

Multi-scale hazard assessment of debris flows in eastern Qinghai-Tibet Plateau area

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Abstract

Process analysis and hazard assessment are essential for the prevention and mitigation of debris-flow hazards in mountainous areas. Many villages and ongoing infrastructure projects in China are vulnerable to large debris flows during heavy rainfall or glacier lake outbursts. Without emergency management planning, such contingencies can lead to extensive loss of life and egregious property damage. In the eastern Qinghai-Tibet Plateau area, debris-flow disasters are a common phenomenon. In this article, we analyzed the spatial distribution, activity and hazard characteristics of debris flows and established a debris-flow database by using geographic information technology. Moreover, we comprehensively analyzed the dynamic process of debris flow at a local scale, the compound effects of debris flows along riverside section and the disaster environment factors of debris flows overall scale of Sichuan-Tibet highway respectively. Accordingly, we built an applicable factor system and a comprehensive framework to quantitatively evaluate debris-flow hazard degree, and then proposed a multi-scale debris-flow hazard assessment method by analyzing typical large-scale debris-flow hazard, debris flows along riverside highway and debris flows in whole traffic corridor, respectively. Especially, with respect to typical large-scale debris-flow disaster, we proposed a dynamic process-based method to analyze debris-flow hazard by using numerical simulation of debris flow, flood analysis, RS and GIS technology. In view of debris flows along riverside highway, we analyzed debris flow process and determined the hazard evaluation indexes and proposed a quantitative method of hazard assessment for debris flow along riverside highways. Regarding to debris flows along whole road, we proposed a quantitative method to analyze the hazard of debris flows and classified hazard levels in the debris-flow prone area along highways. Finally, these proposed methods were applied in case studies in a local scale (K3404 of G318), Xiqu river section and Sichuan-Tibet highway respectively. The results showed that the calculated risk zones consist with the actual distribution and severity of damage of the debris-flow events, which can provide scientific reference for debris-flow risk management and disaster prevention and mitigation of arterial traffic lines.

Keywords: Debris flow; Dynamic process; Hazard prediction; Multi-scale assessment; Qinghai-Tibet Plateau

1. Introduction

The Qinghai-Tibet Plateau, with an average elevation of over 4000 m a.s.l. is often referred to as the roof of our earth, and its mystic and beautiful landscapes have attracted worldwide attention. However, in this region, strong uplift of the Earth's crust creates a complex natural environment, which presents active crustal stress, tremendous elevation difference and dramatic climate change (Dhital, 2015). Large-scale natural disasters commonly occur in the eastern area of the Qinghai-Tibet Plateau. In particular, the formation conditions of debris flows are prevalent, including appropriate lithologic structures and loose materials, and water resource conditions; thus, an increasing number of debris flows seriously devastate local villages and lifeline engineering projects. Therefore, it is vital to develop an accurate evaluation method of debris-flow process and associated hazard in the eastern Qinghai-Tibet Plateau area.

Hazard assessment of debris flow is one of the hottest topics in disaster forecast and disaster prevention, which has gradually being got worldwide attention. Scholars recently have explored various models and methods to

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prevent or reduce debris-flow hazard. In 1957, Scientist C.M. Fowlie Cashman analyzed the jacking force of viscous debris flow body and the relations between initial shear strength and the viscosity in his book *Debris Flow and Road Design in Debris Flow-affected Area*. He did deep research about dynamic experiment and movement mechanism of debris flow (C.M. Fowlie Cashman, 1957). From 1977 to 1988, Scientists in the United States did a cataloging work about road debris flow in California Saratoga, Switzedard area and its northern forest logging area (Ellen and Wieczorek, 1988). Since the 1990's, spatial information technology and computer science provide a powerful technical support in collecting transportation network debris-flow data, which greatly improved the efficiency of analyzing debris flow information and mapping (Carrara et al., 1991). To date, the debris flow investigation and cataloging statistics (Hollingsworth and Kovacs, 1981; Zhong et al., 1988), formation mechanism and experimental observations (Saito, 1969), debris flow physics (Iverson, 1997), the mechanism of debris-flow movement (Takahashi, 1988; Chen, 1988), debris-flow evaluation (Hunger, 1987) and the control technology have made great progress. Some scientists mainly focused on analyzing parameters of debris-flow watershed, which is suitable for hazard analysis of regional debris flow (Hollingsworth and Kovacs, 1981; Smith, 1988; Olivier, 1998). This method has advantages of convenience and strong operation, but is difficult in determining accurate hazardous range of debris flow. Some analyzed debris-flow hazard based on actual field investigation and model test, relationships between debris-flow deposition area and its characteristic parameters, e.g. debris-flow volume, disturbance area of debris-flow watershed (Hunger, 1987; Adachi et al., 1977; Takahashi, 1980; Liu, 1995). This is suitable to analyze debris-flow hazard in areas with the same or similar environmental conditions. Furthermore, through a detailed survey of terrain conditions and physical parameters of debris flow in a debris-flow watershed, scholars simulated movement process of debris flow and identified risk zoning of debris flow (Cui et al., 2011; Hu and Wei, 2005). This method has a better practicability and veracity, but several precise parameters are hardly acquired for determining the debris-flow process. However, the multi-scale hazard assessment of debris flows has not established due to the lack of comprehensive debris-flow theory and method.

In this article, we analyzed complicated debris-flow formation conditions in eastern Qinghai-Tibet Plateau area, and proposed a systematic hazard assessment method of debris flows by combine GIS technologies, mathematics and geosciences models in analyzing the debris-flow hazards at different scales.

2. Methods for regional hazard assessment along Sichuan-Tibet transportation corridor

Debris flow hazard assessment is an important step in debris-flow prevention and risk management. We analyzed the hazard of debris flows on basis of systematic indexes including hill slopes, elevation difference, rocks' shear strength, angle of internal friction, weathering degree of rock stratum, distances to faults, earthquake magnitude, land use types, annual mean temperature, and maximum daily rainfall. Through adopting information acquisition analysis method for the above selected factors, we evaluated the hazard degree of debris flow, and completed debris-flow hazard mapping of Sichuan-Tibet highway with support of GIS technique.

According to the definition of information quantity (Aldo et al., 2002), the occurrence of disaster (Y) is affected by various factors ($X_i, i=1, 2, \dots, n$), which can be expressed as:

$$I(Y, x_1 x_2 \dots x_n) = I_n \frac{P(Y|x_1 x_2 \dots x_n)}{P(Y)} \quad (1)$$

$$I(Y, x_1 x_2 \dots x_n) = I(Y, x_1) + I_{x_1}(Y, x_2) + \dots + I_{x_1 x_2 \dots x_{n-1}}(Y, x_n) \quad (2)$$

where, $I(Y, X_1 X_2, \dots, X_n)$: the amount of information provided by the disaster (Y) is determined by a combination of factors $X_1 X_2 \dots X_n$;

$P(Y, X_1 X_2, \dots, X_n)$: the probability of disaster occurrence under the condition of factor combination;

$P(Y)$: the probability of disaster occurrence.

In the study of mountain disasters, the simplified single factor information model is adopted (Ding, 2013):

$$I = \sum_{i=1}^n I_i = \sum_{i=1}^n \ln \left[\frac{A_i / A}{S_i / S} \right] \quad (3)$$

where, I : the prediction value of one unit information in the study area;

I_i : Factor X_i provides information on disaster occurrence (km^2);

A : the total area of the study area (km^2); A_i : the total area of the unit containing factor X_i (km^2);

S : the total area of disaster unit has occurred (km^2);

S_i : the sum of the unit area of the disaster that occurs in the unit of factor X_i (km^2).

3. Methods for sub-regional hazard assessment along riverside section of highway

Through analyzing the hazard effect modes and damage process along highways, we developed three key indexes, scale of debris flows, deposits on highways and river blockage, to describe the highway disasters quantitatively. These three indexes can be easily quantified and divided into four grades respectively: extreme low hazard, low hazard, middle hazard, and high hazard. Moreover, each grade can be evaluated between 0 and 1 based on their characteristics and survey data from historical events (Table 1).

Table 1 Hazard indexes and hazard grading of highway damage caused by debris flows

Grade	Values of each index	Indexes			
		The total runoff of debris flow (10^4m^3)	Deposit extent of debris flow		River blockage due to debris flow
			Subgrade deposition	bridge headroom deposition	
I	0.0-0.25	<1	0-1/3	0-1/3	<0
II	0.25-0.50	1-10	1/3-2/3	1/3-2/3	0-1/2
III	0.50-0.75	10-100	2/3-1	2/3-1	1/2-1
IV	0.75-1.0	>100	>1	>1	>1

Accordingly, we developed a new method to determine the hazard degree and mapping of debris flow. And the hazard degree of debris flow can be calculated

$$H = H_1 + H_2 + H_3 \quad (4)$$

where, H is the total hazard degree of debris flow, H_1 is the total runoff of debris flow, H_2 is the deposit extent of debris flow, H_3 is the river-blockage due to debris flow.

3.1. Scale of debris flow

The Scale of debris flow is usually indexed by total runoff of a single debris flow which can be calculated by the peak discharge of the water flow and the peak discharge of debris flow.

The peak discharge of the water flow (Q_B) in debris flow gully is calculated through the Eq.(5) which is widely used in Sichuan province (Water Resources Department of Sichuan Province 1984):

$$Q_B = 0.278\varphi \frac{S}{T^n} F \quad (5)$$

where, Q_B is peak discharge of the water flow (m^3/s); Ψ is the runoff coefficient; S is the rainstorm intensity (mm/s); τ is flow concentration time (h); n is the rainstorm attenuation coefficient; F is the catchment area(km^2).

The peak discharge of debris flow is calculated by combining the peak discharge of water flow and the soil supplement, especially channel blockage by debris, as following equation (Zhou et al.1991):

$$Q_c = (1 + \varphi_c) \times Q_B \times D_U \quad (6)$$

where, Q_c is the peak discharge of debris flow (m^3/s); Q_B is the peak discharge of the water low (m^3/s); D_U is the blockage coefficient, shows the quantity of landslide deposits in the channels, normally taken 1~3; φ_c is correction coefficient of debris-flow peak discharge, $\varphi_c = (\gamma_c - \gamma_w) / (\gamma_s - \gamma_c)$, and γ_c is debris-flow density (t/m^3); γ_w is water density (t/m^3); γ_s is solid matter density (t/m^3).

The total runoff of a single debris flow is calculated by applying the empirical Eq.(7) (Ou et al.2006).

$$Q_t = 152.97 Q_c^{1.266} \quad (7)$$

where, Q_t is total runoff of a single debris flow (m^3) and Q_c is peak discharge of debris flow (m^3/s).

3.2. Debris-flow deposition parameters

The mud depth and deposition range of debris flow are critical parameters to identify debris-flow hazard. Applying debris-flow hazard prediction method (Liu, 1995), the parameters the deposition area, the maximum deposition length, and the maximum deposition depth can be calculated by using the following models (Liu, 1995; Chen et al. 2011):

$$\begin{aligned} S_d &= 38.41(V_c G \gamma_c / \ln \gamma_c)^{2/3} \\ L_d &= 8.71(V_c G \gamma_c / \ln \gamma_c)^{1/3} \\ h_d &= 0.017[V_c \gamma_c / (G^2 \ln \gamma_c)]^{1/3} \\ V_c &= (\gamma_c \gamma_w) Q_c / (\gamma_s \gamma_w) \end{aligned} \quad (8)$$

where, S_d is the deposition area of single debris flow (m^2), L_d is the maximum deposition length(m), h_d is the maximum deposition depth (m), V_c is the maximum volume of supplementary loose debris(m^3), Q_c is the peak discharge of debris flow (m^3/s), G is the deposition slope($^\circ$), γ_c is the density of debris flow (t/m^3), γ_w is water density (t/m^3); γ_s is solid material density (t/m^3)

3.3. Degree of river blockage

According to deposition parameters of a single debris flow, river blockage degree can be calculated by the following equation:

$$H_3 = (L - l) / B \quad (9)$$

where, H_3 is the river blockage degree of debris flow, if $H_3 \geq 1$, debris flow completely blocks the river, H_3 is equal to 1. L is the maximum deposition length of debris flow (m), l is the distance between river bank and the mouth of debris flow gully(m), B is the river width (m), the parameters B , l can be calculated from topographic data.

4. Methods for local hazard assessment of debris-flow inundation

4.1. Numerical approach for modeling debris-flow processes

Flow velocity is a key parameter for identifying the impact force of a debris flow, while the flow depth can reflect the silting hazard (O'Brien et al., 1993; Kienholz, 1999; Rickenmann, 2001; Wei et al., 2006). When discussing debris-flow deposits, the debris-flow motion equation includes three important variables: mud depth, the x -velocity component, and the y -velocity component,

$$\begin{aligned} \frac{Du}{Dt} &= gS_{xx} - gS_{fx} \\ \frac{Dv}{Dt} &= gS_{yy} - gS_{fy} \end{aligned} \quad (10)$$

where, u and v are x -component and y -component velocities respectively (m/s), g is acceleration due to gravity(m/s^2), S_{xx} is the bottom slope of the deposition area in the x -direction ($^\circ$), S_{yy} is the bottom slope of the deposition area in the y -direction($^\circ$), S_{fx} is the friction gradient of the debris flow in the x -direction ($^\circ$) and S_{fy} is the friction gradient of the debris flow in the y -direction($^\circ$).

The model treats debris-flow masses as aggregates of many small particles, each of which has its own mass and velocity. To solve Eq. (2) numerically, Hu et al. (2005) improved the particle model originally developed by Wang et al. (1997), while Cui et al (2011b) discussed the method and approximated the debris-flow movement by using the forward difference for each particle. The difference equations can thus be expressed as

$$\begin{aligned}\frac{u_k^{n+1} - u_k^n}{\Delta t} &= gS_{sx}^{n,k} - gS_{fx}^{n,k} \\ \frac{v_k^{n+1} - v_k^n}{\Delta t} &= gS_{sy}^{n,k} - gS_{fy}^{n,k}\end{aligned}\quad (11)$$

where, u_k^{n+1} , v_k^{n+1} are the values of u and v for the k -th particle at time $n + 1$, respectively, and u_k^n , v_k^n , $S_{sx}^{n,k}$, $S_{sy}^{n,k}$, $S_{fx}^{n,k}$, and $S_{fy}^{n,k}$ are the values of u , v , S_{sx} , S_{sy} , S_{fx} , and S_{fy} for the k -th particle at time n .

4.2. Method for local hazard analysis

Hazard analyses of debris flows provide information on the hazard activity. This analysis assesses the debris-flow hazard degree which is useful in land utilization, urban planning, road-line selection and disaster mitigation management. With the development of debris flow motion equations and computer technology, numerical simulation provides an efficient and quantitative approach for such hazard analysis.

Besides the impact and silting hazards caused by individual debris flows, large-scale debris flows also have the following particular characteristics: a) Debris flows occurring upstream of a township may cause a river blockage, resulting in a dam-breaking flood. b) A debris flow blocking a river downstream area will create a barrier lake that will cause inundation loss.

In order to analyze the hazard characteristics of debris flows, we propose a systematic and quantitative hazard analysis method supported by numerical simulation of debris-flow movement.

Considering the compound characteristics of debris flow and its following hazards including burying hazard by debris flows, inundating hazard by dammed lakes and scouring hazard by outburst flood and torrent flow, the model of hazard assessment was established and the proposed model is expressed as

In order to analyze the hazard characteristics of debris flows occurring in a group around mountain townships, we

propose a systematic and quantitative hazard analysis method supported by numerical simulation of debris-flow movement and flood analysis. The proposed model is expressed as

$$H = H_e + H_h + H_i + H_f \quad (12)$$

where, H is the total hazard degree, H_e is the hazard caused by the impact force of the debris flow indexed to the maximum kinetic energy value in each grid during the whole debris-flow movement process, H_h is the hazard caused by debris flow silting indexed to flow depth, H_i is the inundating hazard of the barrier lake indexed to the inundated backwater depth, and H_f is the dam-breaking flood hazard indexed to the highest water level of the flooding.

5. Results

5.1. Study site

In this article, the Sichuan-Tibet transportation corridor, which is the most significant transportation corridor in the western mountain areas of China and connects the provincial capital cities of Sichuan and Tibet, is severely affected by debris flows. The Xiqu River section of the Sichuan-Tibet Highway is located in the Hengduan Mountain area of the eastern Qinghai-Tibet Plateau and is taken as a study area to analyse the hazard characteristics of debris flows. In this section, Haitong Watershed is located at right bank of Xiqu River. The highway from Chengdu to Lhasa is situated at the left bank of Xiqu River in this site. Haitong Watershed is characterized by the shape of quasi-rectangle and has 5 major gullies with V-shape and the mountain slope of 20~40°.

5.2. Regional hazard assessment along the Sichuan-Tibet transportation corridor

Through adopting information acquisition analysis method in session 2.1, the hazard degree of debris flow was evaluated, and debris-flow hard mapping of Sichuan-Tibet highway was completed with support of GIS technique (Figure 1). The proposed method divides the hazard degree along the highway into 5 levels: very low, low, medium, high and very high. The high hazardous areas along G318 Sichuan-Tibet highway are mainly located in the medium,

high, very high levels, which account for 71.99% of the whole highway area. They are located in the canyon area of Dadu River, Jinsha River, Lanchang River, Nu River and Palongzangbu River. Referring to these areas, the debris - flow prevention project should be strengthened in road construction and land designing. While the very low hazardous areas are relatively small, accounting for only 4.21%, which are located in the sections of Chengdu plain area and Tibetan plateau area. The analyzed results above are consistent with results from the actual debris flows situation along Sichuan-Tibet highway. Thus, this hazard evaluation results are suitable for providing debris-flow risk analysis and line selection for new road.

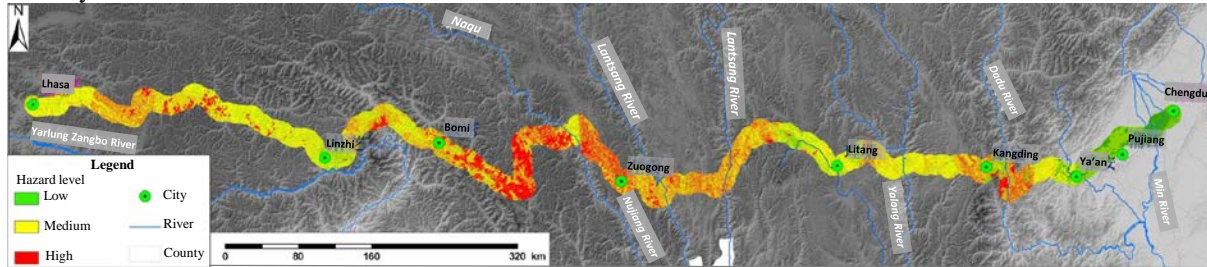


Figure 1 Hazard zonation map of debris flows along G318 Sichuan-Tibet Highway

5.3. Sub-regional hazard assessment along the Xiqu section of the Sichuan-Tibet highway

Applying Eq.(4), hazard degree is calculated in Xiqu section of Sichuan-Tibet highway. The calculated hazard values fall in the range of 0.75 ~2.75. According to the natural divided points as data analysis for zonation mapping with support of natural breakpoint method, the hazard degrees are graded into 3 grades as low hazard, medium hazard and high hazard. The results are shown in Figure 2. After analyzing debris-flow hazard for the whole highway, the total length of highway in high hazard area is 11.35 km, 24.34 km in medium risk area, 21.91 km in low hazard area, respectively. Furthermore, the length of highway in high hazard area is accounted for 19.7% of total length of highway, located in the No.6 highway maintenance squad and the section from the No.4 highway maintenance squad to Haitong army service station where the advantageous conditions (major faults pass through, loose mass and large longitude) give privilege to form large-scale debris flows; the total length of highway in low low area is located in the west section of the No.6 highway maintenance squad, the section between Xiqu River power station and Dongla Mountain, and the exit area of Xiqu River, where debris flows bring little damages for highway.

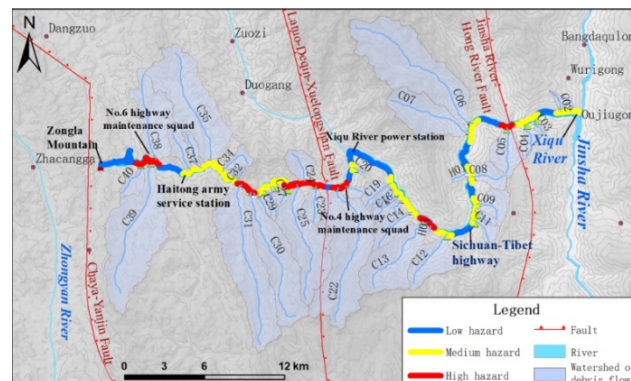


Figure 2 The hazard map of the Xiqu section of Sichuan-Tibet highway

5.4. Local hazard assessment of debris flow in the Haitong watershed

The large-scale debris flow occurs on June 23th, 2012 and its following hazards seriously destructed G318 Highway. Debris flows delivered about 10,000m³ sediments and formed a deposition fan with the length of 230m along river, the width of 100m and the average depth of 7~8m, the peak depth of 11m. The highway at the opposite bank was directly buried about 230m by debris-flow deposits. Moreover, debris flow blocked Xiqu River and produced a dammed lake of 100 000 m³ reservoir volume with the length of 300m, the average width of 60m and the mean depth of water 8-10m. The water of dammed lake submerged about 160m highway at the upper of the dam.



Figure 3 Landscape of Haitong Watershed after 6.23 large-scale debris flows
(a. Taken in June 2012, Deposition dam:200m length, 100m width and 6-8m depth; b.Taken in Sept. 2013)

The parameters of the debris flow on June 23, including velocity and discharge which were obtained from the cross-section at the outlet and material components from deposit sample test, were input into a dynamic movement model of debris flow to simulate and analyze deposition process and result(Figure 4). Then hazard of debris flow was implemented using the formulae (12). The result showed that the influenced and endangered highway was about 820m, and 380m, 330m and 110m was in high-danger zone, middle-danger zone and low-- danger zone, respectively (Figure 5), and those in middle--danger zone and high--danger zone covered 86.5%. The destructed highway on site was about 860m and the total of the buried and submerged highway was about 650 m, which agreed with those from simulated model. Therefore, the models for movement simulating and risk assessment strongly benefits to prediction and prevention and reduction of risk and mitigation of debris-flow hazards.

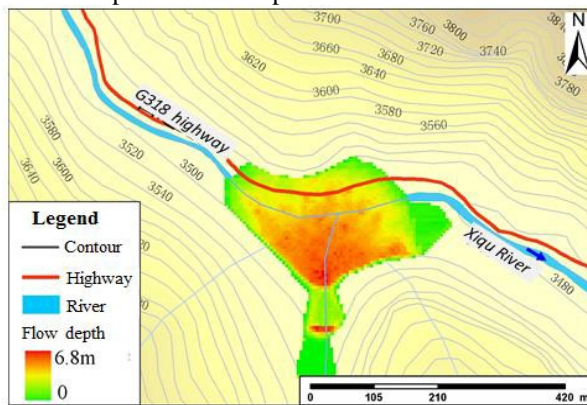


Figure 4 Dynamic simulation result of debris flow in the outlet

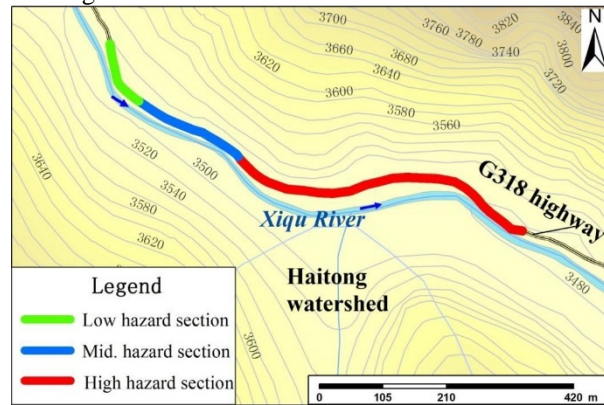


Figure 5 Risk map of debris flow in Haitong Watershed

6. Summary and Conclusions

The Sichuan-Tibet highway and railway are the main traffic trunks line in the western mountain areas of China. Unfortunately, this road has long been severely affected by debris flows. The steep terrain, numerous unconsolidated soil produced by complex lithology and hydrologic meteorological, and the high intensity rainfall are very conducive to the formation of large scale debris flow. Various types of debris flow are widely spread along the major road, which strongly affect road safety.

We have analyzed the spatial distribution, activity and hazard characteristics of debris flows. Moreover, we comprehensively analyzed the dynamic process of debris flow at a local scale, the compound effects of debris flows along riverside section and the disaster environment factors of debris flows overall scale of Sichuan-Tibet highway respectively. Accordingly, we built an applicable factor system and a comprehensive framework to quantitatively evaluate debris-flow hazard degree, and then proposed a multi-scale debris-flow hazard assessment method.

The high hazardous areas along G318 Sichuan-Tibet highway are mainly located in the canyon area of Dadu River, Jinsha River, Lanchang River, Nu River and Palongzangbu River. Referring to these areas, the debris-flow prevention project should be strengthened in road construction and land designing. Among them, the Xiqu River section of Sichuan-Tibet highway was seriously affected by debris flow. The large-scale debris flow on June 23, 2012 at Haitong Watershed was composed by the hazard chain including flash flood, debris flow, dammed lake and outburst flood. The risk assessment based on dynamic model indicated that the high-danger zone and middle-danger

zone occupied 86.5%, where were buried by debris-flow deposits or submerged by the following dammed lake, which agreed with the actual. According to the characteristics, hazards and risk of 6.23 debris flows, the protection measures, including dangerous debris-flow identification, risk assessment, rational route, highway protection, integrated control and emergency plan, were recommended to reduce highway hazards.

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