

Typhoon-triggered Debris Flow Hazard Prediction in Southeast Mountain Area in Zhejiang Province

Yiming Wang^{1,2,*}, Kunlong Yin¹

¹China University of Geosciences, Wuhan, China

²The 11th Geological Brigade in Zhejiang Province, Wenzhou, China

*Corresponding author e-mail: wzwym@139.com

Abstract. This paper presents a debris flow hazard prediction procedure for different prediction stages. At preliminary prediction stage, Melton ratio (R) is applied to predict the debris flow basing on its linear connection with debris flow occurrence frequency during Typhoon Rananim. At detailed prediction stage, a factor-combined model is brought in to predict the hazard degree. The prediction procedure is applied to 14 typical debris flows in southeast mountain area in Zhejiang Province, the results conform to the characteristics of typhoon-triggered debris flows in study area.

1. Introduction

Typhoon-triggered Debris Flow refers to the debris flow directly caused by the typhoon rainstorm. In the past, typhoon-triggered debris flow have caused severe disasters. On August 13, 2004, for example, Typhoon Rananim landed Zhejiang province and hit the northern mountainous area of Yueqing. It caused heavy rainfall and triggered group-occurring debris flows and other kinds of landslides in Longxi Township, and Xianxi Township, leading to death or disappearance of 42 people [1].

In the early 1970s, Japanese scholars such as Tokuyama started to do some researches on how to predict the hazard of debris flow basing on geomorphic conditions, types of debris flow and precipitation [2]. Such researches began in the late 1980s in China. Among them, comprehensive assessment method of the severity of single-gully debris flow proposed by Bingyan Tan [3] and multi-factor comprehensive assessment method proposed by Xilinx Liu [4] are the represents. Fortunately, significant progress can be witnessed in the field of the hazard degree of debris flow after nearly 30-years development. The prediction methods have gradually developed from the initial classification score model, classification assignment model, to the function assignment model [5], and from qualitative, semi-quantitative to quantitative. In spite of this, domestic and foreign researches seldom focus on typhoon-triggered debris flow hazard degree.

In this paper, a debris flow hazard prediction procedure is introduced at different study stages. At the preliminary prediction stage, it is based on the connection between debris flow occurrence frequency and a topographical index. At detailed prediction stage, a model is based on combinational factors and information entropy theory. The hazard prediction procedure is applied on 14 typical typhoon-triggered debris flows in the southeast mountain area of Zhejiang province.



2. Geological background of the study area

Wenzhou is located on the southeast of Zhejiang province. It borders Fujian to the south, and looks out to the East China Sea on its eastern coast. Its land area is 11784 km², of which mountainous area is about 9152 km². Its coordinate is 119°37' ~ 121°18'E, 27°03' ~ 28°36'N. At the end of 2016, there were 8182,000 registered residents and 9175,000 permanent residents.

The study area belongs to the southern branch of Kuocang Mountain. The altitude of its highest point (Baiyunjian) is 1611m. Its geological structure belongs to the northern part of Wenzhou-Linhai depression, southeast Zhejiang fold zone, and south China fold system. In this area, folds seldom develop, but fracture structure develops well on a large scale, and regional crust is stable. The whole area is a large area of Mesozoic volcanic rocks -- upper Jurassic continental volcanic rocks and lower Cretaceous volcanic-sedimentary rocks.

Wenzhou belongs to subtropical marine monsoon climate zone. Typhoon-triggered rainstorm and heavy rainstorm mainly occurred during a period from June to November, especially in July, August and September, which account for 88.3-97.2% and 85.5-96.7% [6] of the whole year's rainstorm and heavy rainstorm. The typhoon-triggered rainstorm and heavy rainstorm occur 1.56-2.27 times and 0.88-1.26 times a year respectively.

Typhoon-triggered debris flows occur frequently in Wenzhou mountainous area, and 258 of them are recorded over the past three decades (figure 1). Most of those debris flows are developed naturally. They are medium or small scale and low frequency. They are rain-triggered dilute-collapse debris flows [7], and occur in both branches of the gully. The catchment area of about 80% of debris flow gully is less than 1 km².

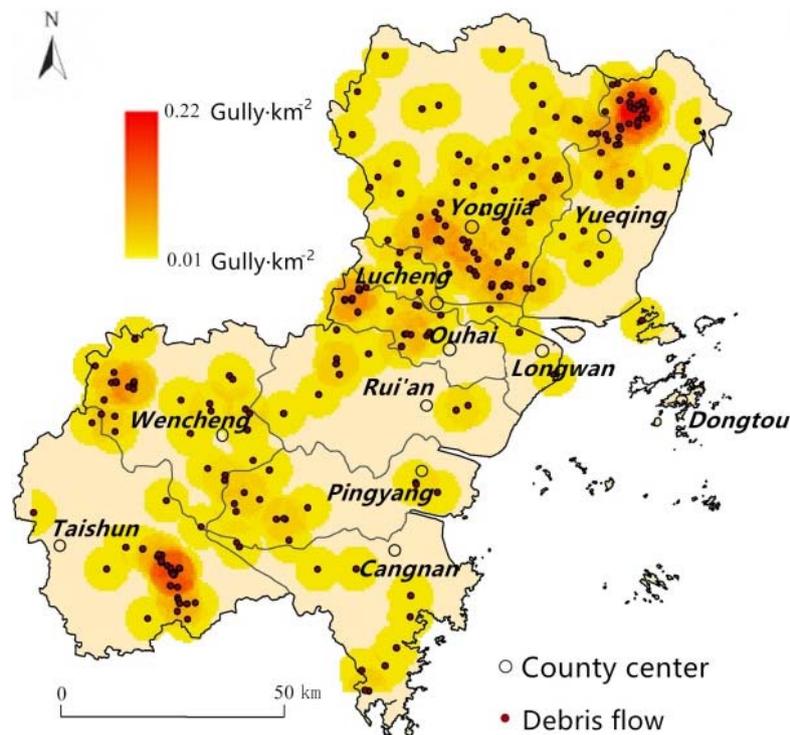


Figure 1. Isodensity map of debris flow in study area

3. Debris flow hazard preliminary predict

Melton ratio(R) is used to preliminary predict the debris flow hazard in the early stage of debris flow protection while filed survey have not been taken.

R was put forward by Melton as early as 1957. After that, Jackson and other scholars (1987) used it to distinguish the debris flow and flood that happened on the Rocky Mountains in southern Canada for

the first time. If R is greater than 0.3, it is supposed to be a debris flow gully. Otherwise, it is supposed to be a flooding gully. Then Bovis and Jakob (1999) studied the southeastern mountains of British Columbia in Canada, and supposed that a debris flow might occur in the gully where the R is greater than 0.53. Besides, D. J. Wilford and other scholars (2004) regarded the combination of R and L (the length of the watershed) as the best combination of indicators to distinguish debris flow ($R \geq 0.6$ and $L \leq 2\text{km}$), flood ($R < 0.3$) and debris flood in other gullies by comparative study [8]. The correct recognition rate of that combination for debris flow, flood and debris flood is 92%, 88% and 92% respectively [9]. Furthermore, Andrew and Tim (2011), using R to test the typical debris flow on North Island New Zealand, supposed that a gully would have significant activity and accumulation characteristics of debris flow if R was greater than 0.5 [9].

R is a topographical index; the calculation formula is as follows:

$$R = (H_{\max} - H_{\min}) / A_s^{1/2} \quad (1)$$

In the above formula, H_{\max} is the altitude of basin's highest point (km), H_{\min} is the altitude of basin's lowest point (km) and A_s is the basin area (km^2).

108 gullies are selected in about 150 km^2 in northern mountainous area of Yueqing (figure 3). The occurrence frequency of debris flows is counted in different gullies, during the period of Typhoon Rananim, and linear regression analysis (figure 4) is being done at the same time. Regression equation of the occurrence frequency of typhoon-triggered debris flows is as follows:

$$F = 0.4735R - 0.0932, r^2 = 0.7405 \quad (2)$$

In the above formula, F is the occurrence frequency of debris flows during typhoon Rananim, and also represents the debris flow hazard (probability). As to study area, basing on formula 2, the debris flow hazard could be divided into 3 grades:

A. Low hazard. When $R < 0.55$, the frequency of debris flow is rather low, so it is supposed to be low hazard for the gully with a $F < 0.17$;

B. Medium hazard. When $0.55 \leq R \leq 1.00$, the frequency of debris flow is in the medium, so it is supposed to be medium hazard for the gully with a $0.17 \leq F \leq 0.38$;

C. High hazard, When $R > 1.00$, the frequency of debris flow is obviously high, so it is supposed to be hazard for the gully with an $F > 0.38$.

4. Debris flow hazard detailed predict

In this paper, combinational factors are selected as assessment units to carry out the detailed prediction according to the characteristics of typhoon-triggered debris flow. And the key of the research is the selection of assessment factors and the determination of their weights [10].

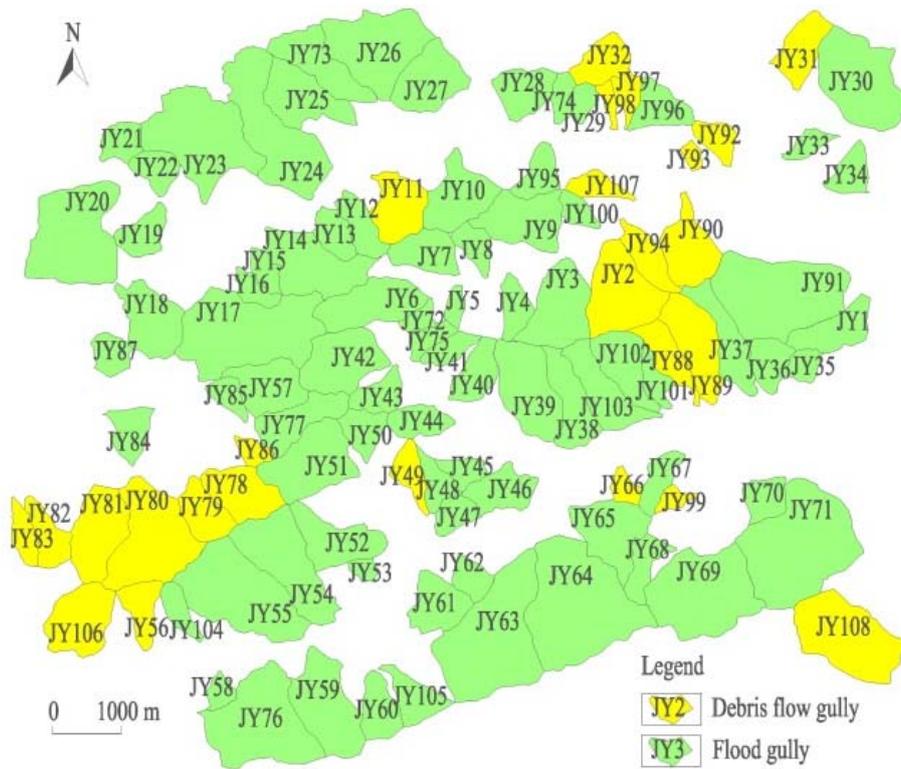


Figure 2. Gully distribution in the northern Yueqing

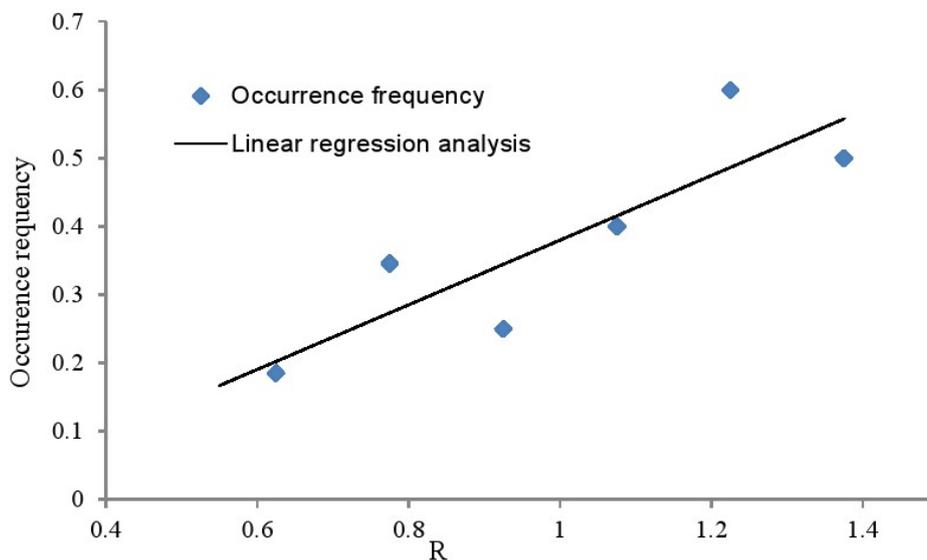


Figure 3. Regression analysis of the debris flow frequency

4.1. Selecting the combinational factors of the debris flow hazard prediction model

Six combinational factors are chosen to predict the debris flow hazard. The debris flow scale (M) reflects solid material accumulation of a debris flow. It can show the ability of the debris flow to transport solid material. The frequency of debris flow (F) refers to the number of debris flows in a unit time. In this paper, Occurrence frequency of debris flow is obtained by Melton ratio (R) in formula 2 indirectly. Gradient (J) reflects the overall slope of the main ditch. Formation zone integral coefficient (C) reflects

the confluence conditions and hydrodynamic characteristics of the basin surface runoff. Typhoon rainfall integrated value (E) reflects the precipitation condition that triggers debris flow in during typhoon. Geological integrated factor (G) reflects the solid materials that are reserved in the gully (table 1).

Among those six combinational factors, the scale (M) and the frequency (F) of debris flow are the main indicators that reflect the hazard degree of debris flow. Gully vertical gradient (J) reflects the terrain condition of debris flow formation. Formation zone integral coefficient (C) and typhoon rainfall integrated value (E) reflects the water condition of debris flow formation. Geological integrated factor (G) reflects the material resources that debris flow composing.

Table1. Combinational Factors of the debris flow hazard prediction model

Code	Combinational Factor (unit)	Formula	Memo
M	The debris flow scale (m ³)	$M=2.035 \times 10^4 \times A^{0.787}$	A is the basin area (km ²)
F	The frequency of debris flow (decimal)	$F=0.4735R-0.0932$	
J	Gradient (dimensionless)	$J=(H_{\max}-H_{\min})/L$	L is main ditch length (km)
C	Formation zone integral coefficient (dimensionless)	$C=A_0/(L_0)^2$	A ₀ is the basin area (km ²) of debris flow formation zone, and L ₀ is the main ditch length (km) of debris flow formation zone
E	Typhoon rainfall integrated value (mm)	$E=B+KI$	B is the total precipitation (mm) of 24 hours before the occurrence of debris flow, I is the total precipitation (mm) of 1 hour before the debris flow, and K is a coefficient valued 5.5.
G	Geological integrated factor (decimal)	$G=1/F_0C_1C_2C_3$	F ₀ is the solid coefficient of rock, which refers to solid coefficient in table 3. C ₁ is the seismic intensity correction coefficient, which refers to the code for seismic design of buildings (GB50011-2010). C ₂ is the fault correction coefficient, which refers to the value in table 4. C ₃ is the weathering correction coefficient.

4.2. Obtaining the weights of combinational factors

The debris flow is an open system with some disorder [11], and the entropy method can make a quantitative analysis to evaluate the confusion degree of a system, objectively evaluate the importance of various factors in the system, which matches the characteristics of debris flow system perfectly. This study adopted the information entropy model to construct the typhoon-triggered debris flow hazard prediction model so that the weight of each combinational factor can be determined.

The entropy method was first proposed by CE Shannon in 1948 and was derived from the concept of thermodynamics, which represented the complex state of the molecules and the uncertainty of the whole system. By analysing the entropy (E) of indicators, the weights can be quantitatively determined - the smaller the E value of indicator is, the more unordered and variable the indicator is, the greater amount of information it can provide, and the greater weight it accounts for; otherwise, it takes up the small weight, which means that it has nearly no impact on the prediction system.

4.3. Classification of hazard degree

The hazard degree of single-gully debris flow can be calculated as follows.

$$H(i) = \sum_{j=1}^n (w_j r_{i,j}) \quad (3)$$

In the above formula: $H(i)$ is the hazard degree of the i^{th} unit, $w(j)$ is the weight of the j^{th} index.

The hazard degree is classified into five grades. H1 ($0 < H \leq 0.2$), H2 ($0.2 < H \leq 0.4$), H3 ($0.4 < H \leq 0.6$), H4 ($0.6 < H \leq 0.8$), H5 ($0.8 < H \leq 1.0$) represent extremely low hazard degree, low hazard degree, moderate hazard degree, high hazard degree and extremely high hazard degree respectively.

5. Application of the predicting model

5.1. Selecting typical gullies

The most representative samples are those typical debris flow events that happen in different areas and different typhoon period. 14 typical debris flows (table 2) that are caused by 7 typhoons after 1999 are selected as the study objects.

Table 2. Typical debris flow gullies in study area

Number	Location	Occurrence time	Typhoon
DG01	Shanggangjing Village, Panqiao Township, Ou hai	1999.9.4	Wendy
DG02	Xiong'ao Village, Quxi Township, Ou hai	1999.9.4	Wendy
DG03	Song'aodi Village, Guoxi Township, Ou hai	1999.9.4	Wendy
DG04	Dakengli Village, Heshen township, Yongjia County	1999.9.4	Wendy
DG05	Xianrentan Village, Xianxi Township, Yueqing	2004.8.13	Ranim
DG06	Shibiyuan Village, Xianxi Township, Yueqing	2004.8.13	Ranim
DG07	Hengshan Village, Xianxi Township, Yueqing	2004.8.13	Ranim
DG08	Menqianyang Village, Xianxi Township, Yueqing	2004.8.13	Ranim
DG09	Gushan Village, Fenglin Township, Yongjia County	2005.8.9	Matsa
DG10	Aoxia Village, Juxi Township, Cangnan County	2006.8.10	Saomai
DG11	Shizhu Village, Shunxi Township, Pingyang County	2015.8.8	Soudelor
DG12	Banxi Village, Sixi Township, Taishun County	2016.9.15	Meranti
DG13	Xixi Village, Sixi Township, Taishun County	2016.9.15	Meranti
DG14	Tieshan Village, Gaolou Township, Rui'an	2016.9.28	Megi

5.2. Preliminary debris flow hazard predict

At the early stage of debris flow hazard prediction, not much field investigation or test have been taken, it is not easy to get every parameter needed to predict the debris flow hazard. But at this stage, it is easy to get the topographical parameters from the topographical maps. All parameters needed to get an R are read from the topographical maps, and their parameters and hazard are listed in the table below.

According to different scales of R, the preliminary debris flow hazard is obtained. Of the 14 typical gullies, 3 of them are high hazard, 10 of them are medium hazard, and just 1 of them is low hazard (table 4).

5.3. Detailed debris flow hazard predict

5.3.1. Weights calculation

The combinational factors of various gullies can be obtained by combining field investigation, remote sensing interpretation with topographic map measurement. Each combinational factor is normalized and the entropy weight of each one is calculated. The calculated weights of combinational factors are shown in table 3.

Table 3. Calculated weights of combinatorial factors

Combinatorial factors	M	F	J	C	E	G
w(j)	0.194	0.167	0.097	0.169	0.087	0.286

5.3.2. Detailed debris flow hazard degree predict

After the normalized combinatorial factor's canonical matrix and weights are substituted into formula 3, the hazard degree of each typical gully is obtained. Of the 14 gullies, 2 of them are high hazard degree, 4 of them are moderate hazard degree, and 8 of them are low hazard degree (table 4).

Table 4. Hazard prediction results of 14 typical gullies

Number	R	Preliminary hazard predict	H	Detailed hazard predict
DG01	1.43	High hazard	0.67	H4
DG02	0.49	Low hazard	0.55	H3
DG03	0.56	Medium hazard	0.60	H3
DG04	0.71	Medium hazard	0.26	H2
DG05	0.97	Medium hazard	0.41	H3
DG06	0.81	Medium hazard	0.30	H2
DG07	0.85	Medium hazard	0.39	H2
DG08	1.18	High hazard	0.68	H4
DG09	0.94	Medium hazard	0.24	H2
DG10	0.57	Medium hazard	0.30	H2
DG11	0.75	Medium hazard	0.37	H2
DG12	1.41	High hazard	0.32	H2
DG13	0.93	Medium hazard	0.42	H3
DG14	0.78	Medium hazard	0.40	H2

5.4. Comparing of the results

In preliminary hazard predict, R is linearly correlation with the frequency of debris flow, debris flow hazard is divided into 3 grades. As to the 14 typical gullies, 3 gullies are predicted as high hazard, 10 gullies are predicted as medium hazard, only 1 gully is predicted as low hazard, considering debris flow have already taken place in the gully, the preliminary prediction results are reasonable. Furthermore, there are 3 gullies preliminary predicted as high hazard, their average detailed hazard degree is 0.56, it is obviously higher than other 11 gullies, which are graded as medium hazard, and their average hazard degree is 0.39. So the preliminary predict could reflect the debris flow hazard preliminarily in study area.

In detailed hazard predict, most geological conditions are considered, and debris flow hazard is divided into 5 grades. All of the 14 typical gullies are classified into low hazard (H2), moderate hazard (H3), and high hazard (H4), there are no extremely high (H5) or extremely low (H1). Among them, DG01 and DG08 are preliminary predicted as high hazard, and detailed predicted as H4 hazard degree. For these two gullies, the preliminary predict and detailed are conformity, and the prediction results are corresponding to reality, as they are the most representative debris flow gullies in the study area, with basin area under 1 km², steep slope, and intrusive rock widely spread in the basin, which is the most debris flow prone rock in the area. Furthermore, 85.7% of the typical gullies are detailed predicted as low hazard (H2) and moderate hazard (H3), respectively 28.6% and 57.1%. This basically conforms to the characteristics of typhoon-triggered debris flow in Wenzhou mountainous area, and is in accordance with the actual situation that debris flows in the area are medium or small in scale, low in frequency. It is difficult to form a debris flow unless a strong rainfall occur there, and even though all conditions are met, the scale of the debris flow is generally small.

6. Conclusion

In this paper, according to different prediction conditions, a debris flow hazard prediction procedure is introduced.

First of all, Given that the debris flows in the study area are low-frequency or extremely low frequency, Melton ratio (R) is applied to preliminary predict the debris flow basing on its linear connection with debris flow occurrence frequency during Typhoon Rananim.

In detailed prediction stage, a factor-combined model is brought in to predict the hazard degree. The combinational factor: including scale of debris flow (M), the frequency of debris flow (F), gully vertical gradient (J), formation zone integral coefficient (C), typhoon rainfall integrated value (E) and geological integrated factor (G) are used to predict the debris flow hazard degree, and the combinational factor's weights can be obtained using entropy method.

The prediction procedure is applied to 14 typical typhoon-triggered debris flows. In preliminary hazard predict, 3 gullies are predicted as high hazard, 10 gullies are predicted as medium hazard, only 1 gully is predicted as low hazard, the results are reasonable. In detailed hazard predict, 2 gullies are predicted as high hazard (H2), 4 gullies are predicted as moderate hazard (H3), 8 gullies are predicted as low hazard (H4), there are no extremely high (H5) or extremely low (H1). The results conform to the characteristics of typhoon-triggered debris flow in Wenzhou mountainous area, and they are reliable for the study area.

Acknowledgments

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