Risk evaluation and debris-flow-induced river blocking probability assessment along Duwen highway

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Abstract

On July 10th 2013, due to continuous heavy rainfall in Wenchuan earthquake area, many large-scale debris flows occurred in Taoguan, Qipan gully, as well as in many others places along Duwen highway. Residential areas, factory plants and parts of Duwen highway were destroyed or buried by a large amount of sediments, which also blocked Minjiang river. This caused a direct economic loss of hundreds of millions of RMB. In order to evaluate the risk degree of the debris flows scientifically, in this paper, appropriate evaluation factors are selected to evaluate 6 typical debris flows occurring on 10th July. Grey correlation degree method and entropy method are applied to obtain the weight value of each factor. A mathematical model of risk assessment is established to calculate the risk degree of each gully. For each of the 6 typical debris flow gullies, the evaluating parameters are adjusted accordingly, and the corresponding risk of blocking Minjiang River is also evaluated by using the river momentum ratio to the tributary debris momentum. The calculated results agree well with the actual cases.

Key words: Wenchuan earthquake area, Duwen highway;risk evaluation, river block probability

After Wenchuan earthquake on May 12th2008, the stability of rock soil mass of the shattered mountains is now dramatically reduced in the earthquake area. Landslide and debris flow can be easily induced by continuous heavy rainfall, leading to debris-flow-induced river blocking, or even burst of flood. This will threaten the safety of residents along Minjiang River. Therefore, the risk evaluation on the possibility of debris-flow-induced river blocking is of great importance for effective prevention and control over the debris flow.

In the past research, the essence of the risk assessment has been focusing on the selection and quantization of the evaluation indices and the determination of the weight of those indices. For the determination of the index weight, several methods are generally used, such as Analytic Hierarchy Process (Tie et al., 2006), binomial coefficients(Tao, 1982), grey correlation method(Zou et al., 2003), fuzzy mathematics method(Su et al., 1993), entropy method(Tie et al. 2005), the method of rank correlation coefficient(Chen et al.2013), etc.

The research method of debris-flow-induced river blocking probability includes qualitative analysis(Hu et al. 2009), quantitative calculation(Xu et al. 2002),experimental investigation(Liu et al. 2013), numerical simulation(Wang et al.2005).

In this paper, according to the features of the 6 main debris flow gullies along Duwen highway in Wenchuan earthquake region in July 10th 2013, we use the grey correlation method combined with entropy method to calculate the evaluation index. A mathematics model is established and the risk degree of the debris flow is evaluated. At the same time, combining the character of the region, the blocking probability, i.e., the blocking risk degree of Minjiang river induced by the debris flow, is also evaluated according to the characteristic of the targeted region.

1. The outbreak circumstance of the debris flow

After Wenchuan earthquake on May 12th2008, a huge amount of loose sediments triggered by the earthquake was distributed in the debris flow valley along Duwen highway. The relatively steep slope of the gullies is geographically favorable for the movement of loose solid materials and thus their involvement in debris flow activities. Moreover, frequently occurred debris-flow-induce driver blocking gives rise to a secondary disaster in the earthquake area.

In 2013, a widespread heavy rainfall, lasting from 6th to 10th July, occurred in Wenchuan earthquake region. The intensity of this rainfall reached 104mm/24-hour, which is lower than the expected intensity of “one-in-20 years”. But because the scale of the rainfall at the upstream is much larger than that at the entrance of the gully, the actual average scale of the rainfall is estimated to be larger than the scale of "one-in-50 years".

Affected by the heavy rainfall, over 16 gullies experienced the burst of enormous debris flow, causing tremendous economic losses and casualties. The debris flows also destroyed intercepting dams and drainage canals constructed after the “12-May” earthquake. Part of the sediments rushed into Minjiang river, blocked the watercourse and elevated the riverbed, which brought a potential trouble to the traffic, watercourse and local residents.

Therefore, it is necessary and important to access the risk of debris-flow-induced river blocking in a reasonable and objective way.

2 Selection of the risk assessment index for debris flow

For the selection of the risk assessment index, the following features need to be considered: representative, independent, accessible for measurements and quantification. In this paper, we use the following 6 indices:

(1) Integrality index of the watershed X_1. This index denotes the ratio of the area to the squared length, reflecting the confluence condition of surface runoff. Large value of X_1 corresponds to large scale of peak flow, which is favorable to the formation of debris flows.

(2) The scale of one burst of a debris flow (one in 20 years) $X_2(10^4 m^3)$. This value directly reflects the danger degree of the debris flow. The larger X_2 the larger the potential disaster.

(3) The longitudinal slope X_3 (‰), which represents the initial launching capability of a debris flow gully. The larger the slope, the faster the gully can initially launch a debris flow.

(4)The amount of loose material per unit area $X_4(10^4m^3/km^2)$, representing the distribution density of the loose materials in the watershed.

(5) Averaged annual rainfall X_5(mm).Rainfall is the main cause of debris flow, therefore, large averaged annual rainfall could lead to a high possibility of launching debris flow.

(6) Blockage coefficient X_6 of debris flow. This coefficient denotes the blocking degree of loose materials in a gully. Large blockage coefficient means a large amplification of the gully to the debris flow scale, corresponding to a large potential disaster.

This paper focuses on 6 main debris flow gullies, including Taoguan and Qipan gully, 6 index mentioned above are obtained by analyzing topographic maps and practical out-door investigations. The results are shown in Table1.

3 Establishment of the risk evaluation model

3.1 Grey correlation method

Based on the related theory of grey correlation method (Deng, 1987), the weight of the 6 indices

Table 1Characteristic parameters of the typical debris flow gullies along Duwen highway on July 10th, 2013

The debris flow gully	Integrality index of the watershed X_1	The scale of one burst of a debris flow (one in 20 years) X_2 (10^4m^3)	The longitudinal slope X_3 (‰)	The amount of loose material per unit area X_4 $(10^4m^3/km^2)$	Averaged annual rainfall X_5 （mm）	Blockage coefficient X_6
Taoguan	0.249	108	197	32.4	1,253.1	2.4
Mozi	0.33	67	424	87.5	526.3	2.4
Qipan	0.219	133	192	48.3	528.7	3
Huaxi	0.25	12	287	117.8	598.6	3
Chutou	0.274	60	184	50.6	526.3	2
Zhangjping	0.53	9	317	54.2	1,253.1	2.3

mentioned above can be determined by the following steps:

(1) Combine associated sequence

$$X=\{X_1, X_2, X_3, X_4, X_5, X_6\}$$

$$X_i = \{X_i(1), X_i(2), \cdots, X_i(6)\}$$

(2) Non-dimensionalization.

Depending on practical problems, the dimension of different factors varies. Therefore, Transformation of mean value should be calculated first by using formula (1):

$$X_i^{'}(k) = X_i(k) / \frac{1}{n} \sum_k X_i(k) \qquad (1)$$

Here, *k* denotes the label index of the debris flow gullies, which ranges from 1 to *n*, and *i* represents the label index of the indexes from 1 to *m*.

(3) Sequence of the absolute difference.

The method is as follows:

$$\Delta_i(k) = \left| X_1^{'}(k) - X_i^{'}(k) \right| \qquad (2)$$

(4) Correlation coefficient calculated by maximum and minimum value.

Which is defined by formula (3):

$$\xi_{1i}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_i(k) + \rho\Delta_{\max}} \qquad (3)$$

In this formula, the resolution ratio ρ is taken as 0.5.

(5)Calculation of grey correlation degree

Correlation coefficient is an index describing correlation degree. Take sequence 1 as reference sequence. In order to obtain degree of correlation between comparative sequence X_i and referencesequenceX_1, which is defined as formula (4):

$$\gamma_{1i} = \frac{1}{n} \sum_{k=1}^{n} \xi_{1i}(k) \qquad (4)$$

Then take one of the surplus sequences in turn to be reference sequence, then the grey correlation degree（γ_{ij}）between all comparative factor and analytical factor can be calculated by the above formula.

(6) Weight or factor.

The higher correlation degree, indicating the closer relation with referenced sequence. The weight is defined as follows:

$$w_i = \overline{\gamma(i)} / \sum_{i=1}^{m} \overline{\gamma(i)} \qquad (5)$$

$$\overline{\gamma(i)} = \frac{1}{n} \sum_{j=1}^{n} \gamma_{ij} \qquad (6)$$

Following the above steps, we can calculate the weight of each evaluation factor:

W_1=(0.18，0.153，0.17，0.171，0.168，0.158)

3.2 entropy evaluation method

According to the principle of entropy evaluation method, the evaluation matrix was established, the steps of calculating index weight are as follows:

(1) Standardizing the indicators. Indicators include positive indicators and negative indicators, 6 risk assessment factors chosen in this paper are all positive indicators, which mean that the danger of debris flow is proportional to the indicators. The normalization formula can be written as:

$$a_{ij} = \frac{x_{ij} - \min_i\{x_{ij}\}}{\max_i\{x_{ij}\} - \min_i\{x_{ij}\}} \qquad (7)$$

$$(i = 1,2,\cdots,m; j = 1,2,\cdots,n)$$

The normalized matrix is denoted as $R = (a_{ij})_{n \times m}$.

(2) Calculate the eigen weight $p_{ij}$of the *i*th index below the *j*th evaluate indicators as shown in formula (8):

$$p_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \qquad (8)$$

Table 2Classification of evaluation index and assignment

grade	X_1	X_2	X_3	X_4	X_5	X_6	value
1	≤0.1	≤1	≤50	≤20	≤100	≤1	0
2	(0.1)-0.2	(1)-10	(50)-100	(20)-50	(100)-500	(1)-1.5	0.3
3	(0.2)-(0.3)	(10)-100	(100)-(200)	(50)-(100)	(500)-(1000)	(1.5)-(2.5)	0.7
4	≥0.3	≥100	≥200	≥100	≥1000	≥2.5	1

(3) Entropy E_j ofthe *j*th index is calculated as shown below:

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij} * \ln p_{ij} \qquad (9)$$

In order to gurantee E_j ranges from 0 to 1, $\ln p_{ij}$ was defined to be 0 when p_{ij}equals to 0, then $1-E_j$ is taken as utility value.

(4) Calculate the weight of the jth index usingentropy method, formula is as follows:

$$w_j = \frac{1-E_i}{m-\sum_{i=1}^{m} E_i} \qquad (10)$$

Following the above steps, the weight of the indices can be calculated by Matlab programming:

$$W_2 = (0.171, 0.058, 0.238, 0.120, 0.322, 0.091)$$

3.3 The comprehensive evaluation model and simulations

Based on linear weighting method, the risk assessment model of the debris flow gully is established in this paper. The risk degree of each debris flow gullies is calculated. We first combine these two sets of weights, then classify and assign the 6 evaluate indices according to Table 2 (value in the brackets means it is not included in this degree). Finally we substitute the combination weighting into the risk assessment model, as shown in formula (11):

$$P(i) = \sum_{j=1}^{m} W_j^{*} x_{ij}^{'} \qquad (11)$$

$$W^{*} = uW_1 + (1-u)W_2 \qquad (12)$$

Here, $x_{ij}^{'}$ is the assignment result, P(i) is the calculated value of risk degree.

Take *u* as a half, then the risk degree and risk grade of each debris flow are calculated using the above evaluation model. The results are shown in Table 3:

Table 3Classification of risk assessment

danger grade	classification description	range of each grade
1	mild dangerous	≤0.35
2	intermediate dangerous	0.35-0.60
3	severely dangerous	0.60-0.85
4	extremely dangerous	≥0.85

The debris flow gullies are generally of high danger on the whole under current condition, which is consistent with the actual condition in spot.

4 Debris-flow-induced river blocking probablity

Compared to flood, debris flow is fluid with higher density and viscosity and it contains large amount of huge rocks. After fluid into the river, density current was formed with the river fluid because of the difference from the river in density, Scoured by the river, the debris flow was partly taken away, partly stays in the channel which causes congestion. The main cause of river blocking includes intersection angle between the debris blow gully and the river, the flow rate of the debris flow ratio to that of the river, density of the debris flow, lasting period, solid matter quantity of the debris flow and grain composition etc.

The probability of blocking river is namely the influence degree of the main river by the debris flow.If the energy of the debris flow is greater than that of the main river, then the probability of blocking river is high. The component in the main direction of river width of tributary stream power ratio to that of the main river is taken as the risk degree of blocking river by the debris flow(Xu et al.2002).

$$K = \begin{cases} \dfrac{\gamma_s q J_s}{\gamma_w Q J_w}\sin\theta, \theta \le 90^{\circ} \\ \dfrac{\gamma_s q J_s}{\gamma_w Q J_w}[1+\sin(\theta-90^{\circ})], \theta > 90^{\circ} \end{cases} \qquad (13)$$

Here, *K* is the influence degree on the main river by the debris flow, that is, blocking risk level; q and Q is the peak discharge of the debris flow and river respectively; γ_s, γ_w is the density of the tributary and the main river respectively; J_s, J_w describes the longitudinal slope of the tributary and the main river respectively; θ denotes the intersection angle of the tributary between the main river.

The parameters calculation process is as follows.

4.1 The calculation of the density of the debris flow

After the "12-May" earthquake, a large amount of loose solid material with sufficient provenance was piled up in the debris flow gullies in research area. This kind of debris flow is usually viscous. The density of the debris flow determines the sediment concentration of the debris flow, which is available by formulation and look-up table method comprehensively. The equation of formulation method is as follows:

$$\gamma_s = \frac{G_s}{V} \qquad (14)$$

Here γ_s is the density of the debris flow; G_s is the prepared mud weight with the unit t; V is the prepared mud volume with the unit m^3.

4.2 Peak discharge of debris flow calculation

Peak discharge of the debris flow is the key factor of debirs-flow-induced river blocking. With larger peak discharge, the quantity of sediment entering into the main river per unit time becomes bigger, while the probability of river blocking is higher. The peak discharge of debris flow can be obtained by rain-flood correction or by morphological investigation. When using rain-flood correction, the peak discharge of the debris flow and rainstorm are considered to occur at the same time. The formula is as follows:

$$Q_C = (1+\phi)Q_B \cdot D_C \qquad (15)$$

In this equation, Q_c is the peak discharge of the debris flow with rainfall frequency of P. Q_B is the design discharge of the flood triggered by rainstorm with rainfall frequency of P. $D_C$is the blockage coefficient of the debris flow. ϕ is the mud correction coefficient , the formula is as follows:

$$\phi = (\gamma_C - \gamma_W)/(\gamma_H - \gamma_C) \qquad (16)$$

4.3 Confluence angle and gradient

Intersection angle is generally regarded as the key factor for debirs-flow-induced river blocking, which dominates the effect of debris flow on the main river. The slope is an important index reflecting the debris flow gully and main river energy release, which can be obtained by remote sensing images.

4.4 Water flow of Minjiang river

The average water flow of Minjiang river is ranging from 168 to 268m^3 per second, in flood period, it is about 1890m^3 per second. The debris flows occur successively in the gullies, leading to the river blocking. Using Formula 12 with the above parameter values, the risk of river blocking is calculated, as shown in Table4.

4.5 Conclusions of debris-flow-induce driver blocking probability

In the calculations of river blocking probability, the parameters for the main river and the branch were adjusted accordingly by considering the specific circumstance of each gully. Taking the critical index K=10, we calculated the blocking probability of Minjiang river by the debris flow. The calculated results agree with the practical case occurring on 10th July 2013.

At the entrance of Taoguan gully, huge number of industrial plants and relatively small gully slope make Taoguan gully an ideal place to buffer and store debris flow. Moreover, the debris flow at the upstream blocked Minjiang river, this caused a lift of the river bed at the entrance of Taoguan gully, leading to a faster water flow, thus diluting the debris flow. Therefore, the debris flow at Taoguan gully did not contribute to the blocking of Minjiang river.

The debris flow occurring at Huaxi gully (600meters away at the downstream of Mozi gully)prior to the oneat Mozi gully,blocked Minjiang river and induced water flowing backwards. This reduced the velocity of the water flow of Minjiang river. In addition, highway bridge piers tend to hinder the movement of debris flow as well. Finally, Mingjiang river was seriously blocked with water level lifted by 7 meters, resulting in a complete disruption of G213 and Duwen highway.

For Qipan gully, even with alluvial fanbeing 3300meters long, the burst of materials in debris flow could not be effectively directed to Minjiang river due to a low longitudinal slope of merely 73‰. Over two-thirds of Mingjiang surface was occupied by the debris flow.

After the occurrence of debris flow at Huaxi gully, huge amount of loose materials was washed out and carried to the region between the entrance of the gully and Minjiang river bed. This lifted the river bed close to Dunwen highway. The third bridge in Caopo and the traffic was disrupted. The crashed bridge fell down and lied vertically beneath the bridge of Dunwen highway, leading to a complete blocking of Minjiang river. This accelerated the formation of Minjiang river blocking by

Table 4 Risk level and risk grade of different debris flow gullies

the debris flow gully	Taoguan	Mozi	Qipan	Huaxi	Chutou	Zhangjiaping
Risk degree	0.808	0.814	0.711	0.842	0.7	0.845
Risk grade	**severely**	**severely**	**severely**	**severely**	**severely**	**severely**
Blocking river risk degree	6.1	19.3	17.3	20.1	8.4	18.4
River blocked or not	no	yes	yes	yes	no	yes

debris flow and dammed lakes.

For the debris flow at Chutou gully, one burst of debris flow contains solid materials of about 50000 square and over half of the watercourse was occupied. The mainstream was squeezed to the left and carried away by the upstream flow. The river blocking was not formed.

The upstream rainfall intensity of Zhangjiaping gully is relatively low, the discharge of Minjiang river is later than the debris flow at Zhangjiaping gully, the deposit body caused clogging of Minjiang river and occupied 80 percent of the watercourse width.

5 Conclusions

Based on geologic investigations on 6 typical debris flow gullies and the analysis of the characteristic parameters. the risk evaluation and probability of river blocking were studied. The conclusions are as follows:

(1) According to the characteristics of the debris flows in earthquake area, 6 risk evaluation indices were determined: integrality index of the watershed, rush scale of the debris flow once a time, the longitudinal slope, loose material reserves in unit, Annual mean rainfall, blockage coefficient separately. Among these, the blockage coefficient gives full consideration to the dam break phenomena and the amplification effect caused by the debris flow gullies in Wenchuan earthquake disaster region afterwards.

(2) Combining grey correlation method with entropy value method, the calculated risk degree of the 6 debris flow gullies agrees well with the real case.

(3) The tributary stream power ratio to that of the main river is taken as the risk degree of river blocking by the debris flow. The particular situation of each gully is analyzed, including the rainfall, slope, flow rate of the main river and the blocking effect of plants and piers. The calculated river blocking probability is consistent with the practical situation.

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