Abstract

To effectively deal with the frequent natural disasters and make good decisions, a clear and scientific understanding of the highway network’s resistant ability against disasters should be worked out. This paper aims to propose a set of comprehensive evaluation methods for this ability and its conclusion analysis. Using the Analytic Hierarchy Process, a comprehensive evaluation index system is established. Subsequently, based on the fuzzy mathematics, the fuzzy comprehensive evaluation model is established, and the specific steps of the fuzzy comprehensive evaluation are executed. Furthermore, according to the short plate theory, this paper adopts retrospective analysis to discuss the evaluation conclusion. Finally, in order to verify the feasibility and practicability, this paper takes Hangzhou national and provincial trunk highway network as a case study. The results show that the comprehensive score of this network is 83.429 which belongs to the "General" level. Through the conclusion analysis, this paper identifies the weaknesses of Hangzhou national and provincial trunk highway network against natural disasters. Limitations of the proposed method are also discussed in this paper.

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Keywords: Highway network; resistant ability against natural disasters; Analytic Hierarchy Process (AHP); fuzzy comprehensive evaluation; retrospective analysis

1. Introduction

With the rapid development of urbanization, highway network is increasingly becoming the important skeleton between and within the urban agglomerations, and it plays an important role in economic and social development of a country or region. However, the frequent natural disasters caused the highway transportation system the hardest hit which is increasingly serious in recent years. In early 2008, snow and ice storms in South China led to a large area of the highway transportation system paralyzed and did significant damage to property. Since
Wenchuan earthquake in 2008, Wenchuan section of 213 national highway known as "epicenter lifeline" has been interrupted thrice by landslide, the smooth conduct of disaster relief has been seriously affected. Frequent natural disasters challenge the construction and management of the highway transportation system, restrict the enhancing of the capacity of services, are not conducive to the rapid development and transformation of the highway transportation undertakings, and are becoming the focus of attentions of government and academia. In order to deal with the natural disasters, we must have a clear understanding of the highway network’s resistant ability, and then improve its weaknesses. On this basis, we could do better in prior warning, emergency management, and restoration work while fighting against natural disasters.

Developed countries have begun the natural disasters evaluation while continued to study the disaster mechanism since the 1970s. A Japanese natural disaster science comprehensive research committee headed by Hasegawa carried out a large number of research and practice in prediction and control for natural disasters causes and inducement factors, mechanism of disaster expanding, preventing and mitigating system for natural disasters, etc., especially in the evaluation of earthquake, flood, tsunami, mudslide, landslide and other disasters. They emphasized disaster survey, statistic, evaluation, and determination of mitigation responsibilities and rescue measures in disaster relief regulations (Lu et al., 1987). Li et al. (2006a) investigated the historical disasters of Chongqing trunk highways and analyzed the disaster characteristics including the natural climate, the engineering geology, the distribution and characters. Peng et al. (2009) analyzed Guizhou Province highway’s geological disaster distribution characteristics, development characteristics and forming condition on the basis of the on-site investigation information. Using the GIS technology, they got the all-around result, which was combined with model calculation result of the dangerous section on geological disaster and the section result of analogy analytical method. Song et al. (2005) put forward the assess method of the development degree, harmfulness, development trend and the risk of highway geological disaster based on the characteristics of highway engineering and the field investigation of geological disaster along highway. Li et al. (2006b) investigated the characters of Chongqing trunk highways, and set up an index system to rate its resistant ability against disasters with the help of Analytic Hierarchy Process (AHP), at last they made a fuzzy synthesize rating them using the Fuzzy Rating Theory. Zhao (2007) analyzed the theories and measures of risk and vulnerability evaluation, carried out the evaluation of highway disaster vulnerability with Fuzzy Comprehensive Measure based on the index system, the figure results were turned into pictures with software of GIS. In conclusion, a unified evaluation system is still lacking for the losses and risks caused by various natural disasters. There are often a set of evaluation indicators and standards individually, lacking of overall operability. Meanwhile, the evaluation for highway’s resistant ability against natural disasters is just a separate study on some disasters for a single highway, there are few systematic studies on resistant ability evaluation from the perspective of the regional highway network.

This paper aims to propose an evaluation and conclusion analysis method for the resistant ability to consider a variety of natural disasters on the highway network on the basis of relevant research results at home and abroad. This method could provide support to the strategies of improving and optimizing the highway network’s resistant ability against natural disasters. This paper is organized as follows. The basic theories and the method of comprehensive evaluation and conclusion analysis are presented in Section 2. The case study of Hangzhou national and provincial trunk highway network is presented in Section 3. The relevant issues are discussed in Section 4 followed by conclusions.

2. Methodology

2.1. Establishment of comprehensive evaluation index system

Highway network’s resistant ability against natural disasters which is systematic and comprehensive has many influencing factors. We categorize these factors from two aspects of internal cause and external cause.
The internal cause is the internal basis of the development, here it refers to the influencing factors of the highway network’s inherent natures which are ended up with the completion of the highway network and are constant unless the network is new constructed or rebuilt. These factors can be further divided into factors under normal condition and under disaster condition. Factors under normal condition are network’s structure characteristics and general natures, including Network Density, Connectivity, Convergence Nodes Density, Grade Level and Accessibility. They are the same whether the network is under normal condition or natural disaster. Factors under disaster condition, such as reliability (Du et al., 1997; Mine et al., 1982; Chen et al., 2002), vulnerability (Berdica, 2002; D’ Este et al., 2001), robustness (Sakakibara et al., 2004), etc. refer to the network’s stability characteristics. These factors belong to the special nature related to natural disasters and come out only when natural disaster occurs. We analyze the stability of the highway network using the Connective Reliability Analysis Method, because the most important issue of the research on highway network fighting against natural disasters is that the connection should be guaranteed rather than the "smooth" of traffic. According to the topology of highway network, link (unit) reliability is determined first, and then the route reliability and the reliability between nodes (network reliability) are obtained based on the Full Probability Analysis Algorithm. Link reliability is determined using disaster reduction method.

The external cause is the external reason of the development, here it mainly refers to the influencing factors management departments acted on the highway network. These factors, which play roles through internal cause of the resistant ability against natural disasters and manifest through the highway network, can be equal to the management and maintenance of the highway network, including the peacetime preparation and disaster response. In this paper we choose the following characteristics, Daily Maintenance Situation, Information Level of Management, Disaster Prior Warning Mechanisms and Contingency Plans, Capability of Emergency Rescue, and Coordination and Linkage Levels of Disaster Management.

With the help of AHP, we expound and summarize the above factors and obtain the evaluation indicators. The comprehensive evaluation index system is shown in Fig. 1 and the specific indicators are described in Table 2.

![Fig. 1. Comprehensive evaluation index system for highway network’s resistant ability against disasters](image-url)
2.2. Fuzzy comprehensive evaluation

Some evaluation indicators of the highway network’s resistant ability against disasters are determined while some are not, meanwhile, the relationship among the indicators and the boundary of ability level are not very precise. Therefore, fuzzy comprehensive evaluation method is brought up to evaluate the ability. The steps of the method include the establishment of the factor set, judgment set, and weight vector, single factor evaluation and multivariate comprehensive evaluation, etc.

Step 1 Determination of the objective being evaluated

Generally, the objective being evaluated is the overall highway network in the region, which can be the national, provincial, municipal or county overall network.

\[ X = \{ x_0 \} \]  

where \( x_0 \) is the overall highway network in the region.

Step 2 Establishment of the factor set

Based on the comprehensive evaluation index system of Fig. 1, we adopt the following factor set.

Level 1 \( U = \{ U_1, U_2, U_3 \} \)  
Level 2 \( U_i = \{ U_{i1}, U_{i2}, U_{i3}, U_{i4}, U_{i5} \} \)  
\[ U_2 = \{ U_{21}, U_{22} \} \]  
\[ U_3 = \{ U_{31}, U_{32}, U_{33}, U_{34}, U_{35} \} \]  

Step 3 Establishment of the judgment set

We choose triangular fuzzy numbers as the membership functions, and discretize the universe of discourse \([0,100]\) into 5 fuzzy linguistic terms (Weak, Relatively Weak, General, Relatively Strong, and Strong). The threshold of evaluation standard for highway network’s resistant ability against disasters is determined by triangular fuzzy numbers combined with relevant research results of the evaluation method for highway network (see Table 1 and Fig. 2).

<table>
<thead>
<tr>
<th>Score</th>
<th>Fuzzy linguistic term</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S \geq 95 )</td>
<td>Strong</td>
</tr>
<tr>
<td>( 85 \leq S &lt; 95 )</td>
<td>Relatively Strong</td>
</tr>
<tr>
<td>( 75 \leq S &lt; 85 )</td>
<td>General</td>
</tr>
<tr>
<td>( 60 \leq S &lt; 75 )</td>
<td>Relatively Weak</td>
</tr>
<tr>
<td>( S &lt; 60 )</td>
<td>Weak</td>
</tr>
</tbody>
</table>

Fig. 2. Membership functions of evaluation for highway network’s resistant ability against disasters defined in Table 1
After the threshold of evaluation standard is determined, we can obtain the score whose fuzzy membership degree is 1 according to the membership functions and define the judgment set \( V \).

\[
V = \{ v_1, v_2, v_3, v_4, v_5 \} = \{ 100, 90, 80, 70, 50 \} = \{ \text{Strong, Relatively Strong, General, Relatively Weak, Weak} \}
\] (4)

**Step 4 Establishment of the weight vector**

The methods of determining the weights can be divided into three aspects of subjective weighting method, objective weighting method, and combination weighting method. Each method has its own advantages and disadvantages. In practice, the Least Squares Method and Eigenvector Method are widely used.

\[
\text{Level 2 } A_1 = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \end{pmatrix} \\
A_2 = \begin{pmatrix} a_{21} & a_{22} \end{pmatrix} \\
A_3 = \begin{pmatrix} a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \end{pmatrix}
\]

(5)

\[
\text{Level 1 } A = \begin{pmatrix} a_1 & a_2 & a_3 \end{pmatrix}
\]

(6)

**Step 5 Fuzzy comprehensive evaluation of Level 2**

- **Single factor evaluation**

Establish a fuzzy mapping from \( U \) to \( F(V) \), \( \tilde{f} : U \rightarrow F(V) \)

\[
\forall u_i \rightarrow \tilde{f}(u_i) = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \ldots + \frac{r_i}{v_n}
\]

(7)

where \( r_{ij} \) is the membership degree of factor \( u_i \) to grading \( v_j \) \((i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)\).

Hence the single factor appraisal sets are obtained.

\[
R_i = (r_{i1}, r_{i2}, \ldots)
\]

(8)

The single factor appraisal matrix \( R \) is also obtained whose rows are the single factor appraisal sets, and the matrix is a fuzzy one. In this paper, \( R_k (k = 1, 2, 3) \) represents the single factor appraisal matrix of Network Structure, Network Stability, or Management and Maintenance Characteristics.

\[
R_k = \begin{bmatrix}
    r_{k11} & r_{k12} & \cdots & 1 \\
    r_{k21} & r_{k22} & \cdots & 1 \\
    \vdots & \vdots & \ddots & \ddots \\
    r_{km1} & r_{km2} & \cdots & 1
\end{bmatrix}
\]

(9)

The membership degrees of sub-factors to grading are obtained according to the different degrees of the resistant ability against disasters combined with the membership functions quantitatively or qualitatively.

Network Structure and Stability Characteristics indicators groups are evaluated by quantitative scoring method. Management and Maintenance Characteristics indicators group is evaluated by experts and the highway management department staff in evaluation region through qualitative and quantitative scoring method.

- **Multivariate comprehensive evaluation**

When we have determined the single factor appraisal matrixes and weight vectors, we can express the fuzzy comprehensive evaluation as follows.
where $B_k$ ($k=1, 2, 3$) is a fuzzy comprehensive appraisal set, $b_{kj}$ ($j=1, 2, \ldots, n$) is a fuzzy comprehensive appraisal indicator whose meaning is the membership degrees of the objectives being evaluated to grading $j$ of the judgment set considering all influences of factors.

**Step 6 Fuzzy comprehensive evaluation of Level 1**

After obtaining the fuzzy comprehensive evaluation result of Level 2, Network Structure, Network Stability, and Management and Maintenance Characteristics are considered as the single factors. Their respective evaluation results of Level 2 are considered as the single factor appraisal sets which constitute the single factor appraisal matrix of the fuzzy comprehensive evaluation of Level 1.

$$ R = [B_1, B_2, B_3]^T $$

(11)

The fuzzy comprehensive evaluation result of Level 1 is obtained by the single factor appraisal matrix and weight vector.

$$ B = AR $$

(12)

According to the above judgment set $V$, the membership degree $b_j$ as weights, the comprehensive score of the objective being evaluated is calculated as follows.

$$ V = \frac{\sum_{j=1}^{5} b_j v_j}{\sum_{j=1}^{5} b_j} $$

(13)

Using the above comprehensive evaluation model, the evaluation result of regional highway network’s resistant ability against disasters can be calculated. Combined with the threshold of evaluation standard, the evaluation level of the ability can be obtained.

2.3. Analysis of evaluation conclusion

By reaching the conclusion, highway network’s resistant ability against disasters has been recognized, but it is not the ultimate goal. Conclusion should be analyzed to identify the key weaknesses of the highway network against natural disasters and then to guide the improving and optimizing work. Retrospective analysis method which is also known as abduction (retroduction) analysis method is used to analyze the evaluation conclusion. This method is a logical method deducing the cause based on the phenomenon characteristic (Wang, 1986; Wang et al., 2008). Its logical structure is as follows.

E (Phenomenon E is observed)
H→E (If H is true, E will be interpreted as a matter of course)
H (Reasonable to believe that H is true)
Retrospective analysis includes two complex forms. The form deducing the causes from different dimensions for the same phenomenon called multivariate retrospective analysis, while the continuous form deducing the high level cause constantly called multi-level retrospective analysis.

**Multivariate retrospective analysis:**  
\[ E, H_1 \rightarrow E, H_2 \rightarrow E, \ldots \]

**Multi-level retrospective analysis:**  
\[ E, H_1 \rightarrow E, H_2 \rightarrow H_1, \ldots \]

The evaluation conclusion analysis for highway network’s resistant ability against disasters is to deduce the causes led to this conclusion retroactively, the causes here are the fuzzy comprehensive evaluation results of the lower level. We limit the retrospective analysis strictly within the framework of the evaluation index system, neglect causes led to the conclusion outside the index system when abduction. The benefits of this are as follows. First, it is an effective way to avoid the chronic illness of probability of the retrospective analysis. Logic model of the retrospective analysis is different from the deductive reasoning, the link between premise and conclusion is probabilistically. While the analysis is limited within the framework of the evaluation index system, the rationality can be verified quantitatively through fuzzy appraisal matrix. Second, the retrospective analysis is in fact the reverse process of the evaluation for highway network’s resistant ability against disasters, analysis backtracking along the thinking of fuzzy comprehensive evaluation is logically rigorous, reasonable, feasible, and capable of combining the two processes of evaluation and conclusion analysis together.

The analysis of evaluation conclusion is a process under the guidance of retrospective analysis, using short plate theory, and backtracking along the thinking of fuzzy comprehensive evaluation. The main process includes three steps.

**Step 1 Retrospective analysis of the final evaluation conclusion**

Final evaluation conclusion is the evaluation result of the highway network’s resistant ability against disasters, whose retrospective causes are the Network Structure, Network Stability, and Management and Maintenance Characteristics in Level 1. Explore the single factor appraisal matrix of the fuzzy comprehensive evaluation of Level 1 \( R \) to find out the line (lines) whose membership degree to low grading is large, the factor be represented by this line (lines) is the disadvantage of highway network against disasters.

**Step 2 Retrospective analysis of the evaluation result of Level 1**

The retrospective causes of the three factors of Level 1 are the factors respectively included in Level 2. Explore the single factor appraisal matrixes of the fuzzy comprehensive evaluation of Level 2 \( R_1, R_2, \) and \( R_3 \) to find out the line (lines) whose membership degree to low grading is large, the factor be represented by this line (lines) is the respective disadvantage of the Network Structure, Network Stability, and Management and Maintenance Characteristics.

**Step 3 Analysis and summarizing**

Summarize factors of Level 2 and classify them by advantages, disadvantages, and potentialities. Combined with the practice analysis, we can find the weaknesses of highway network against disasters through exploring the disadvantages and potentialities.

3. **Case Study**

In this paper, Hangzhou national and provincial trunk highway network (including 9 national highways and 22 provincial highways) is studied as a case. This highway network is shown in Fig. 3.
To determine the weight vectors, experts and researchers of this field are interviewed, at the same time, Hangzhou highway management department staff are also investigated. Furthermore, relevant research results at home and abroad are adopted to make adjustments.

\[
\begin{align*}
\text{Level 2} & \quad A_1 = (a_{11}, a_{12}, a_{13}, a_{14}, a_{15}) = (0.3, 0.2, 0.2, 0.2, 0.1) \\
A_2 & = (a_{21}, a_{22}) = (0.4, 0.6) \\
A_3 & = (a_{31}, a_{32}, a_{33}, a_{34}, a_{35}) = (0.2, 0.3, 0.2, 0.1, 0.2) \\
\text{Level 1} & \quad A = (a_1, a_2, a_3) = (0.4, 0.3, 0.3) 
\end{align*}
\]

When evaluating the factors of Level 2, quantitative evaluation and qualitative evaluation are unified. To make close contact with the actual highway network in Hangzhou, the ideas, methods and conclusions of the research reports by Hangzhou Highway Administration, Hangzhou Transportation Department, Hangzhou Transportation Planning and Design Institute (HHA, 2009; HTD & HTPDI, 2007) are fully taken into consideration.

<table>
<thead>
<tr>
<th>Evaluation indicators</th>
<th>Indicator property</th>
<th>Evaluation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Density</td>
<td>Quantitative</td>
<td>Area Density: 100 km/10^4 km^2 score 85, 75 km/10^4 km^2 score 60; Population Density: 19 km/10,000 persons score 85, 14 km/10,000 persons score 60; Economic Density: 3.0 km/100,000,000 CNY score 85, 4.0 km/100,000,000 CNY score 60. The evaluation scores are determined using the interpolation method; the comprehensive score of Network Density is calculated using the weighted average method.</td>
</tr>
</tbody>
</table>

Table 2. Evaluation method for the factors of Level 2 of Hangzhou national and provincial trunk highway network’s resistant ability against disasters
## Network Connectivity
- **Quantitative**
  - 3.0 score 85, 1.0 score 60. The evaluation scores are determined using the interpolation method.

## Convergence Nodes Density
- **Quantitative**
  - 0.18 score 85, 0.06 score 60. The evaluation scores are determined using the interpolation method.

## Network Grade Level
- **Quantitative**
  - Average Technical Grade: 3.0 score 85, 3.5 score 60;
  - Proportion of the Highways at or above Grade II: 20% score 85, 5% score 60.
  - The evaluation scores are determined using the interpolation method; the comprehensive score of Network Grade Level is calculated using the weighted average method.

## Network Accessibility
- **Quantitative**
  - 80 km score 85, 110 km score 60. The evaluation scores are determined using the interpolation method.

## Route Reliability
- **Quantitative**
  - 0.85 score 85, 0.60 score 60. The evaluation scores are determined using the interpolation method.

## Reliability between Nodes
- **Quantitative**
  - 0.90 score 85, 0.75 score 60. The evaluation scores are determined using the interpolation method.

## Daily Maintenance Situation
- **Quantitative & Qualitative**
  - Score according to the maintenance quality index (MQI) of freeway, rate of good level ordinary highways, maintenance frequency, guarantee of maintenance funding, maintenance equipment, etc.

## Information Level of Management
- **Quantitative & Qualitative**
  - Score according to the coverage of electronic monitoring, information handling, information diffusion, etc.

## Disaster Prior Warning Mechanisms and Contingency Plans
- **Quantitative & Qualitative**
  - Score according to prior warning mechanisms, contingency plans, the implementation and exercise, etc.

## Capability of Emergency Rescue
- **Quantitative & Qualitative**
  - Score according to response time, timely rate, rescue capability can be mobilized, reopened time, etc.

## Coordination and Linkage Levels of Disaster Management
- **Quantitative & Qualitative**
  - Score according to the coordination between highway management agencies and the relevant sectors of society, linkage of the rescue action, etc.

---

Note: Full marks are 100. The raters are scientists grasping the actual situation, technical personnel, and trained practitioners of highway management agencies. Maintenance quality index (MQI) of freeway and rate of good level ordinary highways are evaluated based on "Highway Technical Condition Assessment Standards" (JTG H20-2007), other management and maintenance situations are evaluated in accordance with the specific circumstances of the different highway level actually.

Through calculating, the single factor appraisal matrixes of the fuzzy comprehensive evaluation of Level 2 $R_1$, $R_2$, and $R_3$ are obtained. Fuzzy comprehensive appraisal sets $B_1$, $B_2$, and $B_3$ are also obtained.

$$
R_1 = \begin{bmatrix}
0.40 & 0.13 & 0.20 & 0.03 & 0.24 \\
0 & 0.54 & 0.46 & 0 & 0 \\
0.03 & 0.25 & 0.29 & 0.43 & 0 \\
0.05 & 0 & 0.35 & 0.30 & 0.30 \\
0.11 & 0.34 & 0.22 & 0.22 & 0.11 \\
0.28 & 0.32 & 0.25 & 0.13 & 0.02 \\
0.30 & 0.22 & 0.26 & 0.19 & 0.03 \\
0.24 & 0.24 & 0.30 & 0.18 & 0.04 \\
0.12 & 0.23 & 0.39 & 0.20 & 0.06 \\
0.09 & 0.26 & 0.33 & 0.27 & 0.05 
\end{bmatrix}
$$

$$
R_2 = \begin{bmatrix}
0.39 & 0.21 & 0.11 & 0.25 & 0.04 \\
0.56 & 0.17 & 0.09 & 0.13 & 0.05 
\end{bmatrix}
$$

$$
R_3 = \begin{bmatrix}
0.40 & 0.13 & 0.20 & 0.03 & 0.24 \\
0 & 0.54 & 0.46 & 0 & 0 \\
0.03 & 0.25 & 0.29 & 0.43 & 0 \\
0.05 & 0 & 0.35 & 0.30 & 0.30 \\
0.11 & 0.34 & 0.22 & 0.22 & 0.11 \\
0.28 & 0.32 & 0.25 & 0.13 & 0.02 \\
0.30 & 0.22 & 0.26 & 0.19 & 0.03 \\
0.24 & 0.24 & 0.30 & 0.18 & 0.04 \\
0.12 & 0.23 & 0.39 & 0.20 & 0.06 \\
0.09 & 0.26 & 0.33 & 0.27 & 0.05 
\end{bmatrix}
$$
Furthermore, the single factor appraisal matrix of the fuzzy comprehensive evaluation of Level 1 $R$ is obtained. Fuzzy comprehensive appraisal set $B$ is also obtained.

$$
B = A_1R_1 = \begin{pmatrix} 0.147 & 0.231 & 0.302 & 0.177 & 0.143 \\ 0.492 & 0.186 & 0.098 & 0.178 & 0.046 \\ 0.224 & 0.253 & 0.293 & 0.193 & 0.037 \end{pmatrix}
$$

(17)

$$
B = A_2R_2 = \begin{pmatrix} 0.492 & 0.186 & 0.098 & 0.178 & 0.046 \\ 0.224 & 0.253 & 0.293 & 0.193 & 0.037 \end{pmatrix}
$$

(18)

$B = A_3R_3 = \begin{pmatrix} 0.224 & 0.253 & 0.293 & 0.193 & 0.037 \end{pmatrix}$

(19)

Ultimately, the comprehensive score of Hangzhou national and provincial trunk highway network is calculated as follows.

$$
V = \frac{\sum_{j=1}^{5} b_j v_j}{\sum_{j=1}^{5} b_j} = 83.429
$$

(20)

The score belongs to the "General" level. In terms of membership degree, its membership degree to "General" level is 0.6571 and to "Relatively Strong" level is 0.3429, which implies there is still a great improvement space for the ability against disasters. Compared with the actual situation of Hangzhou highway network, this conclusion is reliable.

Using retrospective analysis method to analyze the evaluation conclusion, we can identify the key weaknesses of Hangzhou national and provincial trunk highway network against disasters.

**Explore $R_1$, Network Structure Characteristic** whose membership degree to low grading is large is a disadvantage; Management and Maintenance Characteristic whose membership degrees to "Strong, Relatively Strong, General, and Relatively Weak" are similar is a potentiality.

**Explore $R_2$, Network Density** whose membership degree to high grading is relatively large is a comparative advantage, but its membership degree to "Weak" is also 0.24, therefore more attentions should be given. Convergence Nodes Density and Network Accessibility whose membership degrees to moderate grading are large are potentialities. Network Grade Level whose membership degree to low grading is large is a disadvantage.

**Explore $R_3$, Route Reliability** is a comparative advantage, but its membership degree to "Relatively Weak" is 0.25, so more attentions should be given.

**Explore $R_4$, Capability of Emergency Rescue and Coordination and Linkage Levels of Disaster Management** are comparative disadvantages.

Summarizing the above conclusion analysis, the key weaknesses of Hangzhou national and provincial trunk highway network against disasters are low Network Density, not reasonable Grade Level, low Accessibilities of some major nodes, low Reliability under disaster conditions, lack of Capability of Emergency Rescue, and weak Coordination and Linkage Levels of Disaster Management. Weaknesses should be improved by reasonable planning, acceleration of the construction, and attentions to both construction and management. In this paper, the recommendations of the priority of the highway construction are shown in Table 3.
Table 3. Recommendations of the priority of Hangzhou highway construction

<table>
<thead>
<tr>
<th>Classification</th>
<th>Name of highway</th>
<th>Name of highway section</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td>Hangxinjing Freeway</td>
<td>Shouchang to Baishaguan</td>
<td>New construct</td>
</tr>
<tr>
<td>Freeway</td>
<td>Qianhuang Freeway</td>
<td>Hangzhou section</td>
<td>New construct</td>
</tr>
<tr>
<td>Freeway</td>
<td>Linjin Freeway</td>
<td>Hangzhou section</td>
<td>New construct</td>
</tr>
<tr>
<td>Freeway</td>
<td>2nd Around City Freeway</td>
<td>Hangchang to Hangxinjing</td>
<td>New construct</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S208 (Wuxing to Fuyang)</td>
<td>connector from former S15 to former S02</td>
<td>New construct &amp; Rebuild according to Grade I</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S210 (Anji to Pan’an)</td>
<td>connector from former S23 to Hangxinjing Freeway</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S211 (Lin’an to Jinyun)</td>
<td>Chaiya Highway (Fengchuan to Xinhe) former S16 Fenshui section</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S212 (Lin’an to Chun’an)</td>
<td>former S18 (Longgang to Yutiao) Changwen Highway (Tuankou to Linqi) Linzuo Highway</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S305 (Xiaoshan to Kailua)</td>
<td>former S05 (Jiulong to Xiyang)</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S306 (Wucheng to Chun’an)</td>
<td>Qianwei Highway</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>Provincial highway</td>
<td>trunk S315 (Jiande to Jiangshan)</td>
<td>former S23 Jiande section</td>
<td>Rebuild according to Grade II</td>
</tr>
<tr>
<td>National highway</td>
<td>trunk G330</td>
<td>Western Extension of Jiande to Chun’an</td>
<td>New construct</td>
</tr>
</tbody>
</table>

4. Discussion

Although the results of the evaluation and conclusion analysis are reliable, it is also necessary to discuss the limitations of this method:

(1) Link reliability is determined by disaster reduction method and the data used are the impacts of historical natural disasters. Owing to the reproducibility of natural disasters, historical data are available. However, with the growing impact of climate change and natural disasters on highway network, an in-depth study of the highway network’s resistant ability against natural disasters combined with weather forecasting and climate change analysis will be more valuable.

(2) This paper is an evaluation of the overall highway network against natural disasters. On this basis, Sub-regional evaluation of the highway network’s resistant ability against various kinds of natural disasters will be conducive to in-depth understanding of the differences of the resistant ability against different natural disasters of sub-regional highway network and more targeted disaster decision-making.

(3) The study on the natural disasters’ impact is only limited to the highway network, however the highways are important channels for the regional disaster rescue, so the natural disasters’ impact should not be only limited
to transportation field. From this perspective, the comprehensive evaluation of the function and role of the highway network will be more meaningful.

5. Conclusions

In this paper, we propose a new method of evaluation and conclusion analysis for highway network’s resistant ability against natural disasters, which considers the overall network and overcomes the defect of the separate study on some disasters for a single highway. The proposed evaluation method can be used to evaluate highway network’s resistant ability against natural disasters objectively and accurately. The analysis of conclusion would make better use of the evaluation conclusion. Through analysis of the conclusion, highway network’s weaknesses against natural disasters can be identified, and then strategies can be put forward to improve and optimize the resistant ability. This will support disaster decision-making and the construction, management, and maintenance of the highway network. Limitations of the proposed method are also discussed. The information technology will be an important means which would help highway network against disasters in the future, how to use advanced technologies to obtain comprehensive and timely disaster information, as well as how to analyze and use the information obtained for evaluation of highway network’s resistant ability against natural disasters effectively will be an important future research direction.

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