Geological Hazard Risk Evaluation for Railway Network of Guizhou Province in China

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Abstract. In recent years, China's high-speed railway has experienced a period of rapid development and being gradually rational. This paper took Guizhou Province as the study area, one of the places in China which are most seriously affected by landslide hazards. The research in this paper was conducted in three steps. Firstly, the landslide susceptibility mapping of railway was acquired by applying competition network model, and a set of conditioning factors were selected as the major landslide-conditioning factors, including elevation, lithology, rainfall, distance from river, distance from tectonic line, karst density and slope. Then, the concept of 'degree of fitting' was proposed in the assessment of railway risk degree, and it was regarded as one of the three elements which determine the railway protection grade on geological disasters. Finally, the matter-element model was established based on extension method, which can be used to evaluate the protection grades for the planned railway on geological disasters by integrating three elements, the train speed, grade of susceptibility mapping, and fitting degree, into the model.

1 Introduction

The research on geological disaster susceptibility mapping began in the 1960s. A considerable amount of research works have been conducted over the past years. Current method for geological disaster susceptibility mapping can be categorized into two groups, i.e., qualitative and quantitative. Qualitative methods are mainly on the basis of some fuzzy approaches, combining with the experiences of the experts to make decisions, and quantitative methods generally rely on mathematical models or some software or data equations to calculate. In abroad, Varnes studied the type and movement processes of slope geological disasters, and put forward early analysis and control methods [1]; Pistocchi et al. established a landslide susceptibility map with expert system method, achieving good results [2]; The Turkish scholar Yesilnacar

utilized artificial neural network model and set up a landslide hazard susceptibility map for Turkish [3]; Melchiorre et.al studied the landslide sensitivity evaluation on the basis of neural network model and cluster analysis [4]. In our country, many research methods about geological hazard susceptibility mapping have also been carried out in recent years. Yin Kunlong at China University of Geosciences studied the alarm and forecast system of sudden geological disasters in Zhejiang Province [5]; Dai Fuchu summarized the various research methods on landslide disasters [6]. Most articles are about susceptibility mapping. The innovation of this article is putting forward of 'fitting degree' concept and establishing the quantitative method of matter-element for evaluating railway protection grade. The flowchart of this paper is shown in Fig. 1.
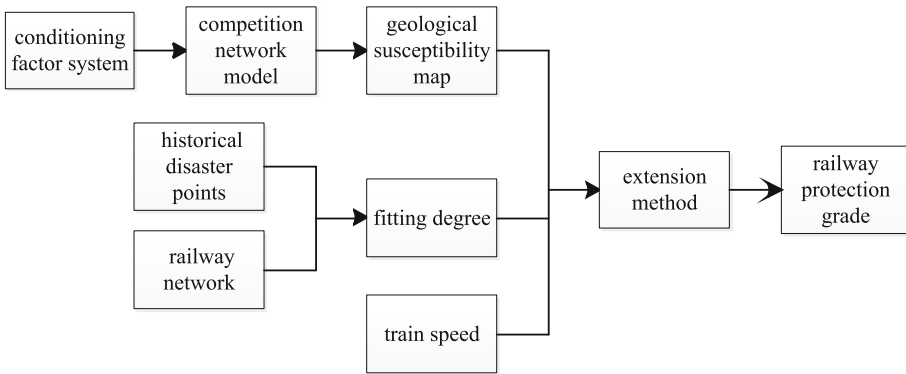

Fig. 1. The flowchart of geological hazard risk evaluation for railway network

2   Geological Hazard Susceptibility Evaluation

2.1   The Selection of Landslide-Causing Factors

According to the geology, topography and other natural conditions, this paper comprehensive selected seven conditioning factors including elevation, lithology, rainfall, distance from river, distance from tectonic line, karst density and slope to determine the geological hazard susceptibility mapping. In order to classify and quantify these hazard factors, this research divided them into several sub-classes. The area of history disaster within each sub-class was calculated and normalized.

2.2   The Determination of Factor Weight Based on Competition Network

Competition network consists of a set of layers, namely, input layer, hidden layer, and output layer (Fig. 2). Each layer in the competition network consists of independent processing units called neurons. These neurons are linked to neurons in other layers through the weights and bias.
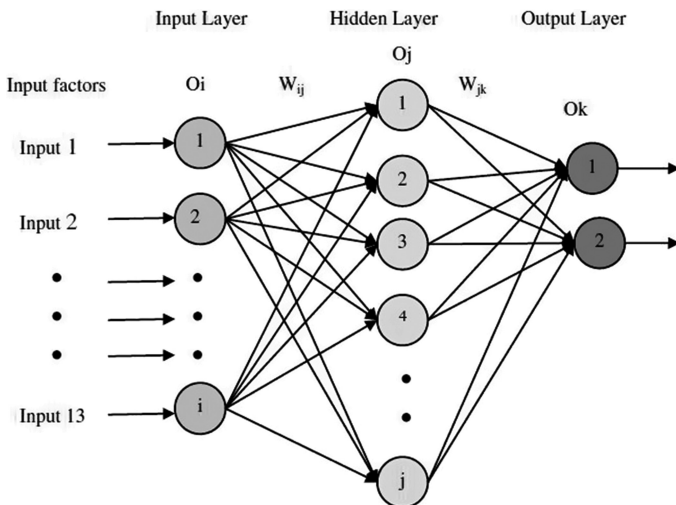
Fig. 2. Architecture of competition network

The normalized data of the seven factors were regarded as the input layers, and the landslide risk degrees as the output layers.

By staking the seven factors together in AcrMap platform, the original layer of each factor was divided into finer and irregular polygons, which contained all normalized data of the seven factors. This paper took the whole Guizhou Province as the study area which was divided into 4073 small polygons, from which twelve typical polygons were selected as the test data. After repeatedly adjusting the weight parameters, the factor weights were acquired through adjusting the 12 polygons to be classified accurately. By using these well-trained data, the whole dataset of Guizhou Province was imported after being trained in one time based on the Matlab software.

2.3 Geological Susceptibility Map of Guizhou Province

After importing the Matlab calculating results into the DBF tables in ArcGIS and rendering different sensitivity degrees based on ArcMap, the landslide susceptibility map is obtained (Fig. 3). According to the difference in landslide susceptibility degree, the study area was divided into five grades: the very low susceptible zone VLS), the low susceptible zone (LS), the moderate susceptible zone (MS), the moderate-high susceptible zone (MHS) and the high susceptible zone (HS). The statistics of the historical disaster area among each risk degree are shown in Table 1.
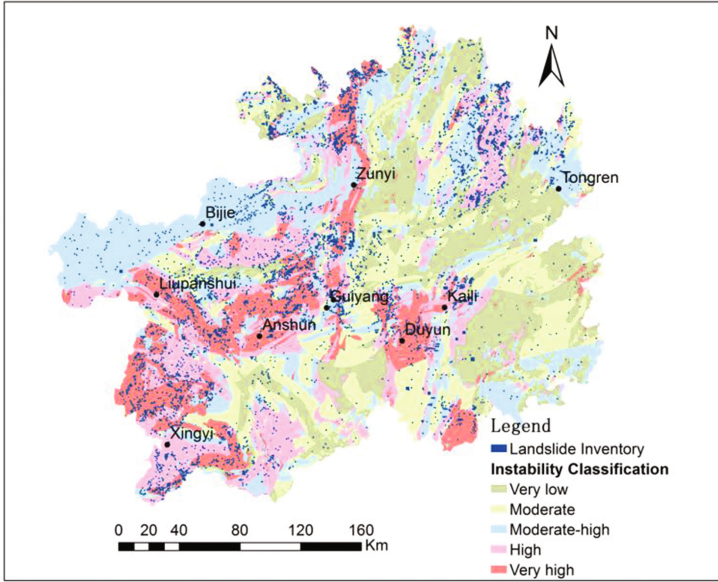
Fig. 3. Landslide susceptibility map of Guizhou Province

Table 1. Landslide distribution in landslide susceptible zones

Landslide susceptible zones	Area		
	Historical landslide area	Coverage area	Landslide density (%)
VLS	1077.63	38659.1	2.79%
LS	1636.20	36190.8	4.52%
MS	2634.69	42506.1	6.20%
MHS	3266.86	33510.1	9.75%
HS	3626.65	25228.9	14.37%

3   The Geological Hazard Risk Assessment for Railway Network in Guizhou Province

According to the geological susceptibility map and historical landslide hazard distribution, we obtained the risk degrees along the planning railway line and got the distribution of landslide points on both sides of railways (Fig. 4). According to the distribution proportion among five landslide risk degrees, each railway was endowed a hazard weight. The five grade weight coefficient $\theta = (7, 5, 3, 2, 1)$. For example, the hazard weight of Hu-Kun passenger special line was:

$$W_1 = w\theta^T = (35.6\%, 25.4\%, 17.3\%, 18.9\%, 2.8\%) \cdot (7, 5, 3, 2, 1)^T = 4.69.$$
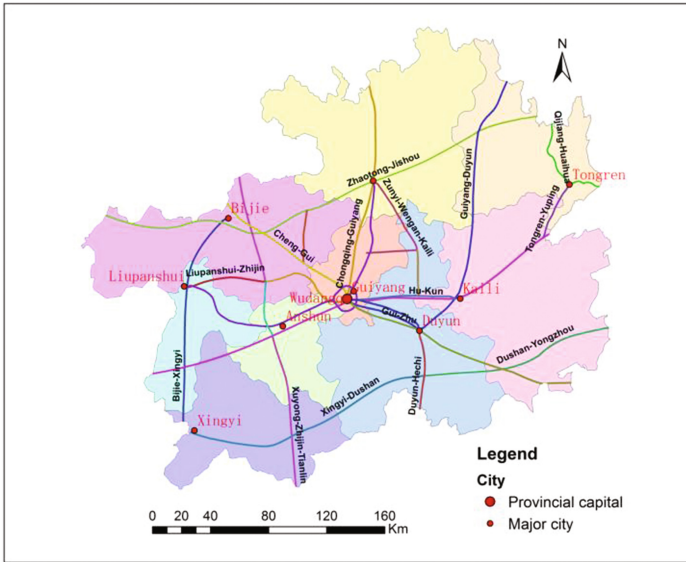
Fig. 4. Planning railways in Guizhou Province

Table 2. The distribution ratio and hazard weight of planning railway lines

Railway lines	Risk degree					
	HS (%)	MHS (%)	MS (%)	LS (%)	VLS (%)	Hazard weight
Hu-Kun	35.6	25.4	17.3	18.9	2.8	4.69
Cheng-Gui	25.1	33.5	32.1	2.5	6.8	4.51
Bijie-Xingyi	48.3	15.1	10.4	20.4	5.8	4.91
Liupanshui-Guiyang-Zunyi	50.0	33.1	11.0	5.7	0.2	5.60
Guiyang-Duyun	15.3	14.8	13.2	50.1	6.6	3.28
Guiyang-Kaili	30.5	20.8	24.5	16.8	7.4	4.32
Tongren-Yuping	0	0	6.8	10.3	82.9	1.24
Zhaotong-Jishou	8.7	10.9	61.5	10.1	8.8	3.29
Liupanshui-Jinzhi	17.6	15.7	41.3	20.4	5.0	3.71
Guiyang-Duyun-Enshi	9.8	18.9	24.0	10.2	37.1	2.93
Duyun-Hechi	33.5	10.2	5.3	51.0	0	4.03
Wengan-Fuquan	0	0	10.0	42.1	47.9	1.62
Xuyong-Zhijin-Tianlin	5.1	45.7	13.1	15.4	20.7	3.55
Jinsha-Xindian	40.6	49.1	1.3	0	9.0	5.43
Xingyi-Dushan	15.9	29.2	3.4	22.5	29.0	3.42
Chongqing-Guiyang	73.2	10.3	11.5	1.9	3.1	6.05
Qianjing-Huaihua	1.7	5.7	70.8	9.5	12.3	2.84
Dushan-Yongzhou	6.8	5.9	22.8	30.9	33.6	2.41
Zunyi-Wengan-Kaiyang	1.2	2.8	7.9	50.1	38.0	1.84
Huangtong-Zhijin	75.6	13.2	11.2	0	0	6.29
Gui-Zhu	19.9	6.5	12.4	25.7	35.5	2.96

The distribution of the 21 planning railway lines in Guizhou Province among 5 landslide risk degrees was shown in Table 2.

3.1 Assessment of Railway Risk Degree Based on Fitting Degree

By using the concept of 'fitting degree' [7–9], it was assumed that each railway line is a regression line (or curve), and the historical disaster points nearby the railway are discrete points on both sides of the regression line. If the historical disaster points more densely distributes in the vicinity of the line, the fitting degree will be greater, and the risk of the railway will be higher.

This paper extracted all the planning railways in Guizhou Province, and took the buffer of 10 km on both sides of the railway lines for research based on ArcMap software (Fig. 5).
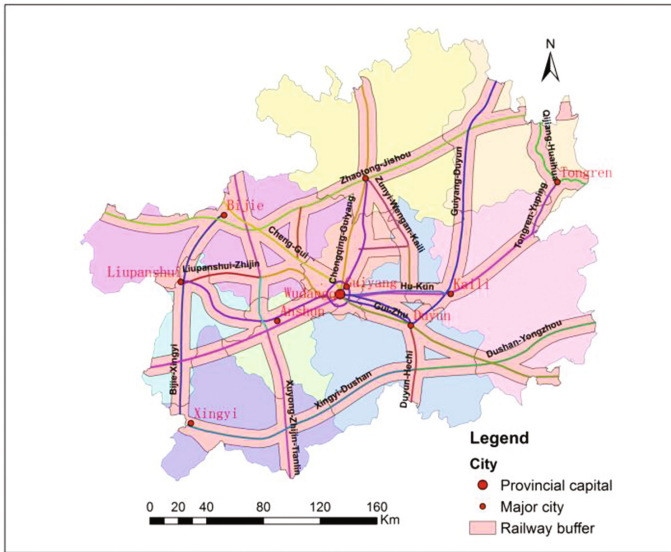

Fig. 5. The landslide hazard distribution within railway buffer of 10 km

The fitting degrees of each railway were calculated in the attribute Table 3.

Table 3. Fitting degree of planning railway lines

Planning railroad	Design speed (Km/h)	Railroad length (Km)	Fitting degree
Hu-Kun	350	482.82	0.38
Cheng-Gui	250	174.44	0.29
Bijie-Xingyi	200	320.34	0.21
Liupanshui-Guiyang-Zunyi	250	409.27	4.24
Guiyang-Duyun	200	395.04	0.14
Guiyang-Kaili	200	120.96	0.17
Tongren-Yuping	200	65.94	0.01
Zhaotong-Jishou	160	510.94	0.01
Liupanshui-Jinzhi	120	89.06	0.41
Guiyang-Duyun-Enshi	250	90.60	3.20
Duyun-Hechi	160	88.49	0.06
Wengan-Fuquan	120	49.66	0.02
Xuyong-Zhijin-Tianlin	120	289.98	0.72
Jinsha-Xindian	120	58.16	0.10
Xingyi-Dushan	160	279.08	0.14
Chongqing-Guiyang	200	345.94	1.54
Qianjing-Huaihua	200	111.95	0.38
Dushan-Yongzhou	160	215.45	0.08
Zunyi-Wengan-Kaiyang	160	147.09	0.33
Huangtong-Zhijin	120	60.53	0.03
Gui-Zhu	300	261.93	0.15

3.2   Railway Protection Grade Assessment

Based on extension method, this paper selected three elements as the matter-element model: train speed, hazard weight and fitting degree. The specific steps were as follows [10–13]:

(1) Determining the classical domain

Table 4 lists the five protection grades according to the numerical characteristics of train speed, hazard weight and fitting degree, respectively.

(2) Determining the segment domain

The segment domain of the protection grade, namely the upper-lower limit of classical domain is expressed as:

$$\mathbf{R}_p = (\mathbf{N}, \mathbf{c}, \mathbf{v}) = \begin{bmatrix} \mathbf{N} & c_1 & V_{p1} \\ & c_2 & V_{p2} \\ & c_3 & V_{p3} \end{bmatrix} = \begin{bmatrix} \mathbf{N} & c_1 & \langle 120, 360 \rangle \\ & c_2 & \langle 0, 4.5 \rangle \\ & c_3 & \langle 1.0, 6.3 \rangle \end{bmatrix} \qquad (1)$$

Table 4. The factors affecting the railway protection grades

Element index	Protection grade				
	I	II	III	IV	V
Train speed C_1	120–160	160–220	220–260	260–320	320–360
Fitting degree C_2	0–0.05	0.05–0.2	0.2–0.5	0.5–1.0	1.0–4.5
Hazard weight C_3	1.0–2.0	2.0–3.0	3.0–4.0	4.0–5.0	5.0–6.3

Where R_p means matter-element model of the railway protection grade; N refers to the protection grade of railway to be evaluated; c_i indicates the evaluation indices; V_{pi} is the value range of the evaluation indices.

(3) Determining the matter-element

Planning railway is expressed in the form of matter-element as:
Hu-Kun passenger special line:

$$\mathbf{R}_1 = \begin{bmatrix} \mathbf{P}_1 & c_1 & 350 \\ & c_2 & 0.38 \\ & c_3 & 4.69 \end{bmatrix} \tag{2}$$

Gui-Zhu fast railway:

$$\mathbf{R}_{21} = \begin{bmatrix} \mathbf{P}_{21} & c_1 & 350 \\ & c_2 & 0.15 \\ & c_3 & 2.96 \end{bmatrix} \tag{3}$$

(4) Determining the connection degree between matter-elements and protection grade

$$\rho(v_i, V_{ti}) = \left| v_i - \frac{a_i + b_i}{2} \right| - \frac{b_i - a_i}{2} \quad (i = 1,2\ldots n) \tag{4}$$

$$\rho(v_i, V_{pi}) = \left| v_i - \frac{a_{pi} + b_{pi}}{2} \right| - v_i - \frac{b_{pi} - a_{pi}}{2} \quad (i = 1,2\ldots n) \tag{5}$$

a_i and b_i are the upper or lower limit of V_{ti}; v_i is the value of the evaluation indices.
The connection function between i-th element and j-th protection grade is:

$$K_j(v_i) = \begin{cases} \dfrac{-\rho(v_i, V_{ti})}{|V_{ti}|}, & v_i \in V_{ti} \\ \dfrac{\rho(v_i, V_{ti})}{\rho(v_i, V_{pi}) - \rho(v_i, V_{ti})}, & v_i \notin V_{ti} \end{cases} \tag{6}$$

(5) Determining the weight coefficient

In this paper, the weight coefficient $\lambda_1 = \lambda_2 = \lambda_3 = 1/3$

(6) Calculating the connection degree based on connection function and weight coefficient

$$K_1(p) = \sum_{i=1}^{3} \lambda_i K_1(v_i) \qquad (7)$$

Repeating steps (4), (5), (6), the connection degree under other protection grade can be obtained. $K_2(p)$, $K_3(p)$, $K_4(p)$, $K_5(p)$

$K_{j0} = \max_{j \in (1,2,...,m)} K_j(v_i)$, the matter-element belongs to K_{j0}. The protection grades of the 21 planning railways are shown in Table 5.

Table 5. The protection grades of each railway

Railway lines	Protection grade					
	K1	K2	K3	K4	K5	Grade
Hu-Kun	−0.77	−0.70	−0.53	−0.25	−0.02	V
Cheng-Gui	−0.76	−0.68	−0.53	−0.20	−0.01	V
Bijie-Xingyi	−0.67	−0.55	−0.37	0.17	−0.19	IV
Liupanshui-Guiyang-Zunyi	−0.86	−0.82	−0.75	−0.53	0.11	V
Guiyang-Duyun	−0.55	−0.35	−0.12	0.06	−0.35	IV
Guiyang-Kaili	−0.61	−0.46	−0.27	0.28	−0.28	IV
Tongren-Yuping	0.5	−0.61	−0.50	0.06	−0.40	I
Zhaotong-Jishou	−0.41	0.26	−0.17	−0.16	−0.41	II
Liupanshui-Jinzhi	−0.43	−0.23	0.27	−0.10	−0.39	III
Guiyang-Duyun-Enshi	−0.57	−0.42	−0.31	−0.44	−0.40	III
Duyun-Hechi	−0.46	−0.26	0.10	−0.04	−0.35	III
Wengan-Fuquan	−0.20	−0.27	−0.04	−0.30	−0.53	III
Xuyong-Zhijin-Tianlin	−0.43	0.24	0.23	0.00	−0.36	II
Jinsha-Xindian	−0.65	−0.50	−0.27	−0.24	0.01	V
Xingyi-Dushan	−0.41	−0.16	0.30	−0.16	−0.41	III
Chongqing-Guiyang	−0.66	−0.49	−0.58	−0.55	−0.01	V
Qianjing-Huaihua	−0.34	0.17	−0.07	−0.38	−0.58	II
Dushan-Yongzhou	0.09	0.00	−0.50	−0.66	−0.75	I
Zunyi-Wengan-Kaiyang	0.10	−0.22	−0.46	−0.69	−0.80	I
Huangtong-Zhijin	−0.86	−0.81	−0.74	−0.44	−0.11	V
Gui-Zhu	−0.55	−0.30	−0.25	0.03	−0.38	IV

It can be seen from Table 5 that the overall 21 planning railways need moderate or high grade protection, and there are even many railroads need key protection such as the six railroads in V protection grade and the four railroads in IV protection grade. The protection grades of the 21 railways are shown in Fig. 6.
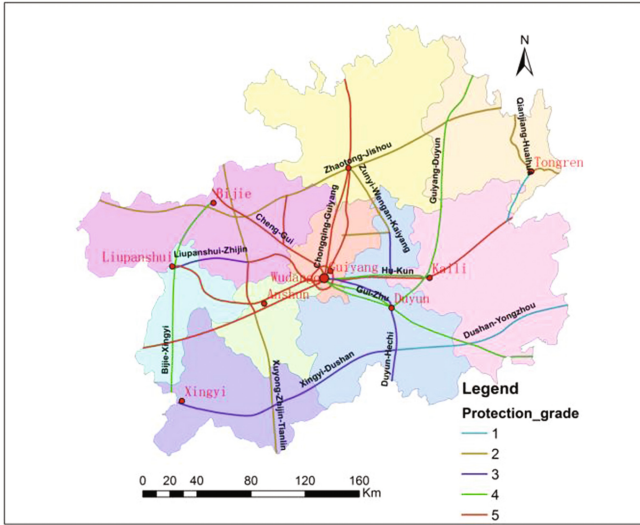
Fig. 6. The protection grade of the 21 railways in Guizhou Province

3.3   Verification of the New Evaluation Method

Among the twenty-one railways, the Hu-Kun railway was in V protection grade, which was the key section to protect. In recent years, Hu-Kun railway area has suffered large amount of geological disasters, and several railway interruption accidents have occurred in Guizhou Province and its surrounding areas. On June 18, 2015, Hu-Kun high-speed railway in Guizhou Province was affected by geological disasters, resulting in the suspension of six multiple unit trains. In July 2014, landslide occurred in the eastern section of Hu-Kun railway, causing 12 h delay of the train. On June 5, 2015, since the heavy rainfall induced landslides, during the railroad broken time, the railway station applied passengers for more than 120 thousand refund or changed tickets. Hu-Kun railway is one of the most serious railroads affected by geological disasters gravely in Guizhou Province. It poses a severe threat to the safety of people's lives and properties and it has an important impact on the traffic safety of Guizhou Province, which are consistent with the evaluation results.

4   Conclusions

1. Competition network model is used to divide the landslide risk mapping into 5 grades. With the increase of risk degree, the distribution of the historical landslide disaster is denser, which indicates that the competition network model is effective and sensitive for the landslide susceptibility mapping.
2. According to the distribution of landslide disaster points on both sides of railway, this paper puts forward the concept of "fitting degree". The greater the fitting degree

is, the closer the landslide disaster points are to the railway line, indicating that the risk of the railway is high, and the higher protection grade will be needed.

3. Extension method is used to calculate the protection grade for planning railway on geological disasters. As establishing the matter-element model, three elements are used: the train speed, fitting degree and the grade of geological disaster susceptibility.

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