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ORIGINAL PAPER

Annual risk assessment on high-frequency debris-flow fans

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Abstract An empirical model of debris-flow risk assessment is developed to estimate annual loss ratio on high-frequency debris-flow fans where more than one hazard events occur every year. Based on observations of debris flows in Jiangjia Ravine, Yunnan Province, China, it is found that Gamma distribution is more appropriate for describing the annual frequency than the exponential distribution, which is supposed to be a good description of the low-frequency cases. Further analyses reveal that the two parameters of Gamma distribution can be explained, respectively, as the number of factors which dominate debris-flow occurrence and one-third of the mean annual frequency. Given the expectation of loss ratio is unchanged for each event we deduced a simple relationship between the expectations of one-event and annual loss ratios. Combined with the Gamma model, an equation is proposed to calculate the expectation of the annual loss ratio, which can be also used to assess the potential risk of fans formed by high-frequency debris flows.

Keywords Debris flow · Alluvial fan · Risk assessment · Annual loss ratio · Gamma function · Probability model

1 Introduction

With increasing threat to lives and properties, debris flow becomes a major hazard in mountainous regions and is catching more and more attention. Many documents described this geomorphic phenomenon and studied its physical mechanisms or statistical characteristics (Pierson 1980; Li et al. 1983; Costa 1984; Davies 1986; Takahashi 1991; Iverson 1997; Rickenmann 1999; Hungr 2005). Debris flows behave as a mass of viscous and

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highly concentrated fluid–solid mixture including water, clay, gravels, boulders, organic matter (Lancaster et al. 2003), and sometimes air; their occurrence is controlled by three dominant factors: water, slope, and loose material in the headwater region. They can rapidly move on steep slopes or gentle channels and have a great destructive power. Although many features are qualitatively known, there are still controversies on their distinction from other mass movements (Hungr 2005). Roughly speaking, debris flows can be somewhat considered as an intermediate process between landslide and hyper-concentration flow in terms of water and sediment content (Coussot and Meunier 1996). They move down on channel like hyper-concentration flow while they can stop at a slope as steep as 10°–20° (Li et al. 1983).

When debris flows slow down and deposit in the downstream of a ravine because of slope reduction or their depth attenuation, the transported solid materials form a deposition zone, which will develop a wide and gentle alluvial fan as long as such a process repeats many times and the floor at the mouth of the ravine is wide enough (May and Gresswell 2004; Hungr 2005). In many mountainous areas, the fan is a good place for crop cultivation, traffic construction, or house erection even they are exposed to the potential debris flows. However, once a new debris flow occurs, objects on the fan will be destroyed. Recent tragedies in Venezuela (Wei et al. 2000; Wieczorek et al. 2001; Larsen and Wieczorek 2006) exhibited the vulnerability of the infrastructures on fans to this disaster.

An important countermeasure against the dilemma between landuse benefit and possible danger is to assess potential risk on the debris fans. If the risk is evaluated correctly in advance, we can make wise investment or insurance strategies to avoid losses, or reduce the risk to an acceptable level by effective mitigation measures. So far various risk assessment methods have been put forward based on physical, geographical, or statistical models of debris-flow hazard (Budetta 2002; Lin et al. 2002; Archetti and Lamberti 2003; Hofmeister and Miller 2003; Liu and Lei 2003; Wei et al. 2003; Hurlimann et al. 2006; Lin et al. 2006; Miller and Burnett 2008). The geographical risk assessment method incorporates weighted factors such as basin relief, precipitation, watershed area, and fault length into a risk index for regional risk mapping (Lin et al. 2002; Liu and Lei 2003). The physical method depends on flow depth and velocity distributions obtained by hydraulic numerical simulation (Wei et al. 2003). If magnitude–frequency relationship can be estimated reliably from historic records or field investigations, risk analysis can be carried out by using statistical model (Budetta 2002; Archetti and Lamberti 2003; Lin et al. 2006). In addition, there are some multidisciplinary approaches (Hurlimann et al. 2006; Miller and Burnett 2008).

In the previous studies, probability models are usually based on basins of low-frequency debris flows. In fact, there exist many high-frequency debris-flow ravines such as Jiangjia Ravine in China where there is at least one debris flow event each year. In the high-frequency cases, more attention should be paid for the recurrences of debris flow in a certain time interval whereas those models only apply to one single event. In this article, with 1 year as the suitable time interval for economic and disaster cycles, we build a probability model to assess the annual potential risk on high-frequency debris-flow fans. The model includes two parts: the probability model of annual frequency and the model of annual loss ratio, which is defined as the ratio of annual loss caused by debris flows to all the assets on a fan. The former is derived from the recorded data of Dongchuan Station in Jiangjia Ravine from 1987 to 2006, and the latter is based on the assumption that the loss expectation of each future debris-flow event is constant no matter when it happens. This model is believed to provide a specific risk assessment method and help to make a tradeoff between possible benefits and losses on similar debris-flow fans.

2 Study area

The study area, Jiangjia Ravine in Dongchuan, Kunming, Yunnan Province in southwest China, is a branch of Xiaojiang River in the upper reaches of Yangtze River. The basin is of 48.6 km^2 drainage area and 2,227 m of relative elevation. The annual rainfall ranges from 700 to 1,200 mm and more than 80% occurs in the rainy season (from June to September). Complex geological structure, fragile rocks, numerous landslides, and abundant rainfall foster frequent debris flows. The highest annual record is 28 events in 1965. In 1961, the Dongchuan Debris Flow Observation and Research Station was set up, a facility of the Institute of Mountain Hazards and Environment, Chinese Academy of Science. Since 1987, the station has performed regular observations and collected a systematic data of debris flows. The station has one observation building about 200 m away from the middle channel, and set up ultrasonic sensors, radar velocimeter, geophone detectors, and rainfall gauges etc. at different locations of the basin. When the station receives the warning signal from monitoring instruments and the observers on duty confirms the occurrence the full process will be recorded with a manual log or video camera. The measurement data of debris-flow samples show that the density ranges from 1,600 to 2,300 kg/m^3 and the volumetric solid fraction is up to 85%. More details about the study area and its debris flows can refer to Kang and Zhang (1980); Li et al. (1983); Cui et al. (2005). Figure 1 shows the annual number of debris-flow events from 1987 to 2006, which is regarded as annual frequency for rare debris flow occurs beyond the rainy season. The long-term record provides a good opportunity of analyzing debris-flow frequency because of lack of such long-duration observation data in other areas and invalidation of post-event investigation methods such as dendrochronology and lichenometry in estimating annual frequency in high-frequency ravines like Jiangjia.

Debris flows in Jiangjia Ravine have formed a huge fan at the mouth and the junction with Xiaojiang River (Fig. 2). The fan narrows the mainstream channel and yields a convex bank on the planform. Although the river flow is able to carry part of fine solid materials transported by debris flows, the rest materials including coarse and some fine grains deposit nearby the outlet. The flow route on the fan varies constantly because of the superelevation and intense erosion of debris flow. Successive debris flows modify the fan irregularly by intersecting with or overlying on the previous deposition zones. The

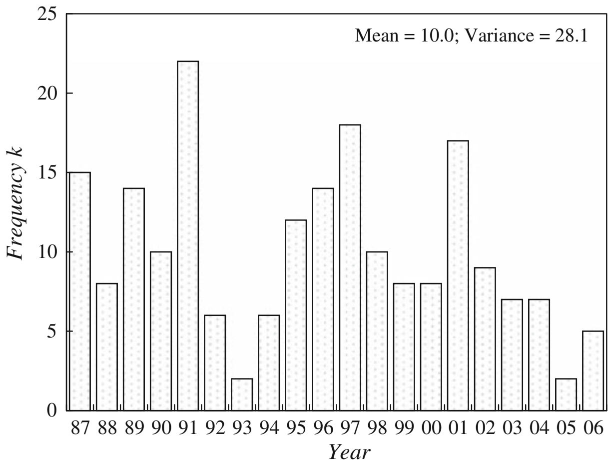

Fig. 1 Annual frequency of debris flows in Jiangjia Ravine from 1987 to 2006. The highest is in 1991, 22 debris-flow events

Fig. 2 Huge debris-flow fan in the confluence of Jiangjia Ravine with Xiaojiang River (face to upstream). Debris flows on August 20th, 2001 in Jiangjia made a serious damage to the crops planted in the alluvial fan by local farmers. The channel width at section A–A′ is about 45.0 m

processes of the fan evolution and channel variation are similar to those described by Field (2001); May and Gresswell (2004). It is difficult to determine the inundation zone by a single event. Instead, we should look at these processes as stochastic and seek for a probability model. In order to do it, the first step is to build a probability model of annual frequency.

3 Probability model of annual frequency

The frequency of debris flows is the key factor of risk assessment. Some studies mainly focused on the relationships between the magnitude and frequency (Steijn 1996; Rickenmann 1999), which are essential not only for risk assessment, but also for engineering prevention. However, in this article, we are only concerned with the annual occurrences of debris flow in a basin. For this purpose, we seek for a stochastic model to characterize the temporal feature of debris-flow events, which can be considered as a series of random points in time dimension. In general, the stochastic process is considered as a good model to describe debris-flow occurrences (Crovelli 2000) though there are some certain special catchments where debris-flow occurrences may be resulted from limited sediment availability or of an important destabilization of the channel and bank stability after a major event and their distribution in time is nonrandom (Zimmermann et al. 1997). Recently, May and Gresswell (2004) introduced the negative exponential distribution as an appropriate model for debris-flow basins in the Oregon Coast Range where the estimated recurrence interval ranges from 98 to 357 years on the assumption that a debris-flow basin has an equal probability of experiencing a debris-flow event no matter how much the time elapsed since the previous one.

However, the exponential model fails to agree with the Jiangjia data (Fig. 3). The mean and variance of the Jiangjia data are, respectively, 10.0 and 28.1 while for exponential

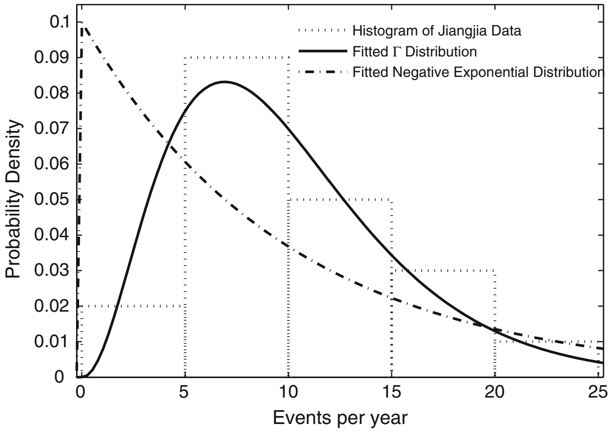

Fig. 3 Histogram and fitted results of Jiangjia data. The bin width in the histogram is determined by Freedom-Diaconis rule and has no effect on the result of Maximum Likelihood Estimation. It is obviously seen that the fitted negative exponential result shows a great deviation from the data

distribution the variance is the square of the mean value. Since the negative exponential, a single-parameter probability density function (PDF), fails to describe the frequency, a two-parameter PDF (namely its expectation is independent of its variance) can be expected to work better. Moreover, the asymmetric histogram in Fig. 3 indicates that some symmetric distributions such as Gauss distribution should be excluded. After testing several ordinary asymmetric PDFs, we find that Gamma function (see Eq. 1) fits best for the Jiangjia data (Fig. 3)

$$f(k; a, b) = \frac{1}{b^a \Gamma(a)} k^{a-1} \mathrm{e}^{-k/b} \tag{1}$$

where $\Gamma(a) = \int_0^\infty \mathrm{e}^{-t} t^{a-1} \mathrm{d}t$ is the Gamma function, k is the frequency, i.e., the number of debris-flow events in 1 year, a and b are, respectively, called shape and scale parameters whose meaning will be discussed later. For Jiangjia Ravine, we obtained $a = 3.2$, $b = 3.1$ by the method of Maximum Likelihood Estimation (MLE). The parameter estimate standard error is 0.973 for a and 1.009 for b, and the 95% confidence intervals of a and b are, respectively, [1.789 5.830] and [1.634 5.865]. The logarithmic value of likelihood for Gamma PDF is −60.48, better than that of −66.05 for negative exponential PDF.

The Gamma distribution reduces to the exponential distribution when $a = 1.0$. That is, the models in the two different regions are not distinct in nature, just of different shape parameter values. In fact, Gamma distribution can be derived from the sum of random variables subject to the same exponential distribution and a is the very number of random variables. Furthermore, an exponential random variable is irrelevant to its history. In the Oregon Coast Range, USA, the volume of sediment and wood stored in the channel has a very strong relationship with the time since the last debris-flow event (May and Gresswell 2003). Only the water content closely related to the precipitation has no dependence on the previous events. However, in the Jiangjia Basin, active landslides are of area of 16.4 km^2, thickness of 15.5–195.5 m, and volume of 1.23 billion m^3 (Hu and Tian 1996). They supply almost exhaustless potential loose mass for the initiation of debris flows. Then the previous events have no effect on the loose material condition. Moreover, the basin has developed so many tributaries that the slopes in the middle and upstream area are in a dynamic balance. Some channels become steeper with erosion, other channels gentler with deposition, but the slope distribution of the whole basin shows no memory of past events.

Therefore, exponential model fits the Oregon Coast Range case because only one factor is of no-memory. However, in the case of Jiangjia Ravine, all the three factors involved by debris flow have no clear dependence on the previous occurrences, so it is subject to the Gamma model with $a = 3.0$, which is close to the MLE fitted result. This implies that the shape parameter a characterizes the basins' contextual settings, i.e., $a = 3.0$ corresponds to high-frequency debris-flow areas where the threshold for debris flow initiation is frequently exceeded and $a = 1.0$ to low-frequency those where the initiation threshold is rarely overrun. Moreover, according to the property of Gamma distribution (its expectation $= a \times b$), the scale parameter in the high-frequency case is

$$b = \frac{E(k)}{a} = \frac{E(k)}{3} \tag{2}$$

where $E(k)$ is the expectation of frequency k. This means that b is equal to one-third of mean annual frequency.

As stated above, the shape parameter is regarded as the representation of different background settings, and we connect the parameter with the number of dominant factors with no-memory property. Although the inference is heuristic to some extent and needs more data to testify, the consequence that the distribution of high-frequency basin is $f(k;\, 3,\, b)$ and the low-frequency is $f(k;\, 1,\, b)$ inspires us that there maybe exists a medium-frequency type where only two dominant factors has the no-memory property and the parameter a is equal to 2.0. The medium-frequency type may be some kind of glacier basins where the water condition depends on past events, but the slope and loose material conditions do not. Certainly, it needs some glacier debris-flow data to verify this supposition.

4 Model of annual loss ratio

Based on the Gamma distribution we will estimate the annual loss on fans by recurrent debris flows. The loss caused by a single event is easy to estimate. The task here is to derive the loss by k events with probability of $f(k;\, 3,\, b)$. In order to avoid the trouble of evaluating real investment or assets on a debris-flow fan, we assume the annual capital variation is zero and introduce the loss ratio, i.e., the ratio of the loss to the assets on the fan.

There are two kinds of loss ratios: the accumulated loss ratio S_k after k events, which is defined as T_k/W; and the one-event loss ratio X_k caused by the kth event, defined as $L_k/(W - T_{k-1})$, where T_k, total loss by k events; W, annual investment or assets on a debris-flow fan, which is assumed to be static and unchanged; L_k, loss by the kth event. It is obvious that $T_k = T_{k-1} + L_k$, from which the following equations can be easily deduced based on the definitions of S_k and X_k:

$$S_0 = 0, \quad S_k = X_k + (1 - X_k)S_{k-1} \tag{3}$$

Taking the expectation on both sides, we obtain

$$E(S_k) = E(X_k) + E((1 - X_k)S_{k-1}) \tag{4}$$

Here, S_{k-1} is uncorrelated with X_k because S_{k-1} is a random variable, which only depends $X_1, X_2, \ldots, X_{k-1}$. Then, Eq. 4 can be rewritten as:

$$E(S_k) = E(X_k) + E(1 - X_k)E(S_{k-1}) \tag{5}$$

Although the real loss of each event is different, the loss expectation of a future event is assumed to be constant because the route and inundating range of debris flow on the fan are random. That is, we assume the expectation of the one-event loss ratio to be constant: $E(X_1) = E(X_2) = E(X_k) = c$. Then Eq. 5 yields:

$$E(S_k) = 1 - (1 - c)^k \tag{6}$$

Combining Eq. 6 with Eq. 1, the expectation of annual loss ratio S can be estimated by:

$$S = E(E(S_k)) = \sum_{k=1}^{K} (1 - (1 - c)^k) f(k; 3, b) \tag{7}$$

where K is the maximum number of debris flow events possibly happened in a year. In practice, K can be cut off at $k = 30$ for $f(k;a,b)$ is very small when $k > 30$, which corresponds to the fact that rarely do more than 30 events occur in 1 year.

In order to observe the influence of b, we plot two c–S curves in Fig. 4, one for Jiangjia Ravine ($b = 10/3$), the other for an imaginary debris-flow ravine with the mean frequency $= 3$ ($b = 1$). One can see that the annual loss ratio nearly approach to 60% even if $c = 0.1$ for the high-frequency ravine. This indicates that for gullies with high-frequency debris flow ($k > 10$, for example), even if c is very small (=0.1), the annual loss ratio will be close to 60%.

Now the question is to determine the one-event loss ratio c (Eq. 7). If the assets such as crops and buildings are uniformly distributed on the fan, c would roughly be proportional to the mean inundated area by debris flows. Intuitively, the inundated area does reflect the mean magnitude of a debris flow, and the larger the inundated area, the higher the loss ratio. If the fan is inundated completely, c should be equal to 1.0, and then S is equal to 1.0 by Eq. 7. However, if there exist a strong frequency–magnitude relationship for a debris-flow basin, i.e., c is related to k, the identical expectation assumption does not hold, and the model of annual loss ratio should be modified. In many regions, where the greater the debris flow magnitude is, the lower its frequency is (Steijn 1996), our model is not appropriate and Eq. 6 has a complex form with the function between c and k.

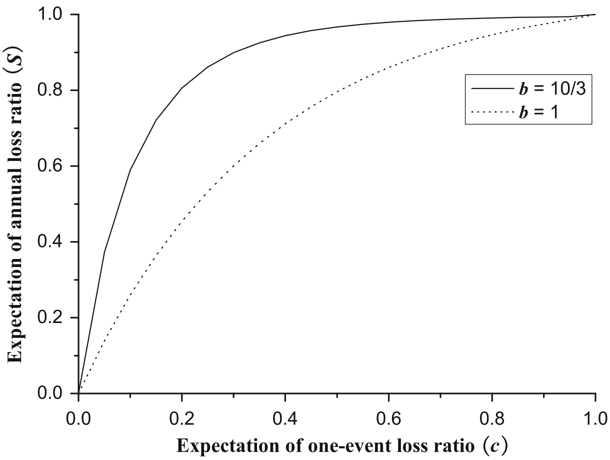

Fig. 4 Curves of the two kinds of expectations calculated from Eq. 7 (k up to 30)

5 Conclusions

This study proposes that the annual loss expectation serves well as the index of risk of debris flows and is used to the risk assessment on the debris-flow fans where more than one event occurs every year. Based on the data of Jiangjia Ravine, we find that Gamma distribution function is quite suitable for modeling the probability characteristic of its annual frequency. The two parameters a and b in the probability model are viewed, respectively, as the number of no-memory dominant factors and one-third of the mean annual frequency. In the low-frequency case, there are only one no-memory factor, and the model reduces to the exponential model. In addition, we develop a simple model to calculate the annual loss ratio by assuming that the expectations of one-event loss ratio are not changed for a certain frequent debris-flow ravine. Combining the probability model with the annual loss model, the annual expectation S can be expressed as the function of frequency with two parameters corresponding to the mean value of magnitude and frequency. The model can be applied to annual risk assessment on the high-frequency fans.

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