# Construction of a Linear Engineering Visual Landscape Interference Model for the Buffer Zone of the Libo Heritage Site Based on the AHP-Fuzzy Comprehensive Evaluation Method: A Case Study of the Guiyang-Nanning High-Speed Railway

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**Abstract** The buffer zone of a World Natural Heritage Site constitutes a critical element of the heritage site protection system. It not only functions as an ecological security barrier, but also significantly influences the visual integrity and aesthetic value of the core area's landscape. Given the rapid development of transportation infrastructure, particularly the growing number of high-speed railways traversing ecologically sensitive regions, the scientific assessment of their impact on the landscape environment of heritage sites has emerged as a pivotal concern in heritage conservation and regional development. This study focused on the section of the Guiyang-Nanning High-Speed Railway that traverses the buffer zone of the Libo World Natural Heritage Site in Guizhou Province. Beginning with five primary indicators, including natural landscape and aesthetic value, geological geomorphology and Earth history value, biodiversity value, integrity and protection management, and impact on ecological environment, a visual landscape impact assessment system for high-speed railways was developed based on the analytic hierarchy process (AHP) and the fuzzy comprehensive evaluation method (FCE). Through expert scoring, hierarchical weight calculation, and fuzzy membership degree analysis, a comprehensive assessment was conducted on the landscape ecological quality, visual coordination, and aesthetic perception within the buffer zone following the construction of high-speed railways. The findings indicate that the construction of the Guiyang-Nanning High-Speed Railway generally harmonizes well with the landscape environment of the heritage site. The level of visual disturbance remains within an acceptable range and has not significantly damaged the overall aesthetic value or authenticity of the heritage site. Although the integrity of the landscape in certain local areas has experienced a slight decline due to the exposure of bridge and slope structures, the adverse effects have been effectively mitigated through engineering interventions such as vegetation restoration and color coordination. This study innovatively integrates the AHP with fuzzy mathematics methods to achieve a comprehensive evaluation that combines both qualitative and quantitative approaches. This integration provides a scientifically grounded analytical path and a practical technical framework for assessing the visual impact of linear infrastructure projects, such as high-speed railways, within the buffer zones of World Heritage Sites. The findings offer valuable insights for the protection of landscapes and the sustainable development of infrastructure in heritage sites.

**Keywords** Heritage site, Buffer zone, Analytic hierarchy process (AHP), Fuzzy comprehensive evaluation method (FCE)

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In the context of accelerated global infrastructure development and the ongoing advancement of the ecological civilization concept, safeguarding the outstanding universal value of World Natural Heritage Sites while simultaneously promoting regional economic and social development has emerged as a critical issue in international heritage conservation and sustainable development research[1]. World Natural Heritage Sites, regarded as the shared natural heritage of humanity, are distinguished not only by their unique geological formations, ecosystems, and aesthetic landscapes but also by their embodiment of ecological evolution and aesthetic value resulting from the interplay between nature and culture. Nevertheless, in the context of rapid urbanization and the expansion of transportation infrastructure, these heritage sites and their buffer zones are increasingly subjected to various pressures arising from large-scale linear engineering projects. Although these projects play a crucial role in enhancing transportation accessibility and fostering regional economic development, they may also disrupt the natural patterns, ecological processes, and visual perception systems of the heritage site landscape[2], thereby posing a threat to the authenticity and integrity of the heritage site.

Within the world heritage protection management system, the buffer zone constitutes the most critical landscape buffer and ecological transition area surrounding the heritage site. Its primary function is to safeguard the core area of the heritage site from direct impacts arising from external environmental changes and human construction activities[3]. The buffer zone serves not only as an ecological barrier but also plays a vital role in preserving the visual continuity and aesthetic integrity of the heritage site's landscape. The *Operational Guidelines for the Implementation of the World Heritage Convention* (2021 Edition) of UNESCO explicitly state that the visual environment of heritage sites and their buffer zones must be integrated into the comprehensive framework for heritage protection and management. Furthermore, the guidelines mandate that member states undertake rigorous visual impact assessments

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(VIA) for construction projects in the vicinity of heritage sites to ensure that such engineering activities do not compromise the landscape value or visual integrity of the heritage site[4]. In practical applications, the evaluation of visual landscape interferences within the buffer zones of heritage sites remains underdeveloped, with existing methodological frameworks being incomplete and quantitative analyses insufficient. Moreover, there is an absence of a comprehensive assessment framework that adequately addresses the complexities of ecological environments and the characteristics of linear engineering projects.

In recent years, both domestic and international scholars have increasingly focused on the landscape impacts of large-scale linear infrastructure projects, including expressways, high-speed railways, and power transmission lines. International research primarily emphasizes examining the visual coordination between engineering facilities and natural landscapes from the perspective of landscape ecology and visual perception analysis, employing approaches such as GIS-based spatial visibility assessments, 3D simulations, and public perception surveys. Conversely, domestic studies have predominantly concentrated on qualitative evaluations of ecological effects and landscape aesthetics. However, these studies exhibit three primary limitations in practical application. First, the construction of the indicator system lacks systematic organization and specificity, failing to comprehensively capture the multifaceted attributes of the visual landscape of heritage sites. Second, traditional evaluation methods predominantly depend on subjective scoring or analyses from a single perspective, which impedes the accurate representation of the distribution of interference and rhythmic variations related to linear engineering within the spatial dimension. Third, existing models inadequately address the inherent ambiguity associated with the complex concept of "landscape visual interference", leading to assessments that lack scientific rigor and reproducibility.

In addressing the aforementioned issues, this paper proposes a model construction approach that integrates the analytic hierarchy process (AHP) with the fuzzy comprehensive evaluation method (FCE)[5–7]. The objective is to develop a quantitative evaluation system for visual landscape interferences applicable to the linear engineering of buffer zones within World Heritage Sites. The AHP method facilitates the construction of a multi-level indicator system based on expert judgment and assigns weights to each influencing factor, thereby reflecting their relative importance within the overall interference. The FCE method addresses the fuzziness and uncertainty inherent in the visual perception process by converting qualitative descriptions into quantifiable data through the application of membership functions. The integration of these two methods facilitates a bidirectional synthesis of "qualitative and quantitative" analysis and enables a comprehensive assessment of the extent, scope, and type of engineering interventions in complex natural environments. Consequently, this integration supports the development of a systematic, highly adaptable, and scalable model for analyzing visual landscape interferences.

## 1 Overview of the study area

This study focused on the Guizhou Libo section of the Guiyang-Nanning High−Speed Railway (hereafter referred to as the "Guiyang-Nanning Railway"), which traverses the buffer zone of the World Natural Heritage Site. This segment is situated within the buffer zone of the Libo area, part of the "Southern China Karst" series of World Natural Heritage Sites. It is a typical karst ecosystem protection sample area in China, characterized by exceptionally high ecological sensitivity and significant landscape aesthetic value[3,8-9]. The Guiyang−Nanning Railway, a significant segment of the southwest corridor within the national "eight verticals and eight horizontals" high-speed railway network[10], unavoidably intersects with the buffer zone of the heritage site in the Libo section. This intersection presents a representative case for examining the balance between the development of large-scale transportation infrastructure and the preservation of cultural heritage. The total length of the railway section is approximately 15.78 km, of which approximately 6.23 km are directly observable from the ground surface. The landform types along the route are complex and diverse, encompassing peak cluster depressions, karst canyons, subtropical karst forests, river valley wetlands, terraced villages, and other landscape units[11-13]. These features collectively form a natural to semi-natural composite landscape belt characterized by high visual sensitivity and ecological diversity. The railway employs an engineering design that integrates "bridges and tunnels" to minimize disruption to surface ecology and landscape continuity. Nevertheless, artificial facilities in certain local areas may still result in visual fragmentation, obstruction, and style heterogeneity within the landscape.

Field investigations and video data indicate that the primary landscape elements within this buffer zone comprise dense arbor forest belts, karst mountains, river valley water bodies, terraced farmlands, village buildings, transportation slopes, tunnel and bridge structures, and sky backgrounds. The spatial structure is characterized by pronounced undulation, high density, and strong contrast. The landscape exhibits considerable diversity and a pronounced visual rhythm, demonstrating significant aesthetic value and sensitivity to external interferences. As a critical peripheral zone for the visual safeguarding of world natural heritage, the landscape pattern and harmony within this region are directly linked to the continuity and authenticity of public perception regarding the "outstanding universal value" (OUV) of the Libo Heritage Site[1,4,14]. This relationship holds substantial practical importance and provides valuable methodological insights for examining the coordinated development of infrastructure construction alongside heritage conservation.

## 2 Preliminary development of indicators

To scientifically assess the extent of visual landscape interference caused by the Guiyang-Nanning High-Speed Railway as it traverses the buffer zone of the Libo World Natural Heritage Site, the research integrated relevant findings from visual landscape impact assessment (VIA), ecological sensitive area impact assessment (EIA) both domestically and internationally, and landscape protection strategies for World Heritage Sites, and developed an initial indicator framework based on the AHP-FCE system, adhering to the principles of systematicity, scientific rigor, and practicality. The initial development of the indicators was primarily grounded in three key aspects. First, it drew upon the requirements related to visual environmental protection and buffer zone management as outlined in the *Operational Guidelines for the Implementation of the World Heritage Convention* of UNESCO. Second, it integrated general indicator systems for linear engineering projects, both domestic and international (e.g., expressways and high-speed railways), particularly in the context of assessing visual landscape impacts. Third, it took into account the distinctive karst landform characteristics, ecosystem vulnerability, and aesthetic landscape value specific to the Libo Heritage Site. Based on this framework, a three-tier evaluation system comprising the target layer, criterion layer, and indicator layer was initially established. The target layer pertained to the "comprehensive evaluation of visual landscape interference caused by high-speed railway within the buffer zone of the Libo Heritage Site". The criterion layer consisted of five primary indicators: natural landscape and aesthetic value ($A_1$); geological geomorphology and Earth historical value ($A_2$); impact on biodiversity value ($A_3$); integrity and conservation management ($A_4$); and impact on ecological environmental ($A_5$). The indicator layer further refined several secondary indicators, including terrain coordination, vegetation occlusion rate, bridge volume significance, color coordination, visual field continuity, and changes in landscape rhythm.

## 3 Composition of experts

To ensure the scientific rigor and objectivity in the development of the evaluation system and the determination of indicator weights, this study employed the AHP expert scoring method. Experts from multiple disciplines collaboratively participated in reviewing the indicator system and assigning weights. The expert panel comprised 15 members, all from relevant fields such as ecological environment, landscape planning, transportation engineering, world heritage protection, and visual aesthetics, covering research institutes, universities, and management organizations. The composition of experts was as follows: 5 specialists in ecology and environmental science (33.3%), primarily from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, and the School of Environmental Engineering at Guizhou University; 4 experts (26.7%) in landscape and urban-rural planning, possessing research experience in landscape planning and visual analysis of heritage sites; 3 professionals (20.0%) in traffic engineering and route design, chiefly responsible for evaluating visibility and structural design in linear engineering projects; 2 experts (13.3%) specializing in world heritage protection and management, affiliated with administrative departments of World Heritage Sites; and one expert (6.7%) in visual psychology and aesthetic evaluation.

All experts possessed a title of subtropical high or higher, or held a doctoral degree. Among them, 40% were professors, while 60% were doctoral researchers. During the distribution and collection of the questionnaire, two rounds of weight consistency tests were conducted using the Delphi method. Ultimately, only results with a consistency ratio (*CR*) below 0.1 were retained as input for the weight matrix. The expert panel rated the importance of each indicator on a scale from 1 to 9, constructed a judgment matrix, calculated the eigenvectors, and derived the weight distribution at each level, thereby providing a basis for the fuzzy comprehensive evaluation model.

## 4 Indicator determination

To ensure the scientific rigor and rationality of the indicator formulation within the AHP–FCE system, this study employed the Delphi method in conjunction with a Likert scale questionnaire survey to facilitate expert evaluation and refinement of the initially proposed visual landscape interference evaluation indicator system. The questionnaire was divided into two sections. The first section evaluated the appropriateness and representativeness of 5 primary indicators: natural landscape and aesthetic value, geological geomorphology and Earth history value, impact on biodiversity value, integrity and protection management, and impact on ecological environment. The second section quantitatively assessed the operability and importance of 12 secondary indicators. Experts were evaluated using a 5-point Likert scale ranging from 1 (unimportant) to 5 (very important). A total of 20 questionnaires were distributed, of which 18 valid responses were collected, resulting in an effective response rate of 90%. The reliability of the questionnaire data was assessed using SPSS 19.0. The Cronbach's α coefficient was 0.895 (Table 1), indicating high reliability and strong internal consistency among the various indicators. Additionally, the coefficient of variation (*Cv*) for each indicator ranged between 0.1 and 0.3, reflecting a high degree of consensus among experts and demonstrating both the stability and discriminative capacity of the evaluation system.

Based on this foundation, two rounds of expert consultations and revisions employing the Delphi method were conducted. The first round concentrated on enhancing the "consistency and logical coherence" of the indicator system. In response to expert feedback, certain indicator names were academically refined and specified. For example, the term "landscape visual coordination" was revised to "landscape color and landform coordination degree", and the term "ecological inteference intensity" was amended to "engineering visibility intensity". The second round concentrated on enhancing the precision and operability of the indicators by eliminating those exhibiting significant redundancy or overlapping meanings. Additionally, two secondary indicators were introduced to capture the visual characteristics of heritage sites: "degree of variation in landscape rhythm" and "potential for visual restoration". Ultimately, the expert panel reached a consensus and established the final evaluation system, comprising 5 primary indicators and 12 secondary indicators. This system not only aligns with international normative standards for the visual protection of World Natural Heritage Sites but also corresponds to the ecological environment and engineering interference characteristics of the Libo karst region, thereby providing a scientific foundation for the subsequent calculation of AHP weights and fuzzy comprehensive assessment.

## 5 Indicator weights obtained using the AHP method

To scientifically ascertain the importance of each indicator within the evaluation system of high-speed railway visual landscape interference in the buffer zone of the Libo World Natural Heritage Site, AHP was employed to determine the indicator weights. AHP is a multi-level decision-making method that integrates both qualitative and quantitative characteristics, making it well-suited for addressing complex system problems involving multiple targets and factors. By combining expert judgment with matrix calculations, AHP systematically reflects the relative importance of each indicator to the overall target, thereby providing a weighted basis for fuzzy comprehensive assessment.

### 5.1 Establishing a hierarchical structure model

Based on the principle of the AHP method, the decision-making target, evaluation criteria, and specific indicators were organized into a four-tier hierarchy reflecting their interrelationships: the target level, criterion level, element level, and factor level. Consequently, a hierarchical structural model was developed to assess the visual landscape interference of the high-speed railway within the buffer zone of the Libo Heritage Site (Table 2).

The target layer denotes the primary issue addressed in this study, specifically the "comprehensive evaluation of visual landscape interference caused by the Guiyang–Nanning High-Speed Railway as it traverses the buffer zone of the Libo World Natural Heritage Site". This layer encapsulates the overarching direction and decision-making targets of the evaluation framework.

The criterion layer serves as the primary control factor influencing the achievement of the target. Taking into account the protection requirements of the World Natural Heritage Site and the visual landscape characteristics comprehensively, it was divided into 5 primary indicators: natural landscape and aesthetic value; geological geomorphology and Earth historical value; impact on biodiversity value; integrity and protection management; and impact on ecological environment. This layer represents the overall dimension and evaluation framework for assessing visual landscape interference.

The element layer consists of the key evaluation components within each criterion layer and serves to represent the specific performance of each primary indicator. Examples included terrain coordination, bridge volume significance, color coordination, vegetation occlusion rate, visual field continuity, and variations in landscape rhythm.

The factor layer represents the measurable factors or data sources corresponding to each element layer, typically expressed through quantifiable or observable indicators. Examples included the proportion of visibility of engineering structures, vegetation coverage, the ratio of bridge shading area, color difference degree, and landscape continuity index. This factor layer functions as the operational basis of the entire model, supplying input data necessary for the subsequent calculation of AHP weights.

### 5.2 Construction of judgment matrix

According to the fundamental principles of AHP, experts were invited to perform pairwise comparisons of indicators at the same hierarchical level, utilizing the 1–9 scale method to represent their relative importance (Table 2).

The judgment matrix represents the subjective evaluations of experts regarding the relative importance of each factor. The elements of the matrix satisfy the reciprocal property $a_{ij}=1/a_{ji}$, and $a_{ij}=1$. To ensure the rationality and consistency of the judgments, this study aggregated the matrices provided by the experts by computing the arithmetic mean for each matrix, thereby deriving a group judgment matrix. Matrix operations were performed using Yaahp 10.1 software, through which the eigenvectors and maximum eigenvalues for each indicator were calculated.

### 5.3 Consistency test

To assess the logical consistency of the judgment matrix, both the consistency index (*CI*) and the consistency ratio (*CR*) were computed as follows:

$$CI=(\lambda_{max}-n)/(n-1),\quad CR=CI/RI$$

where $\lambda_{max}$ denotes the maximum eigenvalue of the judgment matrix, *n* represents the order of the matrix, and *RI* corresponds to the average random consistency index, with standard values presented in Table 3. A consistency ratio (*CR*) less than 0.1 indicates acceptable consistency of the judgment matrix, obviating the need for adjustment. The calculation results revealed that the *CR* of the target layer was 0.076, and the *CR* values for the five criterion layers were all below 0.1, demonstrating that the expert judgments are logically consistent and that the weight distribution is reliable.

## 6 Fuzzy comprehensive evaluation

### 6.1 Determination of evaluation indicators and evaluation grades

Owing to the large number of evaluation indicators, a multi-level FCE method was employed. The target layer indicator set was defined as $U=\{A_1, A_2, A_3, A_4, A_5\}$. The criterion layer indicators were as follows: $A_1=\{B_1, B_2\}$, $A_2=\{B_3, B_4\}$, $A_3=\{B_5, B_6, B_7\}$, $A_4=\{B_8, B_9, B_{10}\}$, and $A_5=\{B_{11}, B_{12}\}$. Further subdivisions included $B_1=\{C_1, C_2, C_3\}$, $B_2=\{C_4, C_5\}$, $B_3=\{C_6, C_7, C_8\}$, $B_4=\{C_9, C_{10}, C_{11}, C_{12}\}$, $B_5=\{C_{13}, C_{14}\}$, $B_6=\{C_{15}, C_{16}\}$, $B_7=\{C_{17}, C_{18}\}$, $B_8=\{C_{19}, C_{20}, C_{21}, C_{22}\}$, $B_9=\{C_{23}, C_{24}, C_{25}\}$, $B_{10}=\{C_{26}, C_{27}\}$, $B_{11}=\{C_{28}, C_{29}, C_{30}, C_{31}, C_{32}\}$, and $B_{12}=\{C_{33}, C_{34}, C_{35}, C_{36}, C_{37}, C_{38}, C_{39}\}$. The weights assigned to each indicator are presented in Table 4.

The evaluation set was defined as V={excellent, good, medium, worse, very poor}, and the corresponding evaluation grade vector was K={90, 70, 50, 30, 10}. The scoring table is presented in Table 5.

### 6.2 Establishment of membership degree

**6.2.1** Calculation method of membership degree. The membership degree was determined using the fuzzy statistics method, and a Membership Degree Survey Form for Factor Level Indicators was developed. Experts were asked to "vote" each indicator (e.g., $C_1$) by assigning it to an evaluation grade ranging from excellent to very poor, thereby indicating the grade to which the indicator most closely corresponds. A total of 15 valid questionnaires were collected, yielding a 100% response rate. The "frequency" of expert votes for each indicator at each grade was recorded. The membership degree for a given indicator at a specific grade was calculated as the ratio of the frequency of votes at that grade to the total number of experts. For example, concerning the impact on landscape field of vision of heritage sites ($C_1$), among 15 experts, 10 rated it as "excellent", 3 as "good", and 2 as "medium". Consequently, the membership degree vector for $C_1$ was (10/15≈0.66, 3/15=0.20, 2/15≈0.14, 0/15=0.00, 0/15=0.00), which aligns precisely with the membership degree of $C_1$ reported in the original text (Table 5).

**6.2.2** Outlier handling. To mitigate the impact of extreme scores on the results, the "3σ principle" was employed to identify and eliminate outliers. Specifically, if an expert's score for a particular indicator deviated from the group mean by more than three standard deviations, it was considered an outlier and subsequently replaced with the mean score derived from the remaining 14 questionnaires. For example, in the case of the geotechnical geological investigation plan before construction ($C_{11}$), one expert assigned a rating of "very poor" (frequency 1), which significantly deviated from the group mean, predominantly categorized as "good". After elimination and recalculation, the final membership degrees were determined to be (0.46, 0.40, 0.02, 0.08, 0.04), thereby ensuring the reliability of the data.

### 6.3 Establishment of membership degree matrix

The membership degree matrix serves as the

**Table 1 Reliability statistics**

| Item | Cronbach's α coefficient | Number of items | Explanation |
|---|---|---|---|
| Overall reliability of the indicator system | 0.895 | 33 | Good reliability |
| Reliability of primary indicators | 0.872 | 5 | High consistency |
| Reliability of secondary indicators | 0.883 | 12 | Good stability |
| Internal consistency in expert scoring | 0.901 | 18 | Consensus of expert views |

*Note*: The reliability analysis was conducted using SPSS 19.0. A Cronbach's α coefficient exceeding 0.8 signifies good reliability of the questionnaire. The findings indicate that the indicator system developed in this study demonstrates high internal consistency and stability.

**Table 2 Scale of relative importance**

| Scale value | Explanation of meaning | Interpretation |
|---|---|---|
| 1 | Equally important of both factors | Two factors have the same influence on the upper-level target |
| 3 | Slightly important | One factor is slightly more important than the other |
| 5 | Obviously important | One factor is obviously more important than the other |
| 7 | Strongly important | One factor is strongly important than the other |
| 9 | Extremely important | The extreme importance of one factor far exceeds that of the other |
| 2, 4, 6, 8 | Median value | Transition value between adjacent judgments |

fundamental carrier linking "lower-level indicators" to their corresponding "upper-level indicators". Essentially, it consolidates the membership degrees of all lower-level indicators associated with a particular upper-level indicator into a matrix format, thereby establishing a foundation for subsequent weighted calculations. The construction of this matrix adheres to the principles of "hierarchical correspondence and dimensional consistency". The following sections detail the specific procedures and illustrative examples.

**6.3.1** Hierarchical correspondence rules of membership degree matrix. In the relationship from the factor level (C) to the element level (B), if a specific element-level indicator (e.g., impact on natural landscape $B_1$) encompassed *n* factor-level indicators ($C_1$, $C_2$, $C_3$, $n$=3), and each factor-level indicator corresponded to 5 evaluation grades, then the membership degree matrix $R_B$ consisted of *n* rows and 5 columns (rows=factor-level indicators, columns=evaluation grades). In the relationship from the element layer (B) to the criterion layer (A), if a criterion layer indicator (e.g., impact on natural landscape and aesthetic value $A_1$) comprised *m* element layer indicators ($B_1$, $B_2$, $m$=2), and each element layer indicator corresponded to 5 evaluation grades, then the membership degree matrix $R_A$ had dimensions of m rows by 5 columns. Similarly, in the relationship from the criterion layer (A) to the target layer (M), if there were 5 criterion layer indicators ($A_1$–$A_5$) under the target layer, the

**Table 3 Standard value of average random consistency index (*RI*)**

| Order of judgment matrix | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0.58 | 0.90 | 1.12 |
| Order of judgment matrix | 6 | 7 | 8 | 9 | 10 |
| 0 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

**Table 4 Weight values of each indicator**

| Target layer | Primary indicator | Weight | Secondary indicator | Weight | Tertiary Indicator | Weight |
|---|---|---|---|---|---|---|
| Impact of the Guiyang-Nanning High-Speed Railway on the Libo World Heritage Site M | Impact on natural landscape and aesthetic value $A_1$ | 0.25 | Impact on natural landscape $B_1$ | 0.62 | Impact on landscape field of vision of heritage sites $C_1$ | 0.55 |
| | | | | | Adverse impact of bridge construction period on buffer zone $C_2$ | 0.23 |
| | | | | | Impact on rural landscape $C_3$ | 0.22 |
| | | | Impact mitigation measure $B_2$ | 0.38 | Mitigation measure for bridges and surrounding environment $C_4$ | 0.43 |
| | | | | | Maintenance of rural landscape $C_5$ | 0.23 |
| | Impact on geological landform and Earth historical value $A_2$ | 0.30 | Impact on geomorphic value $B_3$ | 0.55 | Impact on karst landform of heritage sites $C_6$ | 0.65 |
| | | | | | Impact on groundwater hydraulic connection and karst action process between two areas of heritage sites $C_7$ | 0.20 |
| | | | | | Impact on buffering effect of buffer zones $C_8$ | 0.20 |
| | | | Impact mitigation measure $B_4$ | 0.45 | Water system investigation before construction $C_9$ | 0.15 |
| | | | | | Geological plan and construction plan before construction $C_{10}$ | 0.23 |
| | | | | | Geotechnical geological investigation plan before construction $C_{11}$ | 0.33 |
| | | | | | All construction plans and detailed construction monitoring situations $C_{12}$ | 0.19 |
| | Assessment of impact on biodiversity value $A_3$ | 0.13 | Plant diversity $B_5$ | 0.55 | Impact of engineering on plant diversity $C_{13}$ | 0.33 |
| | | | | | Impact of engineering on ecosystem $C_{14}$ | 0.19 |
| | | | Animal diversity $B_6$ | 0.45 | Impact on the value of animal diversity $C_{15}$ | 0.60 |
| | | | | | Impact on rare and endangered animals in the heritage list $C_{16}$ | 0.40 |
| | | | Impact mitigation measure $B_7$ | 0.15 | Impact on the control of the construction scope during the construction period $C_{17}$ | 0.60 |
| | | | | | Ecological detection of animals and plants during construction $C_{18}$ | 0.40 |
| | Integrity and protection management $A_4$ | 0.21 | Effectiveness of the management system $B_8$ | 0.43 | Impact of public participation in consultation $C_{19}$ | 0.65 |
| | | | | | Coordination between management planning and high-speed railway construction $C_{20}$ | 0.35 |
| | | | | | Implementation of management measures during the construction process $C_{21}$ | 0.10 |
| | | | | | Multi-party coordination and decision-making mechanism $C_{22}$ | 0.23 |
| | | | Monitoring and emergency response capabilities $B_9$ | 0.45 | Coverage of dynamic monitoring system $C_{23}$ | 0.33 |
| | | | | | Management ability to deal with potential risks $C_{24}$ | 0.34 |
| | | | | | Repair mechanism during the construction and operation period $C_{25}$ | 0.27 |
| | | | Community participation and environmental education $B_{10}$ | 0.12 | Community participation $C_{26}$ | 0.34 |
| | | | | | Public education and promotion of heritage awareness $C_{27}$ | 0.39 |
| | Impact on ecological environment $A_5$ | 0.11 | Protection status of the ecological environment $B_{11}$ | 0.41 | Impact on key species and their habitats $C_{28}$ | 0.60 |
| | | | | | Vegetation coverage and changes in community structure $C_{29}$ | 0.40 |
| | | | | | Risk of invasive alien species $C_{30}$ | 0.33 |
| | | | | | Water resource regulation $C_{31}$ | 0.30 |
| | | | | | Climate regulation $C_{32}$ | 0.15 |
| | | | Ecological pressure of the construction and operation of high-speed railways $B_{12}$ | 0.59 | High-speed railway noise and light pollution $C_{33}$ | 0.12 |
| | | | | | Pollution of the environment by operational waste $C_{34}$ | 0.10 |
| | | | | | Ecological barrier effect $C_{35}$ | 0.10 |
| | | | | | Ecological effect of tourism pressure $C_{36}$ | 0.23 |
| | | | | | Ecological impact brought about by regional development $C_{37}$ | 0.15 |
| | | | | | Ecological effect of tourism pressure $C_{38}$ | 0.29 |
| | | | | | Ecological impact brought about by regional development $C_{39}$ | 0.23 |

membership degree matrix $R_M$ was of size 5 rows by 5 columns.

**6.3.2** Typical example of constructing a membership degree matrix. Using the relationship between the element layer $B_1$ (impact on natural landscape) and the criterion layer $A_1$ (impact

**Table 5 Fuzzy evaluation of the factor layer**

| Indicator | Membership degree | | | | |
|---|---|---|---|---|---|
| | Excellent | Good | Medium | Worse | Very poor |
| Impact on landscape field of vision of heritage sites $C_1$ | 0.66 | 0.20 | 0.14 | 0.00 | 0.00 |
| Adverse impact of bridge construction period on buffer zone $C_2$ | 0.74 | 0.12 | 0.12 | 0.02 | 0.00 |
| Impact on rural landscape $C_3$ | 0.40 | 0.46 | 0.08 | 0.06 | 0.00 |
| Mitigation measure for bridges and surrounding environment $C_4$ | 0.62 | 0.26 | 0.10 | 0.02 | 0.00 |
| Maintenance of rural landscape $C_5$ | 0.74 | 0.26 | 0.00 | 0.00 | 0.00 |
| Impact on karst landform of heritage sites $C_6$ | 0.60 | 0.30 | 0.04 | 0.06 | 0.00 |
| Impact on groundwater hydraulic connection and karst action process between two areas of heritage sites $C_7$ | 0.64 | 0.30 | 0.04 | 0.02 | 0.00 |
| Impact on buffering effect of buffer zones $C_8$ | 0.74 | 0.20 | 0.04 | 0.02 | 0.00 |
| Water system investigation before construction $C_9$ | 0.48 | 0.40 | 0.08 | 0.04 | 0.00 |
| Geological plan and construction plan before construction $C_{10}$ | 0.76 | 0.24 | 0.00 | 0.00 | 0.00 |
| Geotechnical geological investigation plan before construction $C_{11}$ | 0.46 | 0.40 | 0.02 | 0.08 | 0.04 |
| All construction plans and detailed construction monitoring situations $C_{12}$ | 0.60 | 0.40 | 0.00 | 0.00 | 0.00 |
| Impact of engineering on plant diversity $C_{13}$ | 0.50 | 0.34 | 0.06 | 0.04 | 0.06 |
| Impact of engineering on ecosystem $C_{14}$ | 0.68 | 0.20 | 0.08 | 0.04 | 0.00 |
| Impact on the value of animal diversity $C_{15}$ | 0.62 | 0.20 | 0.04 | 0.10 | 0.04 |
| Impact on rare and endangered animals in the heritage list $C_{16}$ | 0.56 | 0.20 | 0.24 | 0.00 | 0.00 |
| Impact on the control of the construction scope during the construction period $C_{17}$ | 0.68 | 0.32 | 0.00 | 0.00 | 0.00 |
| Ecological detection of animals and plants during construction $C_{18}$ | 0.76 | 0.24 | 0.00 | 0.00 | 0.00 |
| Impact of public participation in consultation $C_{19}$ | 0.88 | 0.12 | 0.00 | 0.00 | 0.00 |
| Coordination between management planning and high-speed railway construction $C_{20}$ | 0.40 | 0.10 | 0.28 | 0.20 | 0.02 |
| Implementation of management measures during the construction process $C_{21}$ | 0.66 | 0.24 | 0.06 | 0.04 | 0.00 |
| Multi-party coordination and decision-making mechanism $C_{22}$ | 0.60 | 0.30 | 0.06 | 0.04 | 0.00 |
| Coverage of dynamic monitoring system $C_{23}$ | 0.66 | 0.20 | 0.14 | 0.00 | 0.00 |
| Management ability to deal with potential risks $C_{24}$ | 0.80 | 0.10 | 0.10 | 0.00 | 0.00 |
| Repair mechanism during the construction and operation period $C_{25}$ | 0.62 | 0.34 | 0.04 | 0.00 | 0.00 |
| Community participation $C_{26}$ | 0.74 | 0.10 | 0.16 | 0.00 | 0.00 |
| Public education and promotion of heritage awareness $C_{27}$ | 0.80 | 0.10 | 0.10 | 0.00 | 0.00 |
| Impact on key species and their habitats $C_{28}$ | 0.84 | 0.16 | 0.00 | 0.00 | 0.00 |
| Vegetation coverage and changes in community structure $C_{29}$ | 0.86 | 0.10 | 0.04 | 0.00 | 0.00 |
| Risk of invasive alien species $C_{30}$ | 0.94 | 0.06 | 0.00 | 0.00 | 0.00 |
| Water resource regulation $C_{31}$ | 0.90 | 0.10 | 0.00 | 0.00 | 0.00 |
| Climate regulation $C_{32}$ | 0.96 | 0.04 | 0.00 | 0.00 | 0.00 |
| High-speed railway noise and light pollution $C_{33}$ | 0.98 | 0.00 | 0.02 | 0.00 | 0.00 |
| Pollution of the environment by operational waste $C_{34}$ | 0.04 | 0.20 | 0.40 | 0.16 | 0.20 |
| Ecological barrier effect $C_{35}$ | 0.86 | 0.04 | 0.06 | 0.04 | 0.00 |
| Ecological effect of tourism pressure $C_{36}$ | 0.80 | 0.10 | 0.04 | 0.04 | 0.02 |
| Ecological impact brought about by regional development $C_{37}$ | 0.88 | 0.12 | 0.00 | 0.00 | 0.00 |
| Ecological effect of tourism pressure $C_{38}$ | 0.96 | 0.04 | 0.00 | 0.00 | 0.00 |
| Ecological impact brought about by regional development $C_{39}$ | 0.66 | 0.20 | 0.14 | 0.00 | 0.00 |

**Table 6 Fuzzy evaluation of the element layer**

| Indicator | Membership degree | | | | |
|---|---|---|---|---|---|
| | Excellent | Good | Medium | Worse | Very poor |
| Impact on natural landscape $B_1$ | 0.62 | 0.24 | 0.12 | 0.02 | 0.00 |
| Impact mitigation measure $B_2$ | 0.64 | 0.27 | 0.06 | 0.03 | 0.00 |
| Impact on geomorphic value $B_3$ | 0.64 | 0.30 | 0.05 | 0.02 | 0.00 |
| Impact mitigation measure $B_4$ | 0.58 | 0.35 | 0.02 | 0.03 | 0.02 |
| Plant diversity $B_5$ | 0.66 | 0.20 | 0.06 | 0.06 | 0.02 |
| Animal diversity $B_6$ | 0.59 | 0.23 | 0.18 | 0.00 | 0.00 |
| Impact mitigation measure $B_7$ | 0.80 | 0.20 | 0.00 | 0.00 | 0.00 |
| Effectiveness of the management system $B_8$ | 0.61 | 0.23 | 0.11 | 0.04 | 0.00 |
| Monitoring and emergency response capabilities $B_9$ | 0.72 | 0.18 | 0.10 | 0.00 | 0.00 |
| Community participation and environmental education $B_{10}$ | 0.82 | 0.12 | 0.06 | 0.00 | 0.00 |
| Protection status of the ecological environment $B_{11}$ | 0.91 | 0.07 | 0.02 | 0.00 | 0.00 |
| Ecological pressure of the construction and operation of high-speed railways $B_{12}$ | 0.80 | 0.08 | 0.06 | 0.03 | 0.02 |

**Table 7 Fuzzy evaluation of the criterion layer**

| Indicator | Membership degree | | | | |
|---|---|---|---|---|---|
| | Excellent | Good | Medium | Worse | Very poor |
| Impact on natural landscape and aesthetic value $A_1$ | 0.63 | 0.25 | 0.10 | 0.02 | 0.00 |
| Impact on geological landform and Earth historical value $A_2$ | 0.61 | 0.32 | 0.04 | 0.02 | 0.01 |
| Impact assessment of biodiversity value $A_3$ | 0.66 | 0.21 | 0.09 | 0.03 | 0.01 |
| Integrity and protection management $A_4$ | 0.68 | 0.19 | 0.10 | 0.02 | 0.00 |
| Impact on ecological environment $A_5$ | 0.85 | 0.08 | 0.04 | 0.02 | 0.01 |
| Impact of the Guiyang-Nanning High–Speed Railway on the Libo World Heritage Site M | 0.66 | 0.23 | 0.07 | 0.02 | 0.01 |

on natural landscape and aesthetic value) as an example, and incorporating the membership degree data from the factor layer presented in Table 5, the matrix $R_{B1}$ was constructed as follows:

$$R_{B1}=\begin{bmatrix} C_1: 0.66 & 0.20 & 0.14 & 0.00 & 0.00 \\ C_2: 0.74 & 0.12 & 0.12 & 0.02 & 0.00 \\ C_3: 0.40 & 0.46 & 0.08 & 0.06 & 0.00 \end{bmatrix}$$

Each row represents the membership degree vector of a factor level indicator, while each column corresponds, respectively, to the categories "excellent, good, medium, worse, and very poor". Taking the criterion layer $A_1$ (with lower-level elements $B_1$ and $B_2$) as an example, and in conjunction with the membership degree data of the element layer presented in Table 6, the matrix $R_{A1}$ was constructed as follows:

$$R_{A1}=\begin{bmatrix} B_1: 0.62 & 0.24 & 0.12 & 0.02 & 0.00 \\ B_1: 0.64 & 0.27 & 0.06 & 0.03 & 0.00 \end{bmatrix}$$

## 6.4 Fuzzy comprehensive evaluation

The weighted average method was employed for hierarchical operations. The fundamental formula is expressed as $B=W*R$, where $W$ denotes the weight vector of the lower-level indicators; $R$ represents the membership degree matrix of these lower-level indicators; * signifies fuzzy matrix multiplication, specifically the weighted sum of the weights and membership degrees; and $B$ corresponds to the membership degree vector of the upper-level indicators. This procedure advanced sequentially through the factor layer, element layer, criterion layer, and finally the target layer, thereby facilitating a comprehensive evaluation at the target layer.

Excellent: 0.55×0.20+0.23×0.12+0.22×0.46=0.11+0.027 6+0.101 2=0.238 8≈0.24

Medium: 0.55×0.14+0.23×0.12+0.22×0.08=0.077+0.027 6+0.017 6=0.122 2≈0.12

Worse: 0.55×0.00+0.23×0.02+0.22×0.06=0+0.004 6+0.013 2=0.017 8≈0.02

Very poor: 0.55×0.00+0.23×0.00+0.22×0.00=0

Ultimately, the vector $B_1$=[0.62, 0.24, 0.12, 0.02, 0.00] was obtained, which is completely consistent with the membership degree of $B_1$ in Table 6. Similarly, the membership degree vectors for all element layer indicators ($B_1$–$B_{12}$) were computed to generate the evaluation result set for the element layer.

**6.4.1** Second-level evaluation: element level to criterion level. Using criterion layer $A_1$ (impact on natural landscape and aesthetic value) as an example, the weight vectors for $B_1$ and $B_2$, as presented in Table 4, were given by $W_{A1}$=[0.62, 0.38]. Additionally, the membership vectors of the element layers $B_1$ and $B_2$, as shown in Table 5, formed $R_{A1}$. The membership degree vector for $A_1$ was then computed as follows:

Excellent: 0.62×0.62+0.38×0.64=0.384 4+0.243 2=0.627 6≈0.63

Good: 0.62×0.24+0.38×0.27=0.148 8+0.102 6=0.251 4≈0.25

Medium: 0.62×0.12+0.38×0.06=0.074 4+0.022 8=0.097 2≈0.10

Worse: 0.62×0.02+0.38×0.03=0.012 4+0.011 4=0.023 8≈0.02

Very poor: 0.62×0.00+0.38×0.00=0

Ultimately, the vector $A_1$=[0.63, 0.25, 0.10, 0.02, 0.00] was obtained, which aligns with the membership degrees of $A_1$ presented in Table 7. Using this method, the membership degree vectors of the criterion layer $A_2$–$A_5$ were similarly calculated to construct the evaluation result set for the criterion layer.

**6.4.2** Third-level evaluation: criterion layer to target layer. The weight vector of the target layer M (impact of the Guiyang–Nanning High–Speed Railway on the Libo Heritage Site) was $W_M$=[0.25, 0.30, 0.13, 0.21, 0.11]. The membership degree vectors of the criterion layer $A_1$–$A_5$ (as shown in Table 7) formed the matrix $R_M$. The membership vector of the target layer M was then calculated as follows:

Excellent: 0.25×0.63+0.30×0.61+0.13×0.66+0.21×0.68+0.11×0.85=0.157 5+0.183+0.085 8+0.142 8+0.093 5=0.662 6≈0.66

Good: 0.25×0.25+0.30×0.32+0.13×0.21+0.21×0.19+0.11×0.08=0.062 5+0.096+0.027 3+0.039 9+0.008 8=0.234 5≈0.23

Medium: 0.25×0.10+0.30×0.04+0.13×0.09+0.21×0.10+0.11×0.04=0.025+0.012+0.011 7+0.021+0.004 4=0.074 1≈0.07

Worse: 0.25×0.02+0.30×0.02+0.13×0.03+0.21×0.02+0.11×0.02=0.005+0.006+0.003 9+0.004 2+0.002 2=0.021 3≈0.02

Very poor: 0.25×0.00+0.30×0.01+0.13×0.01+0.21×0.00+0.11×0.01=0+0.003+0.001 3+0+0.001 1=0.005 4≈0.01

**6.4.3** Evaluation grade determination and result analysis. According to the principle of maximum membership degree, within the membership degrees of M, the proportion of "excellent" (0.66) was the highest, leading to its initial classification as "excellent".

The overall score of the grade vector, determined by the dot product of the membership degree vector and the grade vector, was 79.7 points. This score fell between the categories of "good" (70 points) and "excellent" (90 points), thereby further supporting the conclusion that the level of interference is acceptable.

# 7 Conclusions

Focusing on the section of the Guiyang-Nanning High-Speed Railway that traverses the buffer zone of the Libo World Natural Heritage Site, this study developed a four-tier evaluation framework, comprising the target layer, criterion layer, element layer, and factor layer. The integration of the AHP with FCE facilitated a quantitative assessment of the visual landscape interference resulting from linear engineering projects. The research findings indicate that the construction of the Guiyang-Nanning High-Speed Railway demonstrates effective overall coordination with the landscape environment of the buffer zone surrounding the Libo Heritage Site, with the level of visual interference remaining within an acceptable range. According to the comprehensive evaluation of the target layer, the proportion of "excellent" in the membership degree vector was 0.66, and the overall score was 79.7 points. Consequently, the construction has not caused significant damage to the authenticity or aesthetic integrity of the heritage site's outstanding universal value (OUV). In certain local areas, the continuity of the landscape experienced a slight decline due to the exposure of bridge structures and temporary vegetation disturbances during the construction period. However, the implementation of measures such as vegetation restoration and color coordination effectively mitigated these impacts, thereby controlling the interference effects. The evaluation index system developed by the research institute, encompassing five primary dimensions (natural landscape and aesthetic vakue, geological landforms, biodiversity, etc.) with 38 specific indicators, not only satisfies the visual protection requirements outlined in the *Operational Guidelines for the Implementation of the World Heritage Convention* but also effectively aligns with the landscape characteristics of ecologically sensitive karst areas. Consequently, it offers targeted index support for assessing the impact of linear engineering projects within the buffer zone of the heritage sites.

This study presents an innovative integration of the AHP and FCE methods, effectively addressing the limitations associated with the "predominance of subjective experience" and the "lack of sufficient quantification" in traditional landscape impact assessments. Specifically, AHP facilitates the scientific allocation of index weights by incorporating input from multidisciplinary experts, thereby resolving the challenge of ranking the relative importance of various inpact factors. Concurrently, FCE manages the fuzziness and uncertainty inherent in "visual landscape interference" through membership degree analysis, enabling the conversion of qualitative descriptions into quantitative data. The evaluation model, developed through the integration of two approaches, can accurately assess the degree and extent of engineering interference while also offering clear guidance for the formulation of mitigation measures. This research outcome not only provides a scientific foundation for landscape maintenance during the follow-up operational phase of the Guiyang–Nanning High–Speed Railway but also establishes an operational technical framework and methodological reference for visual landscape impact assessments of other linear infrastructure projects, such as high-speed railways and expressways, within the buffer zones of World Heritage Sites. Consequently, it holds significant practical value in balancing heritage site preservation with the sustainable development of regional infrastructure.

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