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Research Article

Fuzzy Assessment of Steel Deck Pavement for Long Suspension Bridge of the Fourth Nanjing Yangtze River Bridge

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The Fourth Nanjing Yangtze River Bridge (the Fourth Bridge) with the main span of 1418 m is the largest three-span suspension bridge in China and the third largest in the world. The service circumstance of steel deck pavement on the Fourth Bridge is complex and severe, so that the scheme evaluation for steel deck pavement is a huge program. To rapidly and comprehensively evaluate the schemes for pavement, a fuzzy evaluation method was introduced in this paper. A three-level logical assessment structure including 21 basic impact factors was built according to analytic hierarchy process (AHP), and the weight for each judgment matrix was determined by the Delphi method. Consequently, a fuzzy evaluation theory was used to value each scheme to propose the optimal one. Based on this method, four pavement schemes were evaluated to choose the optimal one, and the performance of the optimal scheme was highly corresponding to the practical engineering practice. The fuzzy evaluation method can supply a theoretical support to fast determine the scheme for long-span steel deck pavement.

1. Introduction

Steel deck pavement is a single- or multilayer composite which paved on the steel bridge decks for protection and satisfaction of the requirement of traffic. With the growing numbers of super engineering projects in decades [1–6], steel deck pavement became more and more important in bridge construction and drew much more attentions in research [7–15]. With the continuous developing and improving, several pavement techniques, such as gussasphalt method [16–19], mastic asphalt method [20–22], epoxy asphalt (EA) method [23–25], and stone mastic asphalt (SMA) method [26–29], performed good properties and were popularized in field application. In China, the improved techniques, for instance, epoxy-resin-stone multilayer pavement and double-layer SMA pavement [30–32], were also well developed to satisfy the local requirement and exhibit good performance. However, cracks and pits are still the main diseases that threaten the service life of asphalt pavement. Although some works were carried out to investigate the propagation or healing properties of cracks [33]. For instance, Li [34] studied the healing properties of asphalt binders at different damage levels by comparative analysing of crack length (CL), pseudoshear stiffness (S), and dissipated pseudostrain energy (DPSE). The results show that the CL-based healing index was a fundamental and accurate parameter to evaluate the healing rate and healing potential of the bitumen. The life prediction for pavement is also important during the bridge construction.

The durability of steel bridge deck pavement was significantly influenced by its material intrinsic properties, cast and curing regime, and geographical, climatic, and traffic conditions so that the pavement performance of each individual bridge was far different. Plenty of research studies were carried out to well evaluate the failure model of steel deck pavement [17, 29, 30, 35–41]. Luo et al. [42]

investigated the fatigue life of epoxy asphalt concrete (EAC) through four criteria, the yield point, the half modulus ratio (SR) point, the peak phase angle point, and the sample failure. The results proved that the fatigue life of EAC was higher than conventional asphalt concrete by one or two orders in magnitude, and EAC pavement was suggested for steel box girder bridges. However, the influence factors for steel deck pavement were various and intricate. Most works focused on only one or two aspects, and the investigation that considered all influence factors and implied an integrated evaluation was rarely reported. Analytic hierarchy process (AHP) is a method for multiobject decision. By the AHP method, the ultimate object is divided into small component elements; then, a hierarchical structure is built for elements based on logical relationship, and the relative importance between elements is determined after comparison. Although the AHP method is developed many years [43, 44], its application on steel deck pavement is still limited.

The Fourth Yangtze River Bridge (the Fourth Bridge) is an important component in the national highway network. The bridge is a three-span suspension bridge, with the length of 5.448 km across the river and the main span of 1.418 km, which is the largest in China and the third largest in the world. The bridge was designed for six-lane highway in two directions, allowed the maximum speed of 100 km/h. Moreover, the environment and the traffic load were also severe. The Fourth Bridge is located at Nanjing, the daily temperature can reach 43°C in maximum and -14°C in minimum, and the temperature inside the pavement layer can even achieve 70°C during summer. Still, the overload ratio of the traffic may exceed 25%. The stability and the durability of the pavement under the heavy temperature and load condition are significantly important.

In this paper, a fast and comprehensive assessment method was established to determine the steel deck pavement scheme for the Fourth Bridge. The influence factors for pavement stability and durability were analysed by the AHP method to build a progressive hierarchical structure, and then the comparison between each two criteria was conducted using the Delphi method. After that, four pavement schemes were compared with a score circulated by fuzzy theory to assess an optimal one. This method supplied a fast resolution for the scheme evaluation of steel deck pavement.

2. Methodology

2.1. Establishing the Hierarchical Structure. Referred to the research papers and practices about steel deck pavement and considered the pavement properties and the functional relationship among factors, a three-level structure was built according to the AHP method [45], as shown in Figure 1. The object layer was the purpose of pavement and used for scheme assessment. The rule level contained the judgment rules for applications, including pavement performance, construction stability, maintenance, and economic benefit. The criterion level was built for detailed properties of pavement and contained 21 factors.

2.2. Establishing the Judge Matrix. According to the AHP method, a pair-wise comparison between each two elements was used instead of a comprehensive comparison. The relative importance of element i to element j was denoted as a_{ij}. Then, a judgment matrix U was built as

$$U = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & \dots & a_{ij} & \dots \\ \dots & a_{ji} = \dfrac{1}{a_{ij}} & \dots & \dots \\ a_{n1} & \dots & \dots & 1 \end{bmatrix}. \quad (1)$$

The value of a_{ij} in U was quantified from 1 to 9 according to the relative importance by the Delphi method [46, 47], as shown in Table 1 [45]. After that, based on the judgment matrix, the weight distribution vector W was calculated with the following equation:

$$\begin{aligned} M_i &= \prod_{j=1}^{n} a_{ij}, \quad i = 1, 2, \dots, n, \\ \overline{W_i} &= \sqrt[n]{M_i}, \\ w_i &= \frac{\overline{W_1}}{\sum_{i=1}^{n} \overline{W_i}}, \\ W &= \left[w_1, w_2, \dots, w_n\right], \end{aligned} \quad (2)$$

where M_i is the product for elements in row i, $\overline{W_i}$ is the n times roots of M_i, and w_i is the normalization for $\overline{W_i}$.

2.3. The Consistency Check for Judgment Matrix. Since the value of elements in the judgment matrix was determined by the Delphi method, which was subjectively, the consistency check for weight distribution vector W was necessary. The check process was proceeded by the following:

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{(n-1)}, \quad (3)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \quad (4)$$

where CI is the consistency index, n is the dimension of the matrix, RI is the random consistency index, and CR is the consistency ratio. $\lambda_{\max}$ is the maximum characteristic root for matrix U and can be calculated from

$$U \cdot W = \lambda_{\max} \cdot W. \quad (5)$$

RI is the average CI from 500 randomly filled matrixes, and the calculated results by Saaty are listed in Table 2 [48]. If CR is less than 10%, the matrix can be considered as having an acceptable consistency [48].

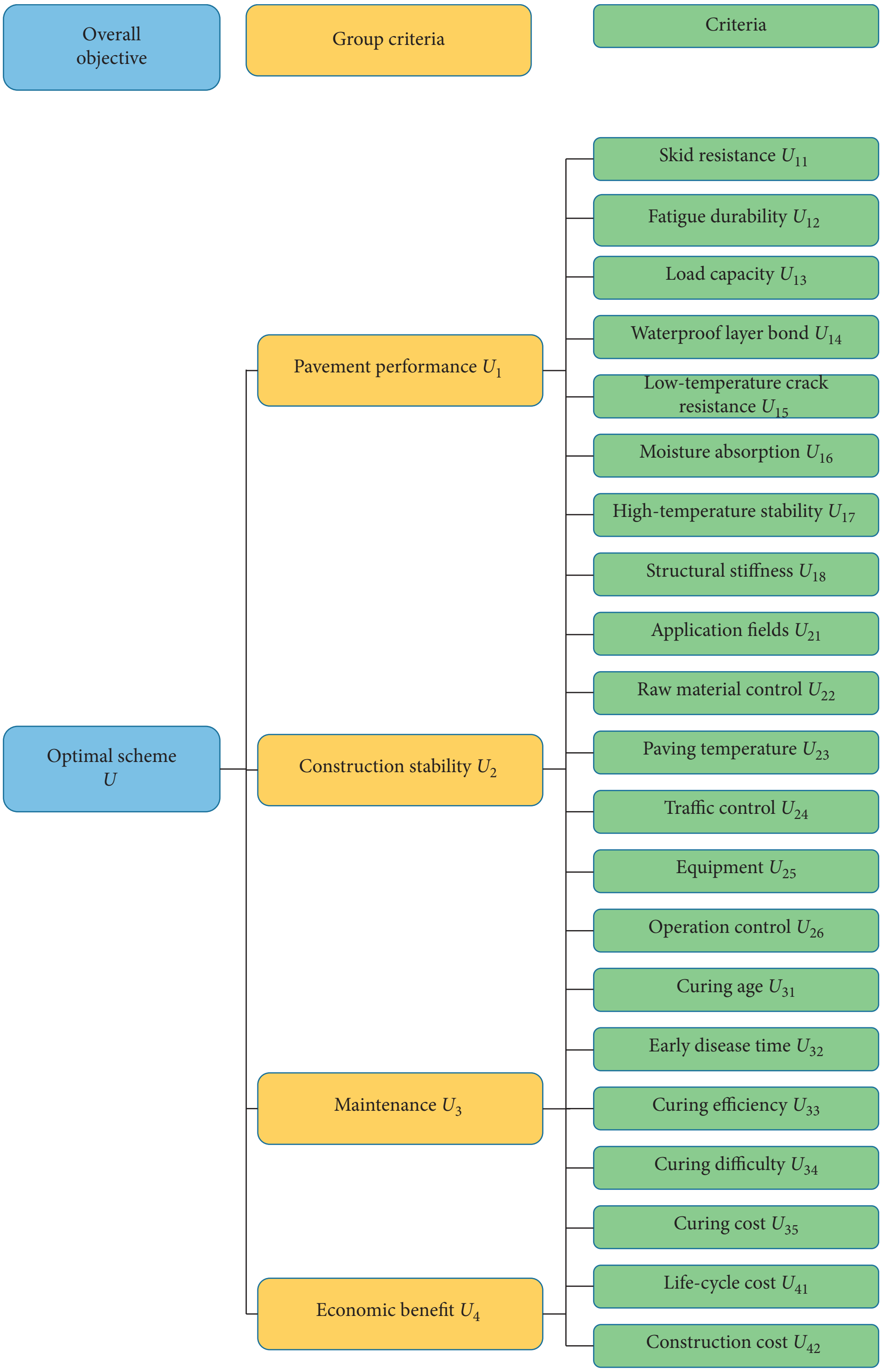

Figure 1: The hierarchical structure for pavement by the AHP method.

Table 1: The value of a_{ij} by 1–9 scale.

Value	Definition
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrate importance
8	Very, very strong
9	Extreme importance

Table 2: Random consistency index of 1–12 dominations by Saaty.

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

2.4. The Fuzzy Assessment. Since the available judgment matrix and the weight vector for criteria were determined, a fuzzy evaluation method was used to evaluate the overall purpose of scheme. At first, each element was judged with a fuzzy judgment set A = (excellent good moderate weak) with four levers. Then, considering the current standard and the reviewers' comments, a fuzzy evaluation matrix R was built as equation (6). At last, the fuzzy comprehensive evaluation matrix V for judgment matrix U was calculated by equation (7), and the scheme with the highest V value was supposed to be the optimal one:

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \cdots \\ R_n \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}, \tag{6}$$

$$V = R \cdot W, \tag{7}$$

where n is the number of criteria, m is the dimension of fuzzy judgment set A, r_{nm} is the ratio that element n in level m and $r_{nm} \in (0, 1)$, and W is the weight vector for judgment matrix U.

3. Results and Discussion

3.1. Judgment Matrix. The overall judgment matrix U was built as $U = [U_1\ U_2\ U_3\ U_4]$ according to Figure 1. U_1 to U_4 are junior judgment matrixes, which corresponded to pavement performance, construction stability, maintenance, and economic benefit, respectively.

According to AHP structure in Figure 1, matrix U_1 contained 8 factors, which were skid resistance, fatigue durability, load capacity, waterproof layer bond, low-temperature crack resistance, moisture absorption, high-temperature stability, and structural stiffness, denoted as U_{11} to U_{18}. Matrix U_2 had 6 factors, including working condition, raw material control, paving temperature, traffic control, equipment, and operation control, signed as U_{21} to U_{26}. Matrix U_3 was composed by 5 factors, that is, curing age, early disease time, curing efficiency, curing difficulty, and curing cost, which is defined as U_{31} to U_{35}. At last, matrix U_4 included 2 factors, life-cycle cost for U_{41} and construction cost for U_{42}. The relative importance for each element was briefly analysed as follows.

The service condition of the Fourth Bridge is mainly high temperature, rainy weather, and heavy traffic, and the annual average temperature meets the requirement index for low-temperature crack resistance so that the fatigue durability, waterproof layer bond, and high-temperature stability of steel deck pavement are important aspects which need more consideration, and the skid resistance and moisture absorption can be optimized by external design as well. In terms of construction stability, the quality of pavement was directly affected by material control, while the operation control, the paving temperature, and the traffic control can be adjusted according to the practical condition during construction. In maintenance issues, the early disease time directly determined the service life of pavement, and curing age and curing efficiency depend on the disease time and disease type. Also, the construction cost is much higher than life-cycle cost to ensure the long service life of the steel deck pavement.

Hence, we comprehensively consider the local condition, the relevant specification, and the reviewers' comments, and the relative importance for elements in senior judgment matrix U and junior matrixes U_1 to U_4, and the calculated weight are listed in Tables 3–7.

The weight vector for junior judgment matrix U_1 to U_4 and senior matrix U was as follows:

(i) $W_1 = [0.0596\ \ 0.2848\ \ 0.1183\ \ 0.1636\ \ 0.0806\ \ 0.0766\ \ 0.1426\ \ 0.0739]$

(ii) $W_2 = [0.0949\ 0.4200\ 0.1343\ 0.0419\ 0.1084\ 0.2005]$

(iii) $W_3 = [0.0647\ 0.5040\ 0.0885\ 0.2055\ 0.1373]$

(iv) $W_4 = [0.25\ 0.75]$

(v) $W = [0.5441\ 0.1868\ 0.1229\ 0.1462]$

3.2. The Consistency Test. After the calculation with equations (6)–(8), the value of $\lambda_{\max}$, CI, RI, and CR for each judgment matrix are present in Table 8.

From Table 8, it is seen that all CR results for each judgment matrix were less than 10%, which indicate that all the judgment matrixes here were available.

3.3. The Fuzzy Evaluation. Four schemes, including gussasphalt plus high-elastic asphalt concrete (GA + AC), double-layer epoxy asphalt (D-EA), epoxy bonding chip layer/resin asphalt/store mastic asphalt multilayer pavement (ERS), and double-layer store mastic asphalt (D-SMA), were proposed for the Fourth Nanjing Yangtze River Bridge steel

Table 3: Judgment matrix of optimum scheme evaluation of steel bridge deck pavement.

U	U_1	U_2	U_3	U_4
U_1	1	3	4	4
U_2	1/3	1	1	2
U_3	1/4	1	1	1/2
U_4	1/4	1/2	2	1
Weight	0.5441	0.1868	0.1229	0.1462

Table 4: Judgment matrix of performance for steel deck pavement.

U_1	U_{11}	U_{12}	U_{13}	U_{14}	U_{15}	U_{16}	U_{17}	U_{18}
U_{11}	1	1/5	1/3	1	1	1/3	1/3	1
U_{12}	5	1	5	1	3	3	3	3
U_{13}	3	1/5	1	1	2	3	1/2	1
U_{14}	1	1	1	1	2	3	2	2
U_{15}	1	1/3	1/2	1/2	1	1	1/2	2
U_{16}	3	1/3	1/3	1/3	1	1	1/2	1
U_{17}	3	1/3	2	1/2	2	2	1	2
U_{18}	1	1/3	1	1/2	1/2	1	1/2	1
Weight	0.0596	0.2848	0.1183	0.1636	0.0806	0.0766	0.1426	0.0739

Table 5: Judgment matrix of construction controllability.

U_2	U_{21}	U_{22}	U_{23}	U_{24}	U_{25}	U_{26}
U_{21}	1	1/5	1/2	3	1	1/2
U_{22}	5	1	5	5	3	3
U_{23}	2	1/5	1	3	2	1/2
U_{24}	1/3	1/5	1/3	1	1/4	1/5
U_{25}	1	1/3	1/2	4	1	1/2
U_{26}	2	1/3	2	5	2	1
Weight	0.0949	0.4200	0.1343	0.0419	0.1084	0.2005

Table 6: Judgment matrix of maintenance for steel deck pavement.

U_3	U_{31}	U_{32}	U_{33}	U_{34}	U_{35}
U_{31}	1	1/4	1/2	1/3	1/3
U_{32}	4	1	5	4	5
U_{33}	2	1/5	1	1/3	1/2
U_{34}	3	1/4	3	1	2
U_{35}	3	1/5	2	1/2	1
Weight	0.0647	0.5040	0.0885	0.2055	0.1373

Table 7: Judgment matrix of economic benefit of steel deck pavement.

U_4	U_{41}	U_{42}
U_{41}	1	1/3
U_{42}	3	1
Weight	0.25	0.75

Table 8: The consistency test results of each judgment matrix.

Index	U	U_1	U_2	U_3	U_4
$\lambda_{\max}$	4.1866	8.6762	6.2809	5.2608	2.0000
CI	0.0622	0.0966	0.0562	0.0652	0
RI	0.89	1.41	1.26	1.12	0
CR	0.0699	0.0685	0.0446	0.0582	0

Table 9: The final score for different schemes.

Scheme	GA + AC	D-EA	ERS	D-SMA
Score	76.31	73.85	68.23	66.14

deck pavement. For each scheme, four junior judgment matrixes (U_1 to U_4) were evaluated by 6 judgers using fuzzy judgment set A, and then a fuzzy evaluation was output. The fuzzy evaluation matrixes R_1 to R_4 for each scheme are shown as follows:

$$R_{1-\mathrm{GA+AC}} = \begin{bmatrix} 0 & 0.85 & 0.15 & 0 \\ 1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \end{bmatrix}, \quad R_{1-\mathrm{D-EA}} = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.75 & 0.15 & 0.1 & 0 \\ 0.75 & 0.25 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.75 & 0.15 & 0.1 & 0 \\ 0.85 & 0.1 & 0.05 & 0 \end{bmatrix}, \tag{8}$$

$$R_{2-\mathrm{GA+AC}} = \begin{bmatrix} 0.85 & 0.15 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 0.85 & 0.15 & 0 & 0 \end{bmatrix}, \quad R_{2-\mathrm{D-EA}} = \begin{bmatrix} 0.8 & 0.15 & 0.05 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.95 & 0.05 & 0 & 0 \end{bmatrix}, \quad R_{2-\mathrm{ERS}} = \begin{bmatrix} 0.75 & 0.15 & 0.1 & 0 \\ 0.8 & 0.15 & 0.05 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \end{bmatrix},$$

$$R_{2-\mathrm{D-SMA}} = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 \\ 0.8 & 0.15 & 0.05 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 0.7 & 0.15 & 0.15 & 0 \\ 0.8 & 0.15 & 0.05 & 0 \\ 0.7 & 0.15 & 0.1 & 0.05 \end{bmatrix}, \tag{9}$$

$$R_{3-\mathrm{GA+AC}} = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.8 & 0.2 & 0 & 0 \\ 0.85 & 0.1 & 0.05 & 0 \\ 0.85 & 0.1 & 0.05 & 0 \end{bmatrix}, \quad R_{3-\mathrm{D-EA}} = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 \\ 0.7 & 0.15 & 0.15 & 0 \\ 0.85 & 0.15 & 0 & 0 \\ 0.85 & 0.1 & 0.05 & 0 \\ 0.9 & 0.1 & 0 & 0 \end{bmatrix}, \quad R_{3-\mathrm{ERS}} = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.9 & 0.1 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 \end{bmatrix}, \quad R_{3-\mathrm{D-SMA}} = \begin{bmatrix} 0.7 & 0.2 & 0.1 & 0 \\ 0.7 & 0.2 & 0.1 & 0 \\ 0.75 & 0.15 & 0.1 & 0 \\ 0.8 & 0.1 & 0.1 & 0 \\ 0.8 & 0.15 & 0.05 & 0 \end{bmatrix}, \tag{10}$$

$$R_{4-\mathrm{GA+AC}} = \begin{bmatrix} 0.8 & 0.1 & 0.05 & 0.05 \\ 0.85 & 0.1 & 0.05 & 0 \end{bmatrix}, \quad R_{4-\mathrm{D-EA}} = \begin{bmatrix} 0.8 & 0.15 & 0.05 & 0 \\ 0.9 & 0.1 & 0 & 0 \end{bmatrix}, \quad R_{4-\mathrm{ERS}} = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 \\ 0.75 & 0.2 & 0.05 & 0 \end{bmatrix}, \quad R_{4-\mathrm{D-SMA}} = \begin{bmatrix} 0.75 & 0.15 & 0.1 & 0 \\ 0.65 & 0.2 & 0.15 & 0 \end{bmatrix}. \tag{11}$$

Taking the GA + AC scheme as example, the fuzzy comprehensive evaluation matrix V_i for each junior judgment matrix was calculated by equation (7), and the results were

$$\begin{aligned}
V_1 &= W_1 \cdot R_1 = [\,0.8825 \quad 0.1086 \quad 0.0089 \quad 0\,],\\
V_2 &= W_2 \cdot R_2 = [\,0.8891 \quad 0.1110 \quad 0 \quad 0\,],\\
V_3 &= W_3 \cdot R_3 = [\,0.8236 \quad 0.1089 \quad 0.0675 \quad 0\,],\\
V_4 &= W_4 \cdot R_4 = [\,0.8375 \quad 0.1000 \quad 0.0500 \quad 0.0125\,].
\end{aligned} \tag{12}$$

Then, the fuzzy evaluation matrix R for senior judgment matrix U was exported as

$$R_{\text{GA+AC}} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} 0.8825 & 0.1086 & 0.0089 & 0 \\ 0.8891 & 0.1110 & 0 & 0 \\ 0.8236 & 0.1089 & 0.0675 & 0 \\ 0.8375 & 0.1000 & 0.0500 & 0.0125 \end{bmatrix}. \tag{13}$$

The fuzzy evaluation matrix V for matrix U was also calculated by equation (7):

$$\begin{aligned}
V_{\text{GA+AC}} &= [\,0.8666 \quad 0.1074 \quad 0.0239 \quad 0.0022\,],\\
V_{\text{D-EA}} &= [\,0.8263 \quad 0.1180 \quad 0.0557 \quad 0\,],\\
V_{\text{ERS}} &= [\,0.8030 \quad 0.1681 \quad 0.0289 \quad 0\,],\\
V_{\text{D-SMA}} &= [\,0.7943 \quad 0.1340 \quad 0.0717 \quad 0\,].
\end{aligned} \tag{14}$$

The evaluation score was the normalization for V. After calculation, the evaluation score for four schemes is shown in Table 9.

The results indicated that the scheme GA + AC with the highest score was the optimal scheme.

4. Conclusion

In this paper, in order to fast and comprehensively assess the steel deck pavement scheme for the Fourth Nanjing Yangtze River Bridge, a fuzzy evaluation method was used to well evaluate the impact criteria. Four alternative schemes were analysed by this method to find the optimal one. The results of this work were summarized as follows:

(1) To comprehensively estimate the optimal scheme of pavement on the Fourth Bridge, all aspects including 21 criteria were selected to assess the overall properties. A three-level logical hierarchical structure containing four judge roles was built according to the AHP method.

(2) The weight of each judgment matrix was determined by the Delphi method, and then the evaluation for the judgment matrix was conducted using the fuzzy evaluation method.

(3) This fuzzy comprehensive evaluation method was helpful for the scheme decision for large-span bridge steel deck pavement.

Data Availability

The Table 2 data used to support the findings of this study have been deposited in research article by Thomas L Saaty (DOI: 10.1016/0022-2496(77)90033-5). The Tables 3–8 data used to support the findings of this study are original and included within the article. The matrix R_1–R_4 data used to support the findings of this study are original and included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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