

ASSESSMENT OF HUMAN RISKS POSED BY DEADLY DEBRIS FLOW IN THE WENCHUAN EARTHQUAKE AREA

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ABSTRACT: Prolonged rainstorms had triggered several large-scale debris flows along Provincial Road 303 near the epicenter of the 2008 Wenchuan earthquake. A lot of concrete-aggregate plants distributed along this road were buried by the runout debris, leading to a large number of fatalities. A Quantitative Risk Assessment (QRA) methodology is being developed for debris flows induced by various rainfall scenarios. QRA for these debris flow hazards is of significance to determine the probability distribution, consequence and human risk profile arising from these disasters. With the aid of Geographic Information System (GIS) platform, a potential channelized debris flow catchment in the study area is identified based on remote sensing images and field study. Rainfall intensity-duration thresholds for the local channelized debris flows are used to determine the occurrence probability under six rainfall scenarios for the purpose of hazard analysis. Subsequently, human losses of debris flow are assessed by considering the variations of rainfall events, and the final human risks can be obtained using a general risk model. Finally, the societal human risks are obtained, which provide a benchmark for studying the long-term human risks of these potential debris flows and engineering decision in the perspective of mining manufacture.

Keywords: Debris Flow, Quantitative Assessment, Human Risk

1. INTRODUCTION

Debris flows are among the most frequent mass movement processes in mountainous areas (Kang et al. 2004; Jakob and Hungr 2005), and are attributed to an adequate supply of loose materials, surface runoff, and steep drainage channels (Takahashi 1981).

The 12 May 2008 Wenchuan earthquake in China triggered about 197,481 landslides (Xu et al. 2013). Numerous loose landslide deposits were retained on steep hill-slopes or in channels. Such deposits are in a quasi-stable state in the dry season but can provide source materials for debris flows in the wet season (Tang et al. 2011; Zhang et al. 2012; Zhang et al. 2013; Zhang et al. 2014). In the past four years, three large-scale debris flows occurred in the Pubugou Ravine near the epicentre of the Wenchuan earthquake on 24 June 2008, 14 August 2010 and 4 July 2011. Approximately 1.76 million m³ of sediment was deposited during these three events. It is expected that debris flows will continue to occur in the coming years. Therefore, it is important to evaluate the risks of debris flows so that the potential loss of lives can be reduced in the future.

This research aims to develop a method to obtain the risk profile of mine debris flows along PR303 in Yingxiu area, and to conduct a case study on Pubugou debris flow to illustrate the methodology.

2. STUDY AREA

The Pubugou Ravine is approximately 3.5 km from the epicentre of the Wenchuan earthquake, Yingxiu, in Sichuan Province, China (Fig. 1). The ravine is characterized by rugged mountains and deeply incised valleys. It has an area of 3.06 km² and elevations ranging between 1,100 m and 3,200 m. As shown in Fig. 1, the ravine consists of two sub-basins, namely the Xiezi Gully and the Wuming Gully. The Xiezi Gully extends 2288 m from the gully mouth to the topmost of the stream, having a local relief of 1580 m and a mean channel gradient of 28°. The Wuming Gully ranges from 1100 m to 1920 m, with a channel length of 977 m and a mean channel gradient of 27°.

The exposed lithology within the study area is mainly composed of four kinds of Proterozoic magmatic rocks; namely, diorite, biotitic granite, granodiorite and hornblende diorite. The maximum and mean annual precipitations within the study area are 1225 mm and 828 mm, respectively. Approximately 68% of the total precipitation falls between June and September. Zhang et al. (2012) and Chen et al. (2012) reported field investigations and numerical analysis of the landslide and debris-flow hazards in the study area.

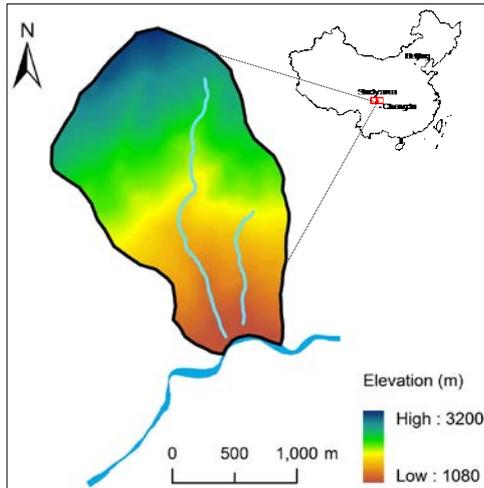


Fig. 1 Location of the study area

3. HAZARDS IDENTIFICATION

During the Wenchuan earthquake, large-scale rock avalanches and landslides took place. A large amount of colluvium was retained on the hill slopes or deposited in the channels (Table 1 and Fig. 2). The landslide scars and the deposition zones together cover more than 50% of the terrain (Fig. 2). The volume of the deposited materials in the Pubugou Ravine was approximately 5.6 million m³ (Table 2). After the Wenchuan earthquake, the hill-slope deposits are at a quasi-stable state under normal weather conditions. Upon a storm event during the rainy season, some of these deposits reactivate, slide down the slope and evolve into channel deposits. Some of the hill-slope materials may also evolve into hill-slope debris flows due to either post-sliding soil movements or bed erosion. The materials in the channels, no matter how far away from the highway, may gradually move to the gully mouth along the channel, which eventually run out as a channelized debris flow under rainstorm conditions. Several concrete-aggregate plants distributed near the gully mouth were buried by the runout debris, leading to a large number of fatalities (Fig. 3).

4. ASSESSMENT OF HUMAN RISKS

4.1 Assessment model

In this section, the risk of debris flow in the Pubugou valley is assessed in terms of the potential loss of lives. The element at risk is taken as the passengers traveling on the road who may be buried by the runout debris should a debris flow event occur. The risk, R , is quantified by

$$R = p_f \times E \times V \quad (1)$$

where p_f = occurrence probability of debris flow; E = element at risk; V = vulnerability related to the run-out distance of the debris.

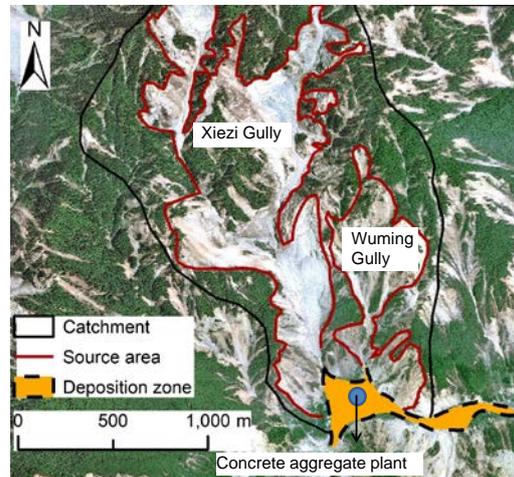


Fig. 2 - Distribution of the source materials within Pubugou Ravine

4.2 Determination of occurrence probability

Rainfall is an essential predictor for the debris flow. It is well known that the correlation between the rainfall and the debris flow is the most widely used method to predict the occurrence of debris flow. Some precious rainfall-induced debris flow data had been collected, a statistical model (rainfall intensity – duration threshold model) is adopted to calculate the occurrence probability.

Logistic regression method is a useful tool for analyzing binary systems. The basic idea to predict the debris flow occurrence probability with logistic regression is to link the observed rainfall intensity and duration, i.e., the debris flow will either occurred or not occurred. The logistic regression model for debris flow prediction can be written based on Eq. (2) as follows

$$P_f = \frac{1}{1 + \exp\{-(b_0 + b_1 \ln I + b_2 \ln D)\}} \quad (2)$$

where b_0 , b_1 , and b_2 are unknown coefficients that can be calibrated using the maximum likelihood method. Based on the post-earthquake data including 27 occurred and 36 non-occurred debris flow cases, values for b_0 , b_1 , b_2 are -7.776, 1.651, and 2.143, respectively.

According to the rainfall threshold model, the debris flow occurrence probability under the six rainfall conditions is obtained (Table 2). The empirical relations are statistically valid and provide threshold rainfalls for issuing warning signals.

4.3 Landslide runout distance

The runout distance of a debris flow is the basis for estimating the element at risk and vulnerability of the landslide (as shown in Fig. 4). When a detailed study is not expected, the runout distance can be estimated using empirical relations. Here the relation proposed by Zhang et al. (2013) is adopted:

$$L_f = 2.04V^{0.18}H^{0.1}e^a \quad (3)$$

where L_f is the predicted runout distance (m); V is the volume of debris flow (m^3); H is the elevation difference of the mass movement (m); ea is a discrete variable, which is expressed using a virtual discrete variable that represents either presence or absence of an attribute; e the natural logarithm base; a is 2.90 (Zhang et al. 2013).



Fig. 3 Runout debris destroyed the concrete aggregate plant near the gully mouth of Pubugou Ravine, and buried the road

Once the runout distance of debris flow is determined, the probability of runout debris reaching the element at risks (P_{L_f}) can be quantified by applying Monte Carlo simulation, considering the uncertainties of the volume of debris flow (Table 2).

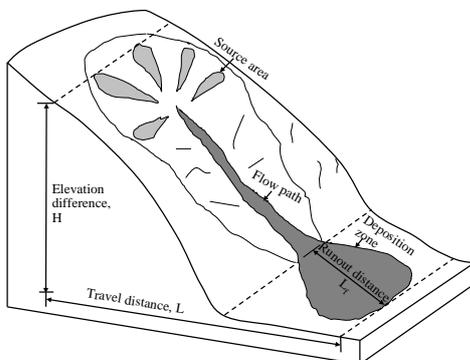


Fig. 4 Parameters related to runout distance of channelized debris flow

4.4 Element at risk during normal operation of the road

The number of people, E , that can be buried depend on the traffic flow and the length of the roads that is buried by debris flows. Assuming a constant traffic flow over the road segment concerned, E may be expressed

$$E = \frac{WTn}{v} \quad (4)$$

where T = vehicles passing through the road per second; W = the length of road that is buried by the collapse of one or several deposits; v = average vehicle speed; n = average number of passengers in one vehicle.

According to the Grade-2 highways design requirements specified for PR303, The value of T is 1/6 vehicles per second and the design vehicle speed is 40 km/h at difficult parts of the road. The number of persons in a vehicle is 2.35, which is obtained during filed statistic analysis.

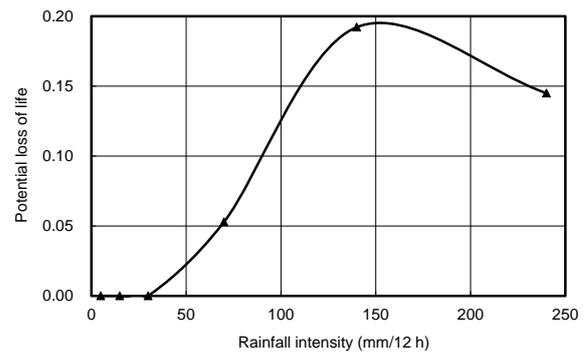


Fig. 5 Relationship between 12 hour rainfall and potential loss of life caused by channelized debris flows in Pubugou Ravine

4.5 Vulnerability

In the study area, the width of the road is 8 m. As shown in Figs. 3 and 4, all the runout material that may run over the road, the calculated runout distance is 104 m. That means that all the debris will bury the road completely. Therefore, it is reasonable to assume that the vulnerability factor, V , is 1.0; i.e., the passengers will be buried once a landslide runs over the passengers (Finlay et al. 1999).

4.6 Risk to human lives

Given the probability of occurrence, element at risk and vulnerability of debris flow, the human risk can be calculated using Eq. (1). The risk is measured

in terms of the potential casualty that could be caused by the debris flow.

Table 1 Volumes of loose materials deposited in channels and hill-slopes

		Xiezi Gully	Wuming Gully
Hill-slope deposits	Number of loose deposits	22	12
	Total area (km ²)	0.64	0.23
	Volume (10 ⁶ m ³)	3.63	1.31
Channel deposits	Total area (km ²)	0.03	0.003
	Volume (10 ⁶ m ³)	0.60	0.06
	Mean width (m)	36	13

The debris flow occurs within a short period so that all vehicles within the landslide area may be buried. In reality, once a debris flow occurred and the road is blocked by the first occurrence of landslide, the rest vehicles may attempt to escape from further landslides.

Table 2 Human risk of debris flow under different rainfall scenarios

Rainfall (mm/12 h)	240	140	70	30
P _f	0.99	0.77	0.12	0.0015
P _{Lf}	0.96	0.74	0.23	0.0006
E	11.75	9.47	7.18	5.12
V	1	1	1	1
R	0.145	0.192	0.053	0

The risks at different rainfall scenarios are summarized in Table 2. The most serious human risk posed by the debris flow is 0.19 under the 140 mm/12 h rainfall condition followed by 0.15 under the 240 mm/12 h rainfall condition. The societal risk can also be graphically presented in the form of potential loss of life (PLL) (Fig. 5). The increment of risk is not significant when the rainfall intensity increases from 5 mm/12 h to 30 mm/12 h rain. However, the risk increases substantially when subject to a rain severer than 70 mm/12 h.

The societal risks of the debris flow under the six rainfall conditions can also be presented in an F-N curve in Fig. 6. One of the advantages of an F-N curve is that it provides additional information on the full range of credible fatal scenarios and the corresponding likelihood of occurrence (Wong et al. 1997). The societal risk acceptance criteria proposed by GEO (1998) are adopted in this paper as a benchmark, which is suitable for a study area with a reference toe length of 500 m or smaller. As shown in Fig. 6, the societal risks of the different rainfall scenarios are mainly located in the unacceptable region.

The impact of the debris flow on the traffic and concrete aggregate plant is significant, potentially involving over 10 casualties in a single slide event. To mitigate the risk, a warning system should be established to reduce the elements at risk when a storm occurs.

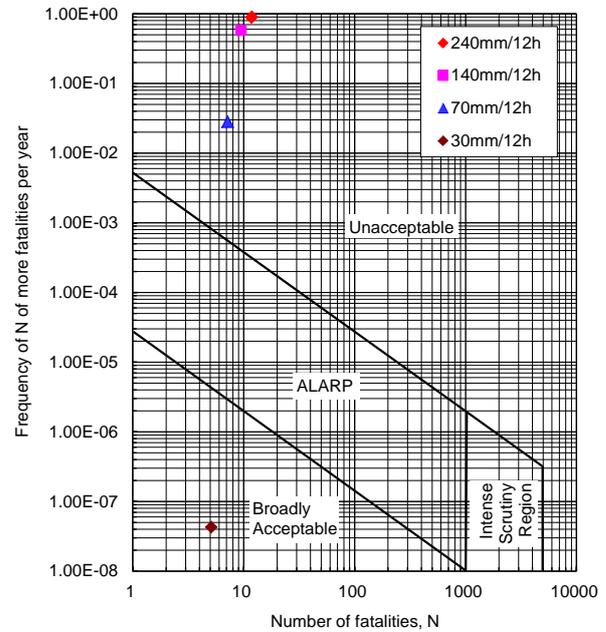


Fig. 6 F-N curves for debris flow in Pubugou Ravine after the Wenchuan earthquake in six rainfall scenarios

5. CONCLUSIONS

The loose deposits formed during the 2008 Wenchuan earthquake on the steep terrains in the Pubugou valley near the epicenter are identified in a GIS platform. These deposits have very high probabilities of failure when subject to a storm and involve into a deadly debris flow. The risks to passengers on the road are also evaluated. Upon failure, the runout debris of debris flow in Pubugou Ravine could run out and beyond the road. Such debris flow could cause over 10 casualties in a single event under normal traffic flow conditions. The human risk under the conditions of 140 mm/12 h is higher than those under the other rain scenarios. Under the extreme rainfall condition of 240 mm/12 h, the failure probability is high and the consequence is very serious. However, the annual frequency is small; hence the final risk reflected in the F-N curve is not the worst. Such risk level is not tolerable; hence risk mitigation measures must be taken and an effective warning system established to reduce the risk level.

6. ACKNOWLEDGMENTS

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