Disaster evaluation of debris flow based on hierarchical architecture

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Received 1 November 2014, www.cmnt.lv

Abstract

The natural factors affecting the occurrence and development of debris flow are discussed in this paper. Some mathematical schemes to evaluate the disaster of debris flow are also studied, to establish an indicator system for existing debris flow disasters. We individually establish a disaster evaluation indicator system from three aspects including point, line and area, to evaluate the disaster of debris flow, and to determine the parameters for relative indictors in disaster evaluations. Meanwhile, quantity scoring method and analytic hierarchy process are adopted to perform consistency test on its results. So a more accurate evaluation of the degree of risk for some specific section or area can be acquired. It is verified to provide scientific direction of the construction of highway and disaster prevention.

Keywords: debris flow; factors; AHP; fuzzy comprehensive evaluation

1 Introduction

Due to its linear structures, the highway will cross different kinds of geomorphic unit's inevitability, involving different complicated geologic and topographic conditions. While it suffers from different disaster risks and debris flow is one of the important threats. The research on highway debris flow classification and disaster evaluation makes up the deficiency of highway transport Industries on debris flow disaster evaluation. It provides support to improve the disaster prevention capability and references to the measures of highway construction at planning, design, execution and maintenance.

As an interdisciplinary subject involving a numerous majors, the research about it is very difficult. Therefore, we can say that debris flow research is getting further development and gradual improvement. However, the research of highway debris flow is so few that it seems to be more important to perform research of evaluation content and evaluation system on debris flow disaster [2-5]. At present, the debris flow researches have focused on basic disciplines of natural and physical science. The study from the engineering field emphasizes on practical implementations. But the research on highway classification, disaster evaluation, subdivision is still weak [6]. There is less integrated evaluation study from point, line, area and regional integration for the debris flow of highways.

Therefore, this paper studies the classifications of debris flow of national highways. It relies on debris flow-prone highway project and provides systematic research on the study methods and indicator structures of risk evaluation. It improves three hierarchical systems of debris flow disaster evaluation: regionality, sections and single-channel debris flow disaster. Then we establish an evaluation indicator system of single-channel debris flow disaster, which performs evaluations with the evaluation factors including activity frequency of historical disaster, lithological level, average gradient of principal drain, debris flow forming drainage area, etc. So the scheme can provide helpful achievements for highway construction and normal operation.

2 Evaluation Methods Study

2.1 HIERARCHICAL ANALYSIS METHOD

When hierarchical analysis method is adopted for systematic analysis, the problem will be hierarchied first. According to problem quality and object to be achieved, the problems are decomposed into different components [7, 8]. These components will be integrated according to different hierarchies based on the influence of mutual relationship and membership degree to form a sequential, low-order, and hierarchal structure. Finally, systematic analysis will come down to weight determination of relative importance based on the lowest level, with respect to the highest level, and the sequence problem of relative order with bad and good. Combined with related application theories of hierarchical analysis, it can be generally divided into four main steps.

2.1.1 Establish the hierarchical structure model of problem

The hierarchical structure is usually divided into target layer, criterion layer and project layer. A box form can be used to depict the subordinating relationship between the hierarchical structure of layers and the factors. When a layer contains more factors, this layer can be further divided into several layers. So model structure is shown in figure 1:

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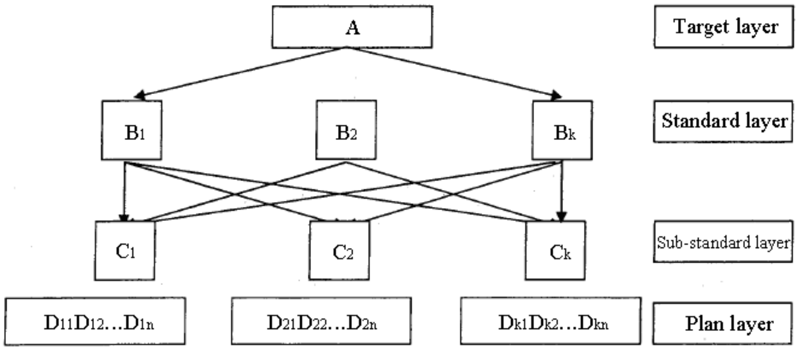

FIGURE1. Hierarchy structure model

2.1.2 Construct judgment matrixes

The elements in judge matrix reflect people's knowledge on various factors' relative importance. Generally l-9 and scaling method of its reciprocal are adopted.

TABLE 1 Judgment matrix

A	B_1	B_2	…	B_k
B_1	a_{11}	a_{12}	…	a_{1k}
B_2	a_{21}	…		a_{2k}
…	…	…	…	…
B_k	a_{k1}	a_{k1}	…	a_{kk}

a_{ij} is the numerical elative expression of B_i . Number 1-9 and their reciprocal values can be always taken as a scale;

2.1.3 Hierarchical single sort and consistency test

The maximized eigenvalue $\lambda_{\max}$ of judgment matrix A and corresponding normalized eigenvector $W=[w_1,w_2,...,w_n]^T$ are computed first.

That is, eigenvalue $AW=\lambda_{\max}W$ of judgment matrix is firstly solved and the maximized eigenvalue W of judgment matrix is acquired after we solve the equation.

Then, it is normalized to get $W=[w_1,w_2,...,w_n]^T$ as the order weight of this layer compared to the last layer;

2.1.4 Total hierarchical sort and its consistency test

If integrated weights of all elements $A_1,A_2,...,A_n$ in above layer are known, the weights will be $a_1a_2...a_n$ respectively. If some factors in B layer, the consistence indicator of ranking is CI_j for A. The corresponding average random consistency indicator is CR_j, the total hierarchical rank of random consistency for B is:

$$CR=\frac{\sum_{j=1}^{n}a_jCI_j}{\sum_{j=1}^{n}a_jRI_j} \quad (1)$$

When $CR<0.1$, that is, judgment matrix is considered to satisfy the consistency, the weight distribution is reasonable. Otherwise, judgment matrix is needed to be regulated until the values acquire satisfied consistency. The final result of AHP is the optimized sequence weight of various decision-making levels relevant to the total object to make decisions.

2.2 FUZZY COMPREHENSIVE EVALUATION

The basic principle of fuzzy comprehensive evaluation [10] is: the disaster factor set as $U=\{u_1u_2...u_m\}$. $u_1u_2...u_m$ is quantity value of disaster-inducing factors, $V=\{v_1v_2...v_m\}$ is evaluation set of disaster evaluation and $V=\{v_1v_2...v_m\}$ denotes corresponding evaluation standard set of V. Disaster factor set and disaster evaluation set can be described by fuzzy relationship matrix R.

$$R=(r_{ij})m\times n=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}, i=1,2,...,m; j=1,2,...,n$$

In the fuzzy relation matrix, r_{ij} is the membership for risk factor u_i when evaluated as level v_i. As for the debris flow disasters, it denotes the probability of factor causing disaster to be evaluated as the j_{th} class, that is, the membership from i to j .In fact, during weight selection, geological disasters have different weight coefficients due to the effects caused by geological disaster. The performance of single factor has different effect on overall performance, so fuzzy weight vector should be determined before integration.

3 Disaster evaluation hierarchical system

3.1 HIERARCHICAL DISASTER SYSTEM AND EVALUATION CONTENT

Considering the distribution features of highway traffic and traffic network, the disaster evaluation of highway debris flow should expand from three levels, according to object and sense of highway debris flow. They are regionality, sections and single-channel debris flow disaster, that is, the evaluation hierarchy of area, line and point.

TABLE 2 Hierarchical divisions for highway debris

Hierarchy	Academic Sense	Practical value	Remarks
Area	1.Debris flow distribution discipline 2. Disaster degree of highway network in debris flow	For national construction, planning and development decision	It is divided according to educational degree and development phases, which is called regional division
Highway section	1.Distribution discipline of highway debris flow 2.Form conditional statistical analysis 3.Establish prediction model of highway geographical disaster 4.Determine countermeasure of disaster prevention and reduction	Used for regional development and planning	It is set based on drainage area and economic development zone
Single-channel	1.Form conditional analysis of highway debris flow 2.Development characteristics of highway debris flow 3.Disaster mechanism of highway debris flow 4.Automatic observation of highway debris flow 5. Establish forecasting model of highway debris flow 6. Foundation of maintenance and prevention	To reduce or prevent geological disaster on highway	It is set by integration of engineering project construction

The disaster research of regional debris flow belongs to the first level, which performs research on distributed situation of national highway debris flow or the features of large administrative region [11]. The main method of this research is to provide regionalization on highway debris flow. It is based on typological region division in the whole scope to perform systematic research on regionalization systems. At the same time, different types of region have better extensibility to offers research of highway debris flow in the second and the third level in the next stage and further regional division. On the contrary, a highway debris flow regionalization is also established based on the second and the third level, which is a process of "macro-specific-macro", that is, the regionalization must provide formation condition analysis of highway debris flow, development features of highway debris flow and specific research of debris flow disaster. Then, based on above conclusions, the distribution discipline of national highway debris flow for nationally strategic decision can be evaluated from the perspective of macro-level.

3.2 CLASSIFICATION

Based on acting factors causing highway debris flow including geographical features, geomorphology, climate, rock-soil types, they are ordered by the importance and scale. The regional division of highway debris flow in China adopts multi-stage regional division. Three-level structure is used here:

(1) First-level is also called classification indicator. It only performs overall division based on influencing factors and structures of disaster-pregnant environment.

(2) Second-level indicator is also called structural indicator which provides single-factor division on acting factors and structures based on the first-level indicator.

(3) Third-level is also called statistical indicator which is the factor indicator divided from the second-level indicator. Each item in this indicator is divided into several grades according to influencing degree.

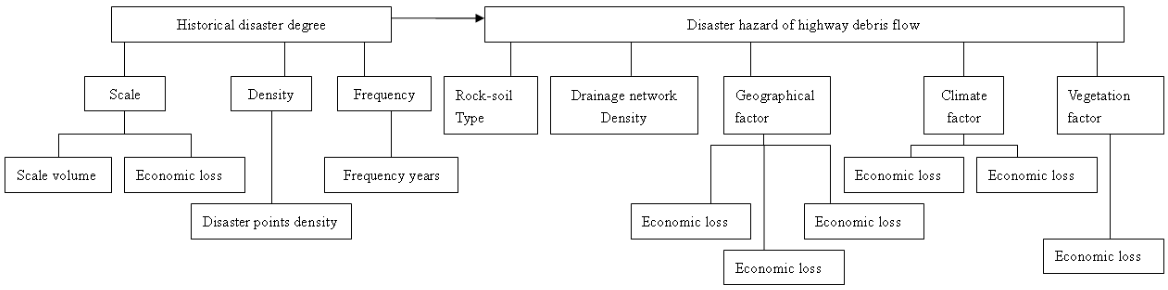

FIGURE2. Debris disaster indicator division system

3.3 FUZZY EVALUATION BASED ON HIERARCHICAL ANALYSIS

On the basis of above hierarchical analysis, we introduce the fuzzy comprehensive judgment method, that is, hierarchical analysis is computed to acquire weight vectors to be introduced in fuzzy comprehensive evaluation. By the integration of hierarchical analysis and fuzzy evaluation, the hierarchical analysis of debris flow disaster evaluation-fuzzy comprehensive evaluation model is established. The debris flow disaster evaluation is consequently established based on partial reliability factor, partial validity factor and available factor, which avoids high demand of computation in traditional stability on investigation quality and reduces the investigation cost. Meanwhile, the evaluation factor and evaluation fuzziness are fully reflected to reduce the defects caused by personal subjective assumption, which is more suited to the objective than general expert scoring method [12]. The evaluation procedures are shown as follows:

Step 1: Set up evaluation factor set and remarks set. Evaluation factor set of disaster-inducing factor is established according to disaster evaluation system of debris flow.

Step 2: Set up fuzzy hierarchy model structure of debris flow. According to influencing disaster evaluation factors of debris flow, the hierarchy fuzzy evaluation model of disaster-inducing factors is established, which can be divided into several hierarchical structures, such as object layer, criterion layer, sub criterion layer and project layer, etc.

Step 3: Sort and consistency test of hierarchy analysis. The maximized eigenvalue and eigenvectors of judgment matrix is performed consistency test according to above computation steps and principles. If they are not qualified, a double-element judgment matrix is established again until they pass the consistency test.

Step 4: Weight coefficient determination. The above maximized eigenvalue matching the feature vector after normalization will be taken as weight coefficient of each disaster-inducing factor to acquire value of A.

Step 5: Providing single factor judgment and establishing fuzzy relationship matrix R. Fuzzy relationship matrix is established between factor set and remark set, and the membership of each disaster factor on indicators can be acquired.

Step 6: Fuzzy comprehensive judgement. For above fuzzy relationship matrix R, $B = A \times R$ is used for disaster evaluation on debris flow.

When determining the fuzzy weighted vectors of judgement factors set, we assume $\alpha_1, \alpha_2, ..., \alpha_m$ is the weight parameters for evaluation factor $\mu_1, \mu_2, ..., \mu_m$ and $\alpha_1 + \alpha_2 + ... + \alpha_m = 1$. So the fuzzy weighted vector of judgement factor $A = (\alpha_1, \alpha_2, ..., \alpha_m)$.

After the weight vector is determined, due to fuzzy comprehensive judgement matrix R we get the comprehensive judgement result $B = (b_1, b_2, ..., b_m)$, $0 \le b_j \le 1$. $B = A \circ R$ Denotes the membership level of fuzzy set of total class, and it can be used to evaluate the disaster of debris flow.

4 Empirical Analyses

On the analysis of cause and effect of debris flow, the evaluation factors influencing debris flow occurrence such as the maximized height difference, average gradient of main channel, drainage area, are chosen to study the features of debris flow. Concerning their different qualities and features, they will form an evaluation systematic block diagram of multi-hierarchy to be taken as reference of hierarchy synthesis evaluation, according to logic relationship among the factors. In order that validity description can be transformed into reliability expression to reach mutual transformation between validity variable and reliability variable, the disaster factor is needed to perform sort division and quantification. The levels of each disaster factor adopt a five-level division and standard quantification value [0, l].

The evaluation set $V = \{V_1, V_2, V_3, V_4, V_5\} = \{I, II, III, IV, V\}$ is established first, which respectively denotes lowest risk, lower risk, moderate risk, high risk and highest risk. Referential evaluation element set $U = \{U_1, U_2, U_3, U_4, U_5, U_6\}$ is also determined, which denotes historical disaster level, geological condition, geographical condition, climate condition, vegetation condition and engineering reasonnable degree. The half-trapezium function is chosen during evaluation to be regarded as membership function. With this research, the function can be written and sort as:

Lowest risk

$$r_{n1} = \begin{cases} 1 & (x \le a_1) \\ \dfrac{a_2 - x}{a_2 - a_1} & (a_1 \le x \le a_2) \\ 0 & (x \ge a_2) \end{cases} \quad (2)$$

Lower risk

$$r_{n1} = \begin{cases} \dfrac{x - a_1}{a_2 - a_1} & (a_1 \le x \le a_2) \\ \dfrac{a_3 - x}{a_3 - a_2} & (a_2 < x < a_3) \\ 0 & (x \le a_1 or x \ge a_3) \end{cases} \quad (3)$$

Moderate risk

$$r_{n3} = \begin{cases} \dfrac{x - a_2}{a_3 - a_2} & (a_2 \le x \le a_3) \\ \dfrac{a_4 - x}{a_4 - a_3} & (a_3 < x < a_4) \\ 0 & (x \le a_2 or x \ge a_5) \end{cases} \quad (4)$$

High risk

$$r_{n4} = \begin{cases} \dfrac{x - a_3}{a_4 - a_3} & (a_3 \le x \le a_4) \\ \dfrac{a_5 - x}{a_5 - a_4} & (a_4 < x < a_5) \\ 0 & (x \le a_3 or x \ge a_5) \end{cases} \quad (5)$$

Highest risk

$$r_{n5} = \begin{cases} 0 & (x \le a_4) \\ \dfrac{x - a_4}{a_5 - a_4} & (a_4 < x < a_5) \\ 1 & (x \ge a_5) \end{cases} \quad (6)$$

r Is the membership function of each evaluation factor, x is the practical value of evaluation factor. A_1, A_2, A_3, A_4 Respectively denotes standard threshold values of evaluation factors on evaluation degree.

$$a_1 = A_1, a_2 = (A_1 + A_2)/2, a_3 = (A_2 + A_3)/2,$$
$$a_4 = (A_3 + A_4)/2, a_5 = a_4$$

The first-level and second-level judgment matrices are:

TABLE 3 First-level judgement matrixes

Indictor	U1	U2	U3	U4	U5	U6	Weight
U1	1	1/2	3	5	2	4	0.2475
U2	2	1	4	6	3	5	0.3778
U3	1/3	1/4	1	3	1/2	2	0.1016
U4	1/5	1/6	1/3	1	1/4	1/4	0.0413
U5	1/2	1/3	2	4	1	3	0.1593
U6	1/4	1/5	1/2	3	1/3	1	0.0725

TABLE 4 Second-level judgement matrix

Indictor	A_3	A_4	A_5	weight
A_3	1	3	2	0.4905
A_4	1/3	1	2	0.3119
A_5	1/3	1/2	1	0.1976

The maximum eigenvalue $\lambda_{\max} = 3.054$, $\frac{CI}{RI} = 0.0463 < 0.1$, which meets the demand for consistency test. In the second-level judgement matrix $U_4 = \{A_6, A_7\}$.

TABLE 5 Second-level judgement matrix for U_4

Indictor	A_6	A_7	weight
A_6	1	2	0.667
A_7	1/2	1	0.333

The maximum eigenvalue $\lambda_{\max}$ =2.0 meets the demand for consistency test.

The hierarchical indicator weight is:

TABLE 6 Weights of hierarchical indicator

	U_1	U_2	U_3	U_4	U_5	U_6	Hierarchical sorting
	0.2475	0.3778	0.1016	0.0413	0.1593	0.0725	
A_1	0.2475						0.2475
A_2		0.3778					0.3778
A_3			0.4905				0.0498
A_4			0.3119				0.0316
A_5			0.1976				0.0201
A_6				0.0667			0.0275
A_7				0.0333			0.0137
A_9					0.1593		0.1593
A_{10}						0.0725	0.0725

Fuzzy relationship matrix is solved by fuzzy matrix, which is shown as:

$$R_{(U_3)} = \begin{bmatrix} 0 & 0 & 0.0825 & 0.175 & 0 \\ 0 & 0.618 & 0 & 0 & 0.382 \\ 0 & 0.222 & 0.778 & 0 & 0 \end{bmatrix} \qquad R_{(U_4)} = \begin{bmatrix} 0 & 0.1 & 0.9 & 0 & 0 \\ 0 & 0 & 0.2 & 0.8 & 0 \end{bmatrix}$$

After the first-level fuzzy transformation:

$$B_{(U_3)} = W_{(U_3)} \times R_{(U_3)} = (0, 0.236, 0.559, 0.086, 0.119) \tag{7}$$

$$B_{(U_4)} = W_{(U_4)} \times R_{(U_4)} = (0, 0.0667, 0.6669, 0.2664, 0) \tag{8}$$

Other first-level indicators have not second-level indicators and they can be acquired by following equations:

$$R_1 = (0, 0, 0.606, 0.394, 0); R_2 = (0, 0, 0, 1, 0);$$
$$R_5 = (0, 0, 0, 0.5, 0.5); R_6 = (0, 0, 0, 0.5, 0.5)$$

Thus, the membership matrix of the first-level indicator is acquired:

$$R = \begin{bmatrix} 0 & 0 & 0.606 & 0.394 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0.236 & 0.559 & 0.086 & 0.119 \\ 0 & 0.066 & 0.667 & 0.266 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}$$

The first-level fuzzy evaluation result is acquired.

$$B = W \times R = (0, 0.0267, 0.2343, 0.611, 0.128) \quad (9)$$

According to the maximized membership principle, 0.611 belongs to high risk areas from 0.6 to 0.8 and the debris flow channel in this location belongs to high-risk debris flow. Meanwhile, according to investigation of on-site and debris flow development in recent years, in contrast to other debris flow materials, the debris flow in this location can be determined to be belonged to high-risk debris flow. It is found that fuzzy comprehensive rate based on hierarchical analysis can be applied to disaster evaluation of debris flow. According to above disaster evaluation model, the disaster evaluation of other debris flow channel can be executed. The evaluation factor quantification of each single-channel debris flow is shown as follows:

TABLE 7 Disaster indicator values of debris ditches

Channel No.	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
1	1.5	25	10	0.159	0.04	12	52.3	15	60
2	1.6	50	22.5	3.95	0.09	12	53.1	15	25
3	1.3	25	24	0.1188	0.1	20	80.2	10	40
4	0.8	25	24	0.142	0.12	18	71.6	30	60
5	1.2	70	30.7	0.14	0.14	25	89.3	18	25
6	3.5	50	33	0.133	0.2	14	61.2	30	40
7	2.2	25	70	0.0669	0.35	11	75.6	25	45
8	2.6	50	76.9	0.354	0.6	13	78.4	30	25

Based on above evaluation methods we get the risk of investigated debris channels in table 8.

TABLE8 Evaluation result

Channel No.	Risk level	Channel No.	Risk level
1	Moderate	5	High
2	Highest	6	Low
3	Low	7	Highest
4	High	8	High

5 Conclusions

There are multiple evaluation factors for risk evaluation of the debris flow. It involves many aspects such as highway environment, natural condition, and its evaluation system is very complicated. The information of disaster-affected bodies shows quality of multi-source, fuzziness, non-deterministic and stochastic, so it is hard to perform data processing and spatial comprehensive analysis. Contra ponding to these characteristics, we adopt fuzzy synthesis evaluation based on hierarchy analysis in this paper. AHP is used to determine the weight parameters of the factors causing disaster. Since AHP reduces empiricism and subjectivism in expert scoring method, moreover, it determines whether the subjective evaluation specialists are deviated from the actual by the analysis of judgement matrix, to improve the scientificalness and rationality. At the same time, a comprehensive evaluation can be acquired with fuzzy comprehensive evaluation to form a novel evaluation method. The scheme is verified to introduce the advantages of various judgments to acquire scientific, object, and comprehensive results for the evaluation experts.

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