feature vector, the order of importance of each evaluation index factor is regarded as the weight distribution.

(3) To test the consistency of the judgment matrix, the following formula can be used:
\[
CI = \frac{1}{n-1} (\lambda_{max} - n) \quad (7)
\]
\[
CR = \frac{CI}{RI} \quad (8)
\]

When CR < 0.10, the judgment matrix is considered to have satisfactory consistency, which indicates that the weight distribution is reasonable.

A total of 26 experts from the fields of tunnel engineering, project management, landscape design, and others were invited to judge the relative importance of the factors and thereby ensure the objectivity and authority of the final evaluation model. According to the questionnaire results of each expert, this study constructs 26 judgment matrices and then conducts weight calculation and consistency tests. After eliminating the data that did not pass the consistency test, 23 weight sets are retained, and the index weight is obtained on the basis of the weighted average.

1) First-level indicators: \( W = (0.75, 0.15, 0.1) \);
2) Second-level indicators: \( W_1 = (0.5, 0.5), W_2 = (0.5, 0.5), W_3 = (0.5, 0.5) \);
3) Third-level indicators: \( W_{11} = (0.24, 0.15, 0.04, 0.57), W_{12} = (0.31, 0.26, 0.20, 0.14, 0.09) \), 
   \( W_{22} = (0.28, 0.28, 0.44), W_{21} = (0.42, 0.35, 0.23), W_{31} = (0.46, 0.23, 0.15, 0.16), W_{32} = 
   (0.67, 0.16, 0.17) \)

3.4. Single-factor evaluation (membership)
The single-factor evaluation matrix is obtained using the membership function. That is, the membership \( r_{ij} \) of \( V_j \) is obtained for each factor \( U_i \). This step is key in the fuzzy comprehensive evaluation method. The matrix is as follows:
\[
R = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1m} \\
r_{21} & r_{22} & \cdots & r_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & \cdots & r_{nm}
\end{bmatrix} \quad (9)
\]

This study refers to relevant norms, research results, and the guidance of experts in related fields and finally determines the specific scoring rules for the third-level indexes. According to the weight set, the scoring results for the second and first levels can be determined. Meanwhile, according to the membership function, the membership matrix can be determined. Given the complexity of the actual situations of tunnels, this study combines quantitative and qualitative methods when making the
scoring rules. For example, the qualitative scoring method is used for the “aesthetic value” of the landscape of the tunnel entrance. The quantitative scoring method is used for the “traffic conditions,” as shown in Tables 4 and 5.

**Table 4. Scoring rules of aesthetic value of tunnel entrance landscape**

| Indexes (Scores) | Scoring rules                                                                 |
|------------------|-------------------------------------------------------------------------------|
| Aesthetic value  | All visual attributes change appropriately, not monotonous. (25)             |
| (100)            | The decoration and functional elements of the entrance are harmonious and     |
|                  | beautiful. (25)                                                               |
|                  | The landscape stimulates the pleasure of the viewer and is impressive. (50)   |

**Table 5. Scoring rules of traffic conditions**

| Indexes (Scores) | Scoring rules                                                                 |
|------------------|-------------------------------------------------------------------------------|
| Traffic flow     | Let the traffic flow (standard volume per day) be $x$ and the score be $y$, $x>0$: |
| (25)             | $y = \begin{cases} 
0, x > 25000 \\
5,15000 < x \leq 25000 \\
10,8000 < x \leq 15000 \\
15,4000 < x \leq 8000 \\
20,2000 < x \leq 4000 \\
25, x < 2000 
\end{cases}$ |
| Traffic mode     | 20 points for one-way traffic and 2.5 points for two-way traffic               |
| (20)             | Let the average speed (km/h) be $x$, and the score be $y$, $x>0$:             |
| Average speed    | $y = \begin{cases} 
0, x > 90 \\
1,80 < x \leq 90 \\
3,70 < x \leq 80 \\
7,5, 60 < x \leq 70 \\
15, x < 60 
\end{cases}$ |
| Range of speed   | Let the average of speed range (km/h) be $x$, and the score be $y$, $x>0$:    |
| (16)             | $y = \begin{cases} 
0, x > 60 \\
5, 40 < x \leq 60 \\
12, 20 < x \leq 40 \\
16, x < 20 
\end{cases}$ |
| Proportion of    | Let the proportion of large vehicles (%) be $x$, and the score be $y$, $x>0$:  |
| large vehicles   | $y = \begin{cases} 
24, x > 80 \\
8, 50 < x \leq 80 \\
16, 20 < x \leq 50 \\
24, x < 20 
\end{cases}$ |

3.5. **Evaluation process**

After determining the factor set, comment set, membership function, weight set, and single-factor scoring rules, this study builds the comprehensive evaluation model of the humanistic attributes of tunnels. The evaluation process is shown in Figure 2.
4. Project example
The evaluation of the humanistic attributes of tunnels is a systematic project that involves the relevant theories and methods of humanistic attribute evaluation and requires the participation of many departments. This chapter describes a fuzzy comprehensive evaluation of the humanistic attributes of the Bo'ao tunnel in Hangzhou, details the evaluation of the humanistic attributes of the tunnel by using an example, and verifies the rationality and practicability of the evaluation model.

4.1. General situation of Bo'ao tunnel
The Bo’ao tunnel in Hangzhou traverses the core area of Qianjiang New Town. It is an important river crossing tunnel connecting the main urban area, Qianjiang New Town, Olympic Sports Expo Center, and Jiangnan suburban area. It has formed an essential pattern of “one river, two banks, and three channels,” along with the Xixing Bridge and Qingchun Road Tunnel. It has improved the traffic capacity across the river and strengthened the traffic links between the north and south sides of the Qiantang River. The Bo’ao tunnel is an essential supporting project for the Asian Games, and its design is under the urban trunk road standard. The total construction period is 36 months, and the total investment is 1.86 billion yuan. Figures. 3 and 4 show the layout of the Bo’ao tunnel.

4.2. Evaluation of humanistic attributes of Bo’ao tunnel
The score of the Bo’ao tunnel is based on the actual situation of the project and the existing engineering data. As the Bo’ao tunnel has yet to operate, the data about its operation are assumed mainly according to the project expectations. According to the scoring rules, the tunnel managers and experts in related fields assign scores.
According to the steps shown in Figure 2, this study obtains the primary scores for the first- and second-level indicators of the human attributes of the Bo’ao tunnel (Table 6).

Table 6. Scores of primary evaluation of the humanistic attributes of Bo’ao tunnel

| First-level index (weight) | Scores | Second-level index (weight) | Scores |
|----------------------------|--------|-----------------------------|--------|
| Safety needs (0.75)        | 94.86  | Safety of construction personnel (0.50) | 98.38  |
| Comfort needs (0.15)       | 98.93  | Safe operation in the tunnel (0.50) | 91.33  |
| Spiritual civilization pursuit (0.10) | 91.33 | Civilized construction (0.46) | 97.68 |
|                             |        | Comfortable environment in the tunnel (0.54) | 100 |
|                             |        | Landscape of the tunnel entrance (0.55) | 88.32 |
|                             |        | Landscape inside the tunnel (0.45) | 95.00 |

As the total score of the primary indicators is 90, the primary scoring result \( P \) of the Bo’ao tunnel should be multiplied by 0.9 after obtaining the weighted average of the scores of the first-level indicators.

\[
P = 0.9 \sum_{i=1}^{3} \omega_i P_i = 0.9 \times (94.86 \times 0.75 + 98.83 \times 0.15 + 91.13 \times 0.10) = 85.87
\]

According to the project’s actual situation, the guiding indicators of the human attributes of the Bo’ao tunnel are scored. The results are shown in Table 7.

Table 7. Scores of primary evaluation of the humanistic attributes of Bo’ao tunnel

| Rule layer                        | Scores | Reasons for bonus points                                      | Bonus |
|-----------------------------------|--------|--------------------------------------------------------------|-------|
| Contributions to the region       | 3      | Improve traffic order and meet travel demand                 | 1     |
|                                   |        | Improve the urban road network planning                      | 0.5   |
|                                   |        | Promote the development of local tourism                     | 0.5   |
|                                   |        | Strengthen the connection between the business district and surrounding areas | 1 |
| Embodiment of the times' characteristics | 3    | Bred valuable innovation achievements, such as "Research on green technology of urban tunnel" | 1 |
|                                   |        | It is an important supporting facility for the Asian Games  | 2     |
| Historical heritage               | –      | –                                                            | –     |

Combining the primary evaluation with the guiding evaluation, the total score of the humanistic attributes of the Bo’ao tunnel is 91.57. According to Formulas 2–5, the membership of the comment set \( V \) is \((1, 0, 0, 0)\). Thus, the comprehensive evaluation result is excellent.

4.3. Analysis and discussion

Two main factors explain the excellent performance of the Bo’ao tunnel project in relation to the humanistic attribute.

1. As an important supporting facility for the Asian Games, the Bo’ao tunnel has attracted the attention of the government and society. The project volume is large, and the investment is sufficient. During site selection, design, and construction, the specification requirements are strictly
implemented. The final construction results also meet the construction expectation for the urban river crossing tunnel.

(2) As a river crossing tunnel, the Bo’ao tunnel strengthens the connection between the two sides of the Qiantang River in Hangzhou and improves the urban traffic order. As a service for the Asian Games, it reflects the level of infrastructure construction in China. Therefore, the evaluation result of the humanistic attributes of the Bo’ao tunnel is reasonable and practical.

This section verifies the rationality and practicability of the evaluation model with a project example (Bo’ao tunnel). First, the evaluation index system is complete and includes most aspects of the humanistic attributes of tunnels. Second, the model is easy to operate. Professionals can easily assign scores according to precise scoring rules and derive comprehensive evaluation results through fuzzy transformation. Third, the evaluation result of this model is reasonable as the final evaluation result for the Bo’ao tunnel is in good agreement with engineering practice.

5. Conclusion and prospect
At present, the comprehensive evaluation of smart tunnels (humanistic attributes) is in its infancy, and the number of related studies is limited. This study uses the AHP-based fuzzy comprehensive evaluation method to build a three-level evaluation system for smart tunnels’ humanistic attributes. With the Bo’ao tunnel as an example, this study builds a comprehensive evaluation model, which is used to evaluate the human attributes of the tunnel. The results are found to be excellent, which verifies the rationality and feasibility of the model.

The research results offer great significance as a reference for the evaluation of smart tunnels. Nevertheless, extensive and in-depth research should be conducted to comprehensively evaluate the resilience, intelligence, and green attributes of smart tunnels and finally form a complete evaluation system.

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