

A Probabilistic Prediction Model for Heavy Rain-Caused Landslides in the Chongqing Region*

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ABSTRACT

Landslide (or rockslide) is a geological disaster that is mainly induced by strong precipitation, among a number of other natural inducing factors. Based on 1615 landslide cases, a statistical analysis is performed to find the relationship among the landslide occurrence time, rainfall 0–10 days ahead, and probability of landslides over the Chongqing region. The results show that 1) strong rainfall-caused landslides occur mainly on the day it rains or 1–2 days after the heavy rain, and as time goes on, the likelihood of the disaster reduces rapidly; 2) the heavier the rainfall, the closer the landslide time is to the precipitation time. A concept of “effective precipitation” is thus developed, and a categorical prediction model for heavy rain-caused landslides is established. Tests show that for categories III, IV, and V landslides, the model forecast accuracy arrives at 29.9%, 75%, and 100%, respectively. This indicates that the categorized probabilistic prediction can serve as a warning for the landslide prevention and mitigation.

Key words: strong rainfall, effective rainfall amount, rockslide, landslide, probability, prediction model

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1. Introduction

Strong precipitation-caused landslides (SPL) are common worldwide, and they occur at high frequency, causing serious damage to human life and property. Landslide prediction is a multi-disciplinary issue. In the research of rock-soil mechanics (Wen, 1996), hydro-geology (Tan et al., 1994), meteorology (Liao and Ma, 2000; Shan et al., 2002; Zhou et al., 2000, 2004, 2008), space information science, geographic information systems (GIS) (Xie et al., 2005), remote sensing, and earthquake monitoring (Cui et al., 1998; Wen, 1996), scientists across the world have performed a lot of studies on landslides. Overall, the key of SPL forecasting lies in understanding various relationships between rainfall and landslide occurrence, and the possible aftermaths. The methods used in these studies include the statistical approach, the theoretical

modeling technique, and the mixed statistics-modeling scheme. These methods are applied to forecasts of landslide occurrences on an individual mountain slope or slopes of a mountain range.

An SPL takes place through infiltration of rainwater into a movable surface and loading and lubrication of a large amount of potentially sliding mass. It takes time for the SPL to occur, and a large number of the disasters do not occur on the day of precipitation but one or more days after the strong rainfall. As shown in Lumb (1965), landslides are related to the current 24-h precipitation amount and the prior 15-day accumulated rainfall. Also, the local meteorologists in Chongqing have discovered through their survey that rockslide bears a relation not only to 24-h precipitation but also to 10-day accumulated rainfall before the rockslide, and with which they proposed a prediction model for the SPL based on categories of

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meteorological conditions. The model can be utilized to make 1–3-day probabilistic prediction of landslides according to daily rainfall and 0–9-day cumulative precipitation prior to the landslide (Liao et al., 2000).

Based on 1615 SPL events over the period of 1980–2006 in the Chongqing region, we attempt to explore the relations between strong precipitation and the time, severity, and likelihood of landslides, from which a probabilistic model is developed and can be employed in landslide prevention and mitigation.

2. Data

The 1615 SPL events during 1980–2006 happen over areas of varying degrees of geological vulnerability and the data are offered by the General Chongqing Municipal Geological Environment Monitoring Agency (GCMGEMA). Rainfall data are provided by the Chongqing meteorological network. The data are processed using mainly statistical methods and the function fitting scheme from the Advanced Grapher (version 2.1), which was downloaded from <http://www.serpik.com>.

3. Calculation of the “effective precipitation”

3.1 24-h precipitation related to landslide timing and probability

As stated earlier, some landslides do not occur immediately after torrential rains. Then, what are the relationships of landslide occurrence to the time and

amount of precipitation? Table 1 shows landslide frequencies at 4 intervals of rainfall intensity on days 0–9 after the precipitation (see the last column for the total). It is found from the 1615 landslide cases that 61% thereof happen on the day with >10-mm precipitation, and 75% within 3 days of the occurrence of heavy rainfall (days 0–2), and as time goes on, the percentage decreases rapidly on the whole (see the rightmost column of Table 1).

Landslides rarely occur when the daily rainfall is 0–9 mm so the corresponding percentages are not given in Table 1. It is found that 1) for rainfalls > 25 mm, the frequency of landslides increases in general (e.g., from 9.42 % to 12.50%). For rainfalls within 10–25 mm, landslides occurrences on days 0–1 are higher than cases with rainfalls within 25–100 mm. This is because rainfall events with 10–25-mm precipitation occur the most often in Chongqing. 2) the larger the 24-h precipitation, the closer the landslide occurrence time to the precipitation time. For 24-h rainfall ≥ 100 mm, the landslide frequency is 23.46% on the same day, a figure exceeding those for 25–50- and 50–100-mm daily rainfall (9.42% and 12.50%, respectively). For rainfalls ≥ 100 mm, almost all landslides occur on the same or the next day, implying that strong rainfall strengthens the abruptness of landslides. 3) the intenser the rainfall, the greater the dynamic and static hydro-pressure and the stronger the infiltration, thus accelerating the advent of the landslide, and vice versa for weaker precipitation.

Table 1. Percentages of landslide occurrences under different 24-h rainfall (mm) categories on 0–9 days after the precipitation

	10–25 mm	25–50 mm	50–100 mm	>100 mm	Total percentage
Day 0	15.58	9.42	12.50	23.46	60.96
Day 1	4.23	1.73	1.92	0.96	8.85
Day 2	0.96	4.04	0.19	0.00	5.19
Day 3	1.35	1.35	0.38	0.19	3.27
Day 4	2.50	4.42	0.58	0.19	7.69
Day 5	2.88	1.35	0.28	0.00	5.38
Day 6	1.15	0.38	0.00	0.00	1.54
Day 7	2.31	0.28	0.77	0.00	3.46
Day 8	0.19	1.73	0.19	0.00	2.12
Day 9	0.58	0.96	0.00	0.00	1.54

Day 0 refers to the day when it rains; day 1 means one day after the rain, etc.

By using a negative exponent function and the Advanced Grapher (version 2.1), the rainfall-landslide weighed coefficient (RLWC) can be expressed as

$$\alpha(x) = 0.6096\exp(-1.93 \times x), \quad (1)$$

where x gives the i th day after the rainfall, with day 0 denoting the day of the precipitation, day 1 as one day after the rain, etc., and $\alpha(x)$ (or RLWC) designates the probability of SPL on the i th day after the

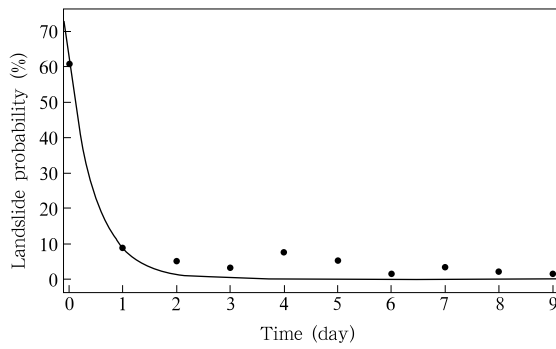


Fig. 1. Function fit of landslide probability on different days after the precipitation.

rain.

The smooth curve in Fig. 1 is a fitting derived from Table 1. The points thereupon denote the statistical evidence (i.e., the frequencies at the rightmost column of Table 1). The fit reaches 99% accuracy. Figure 1 also shows that the intense 24-h precipitation makes greater contributions to landslide occurrences on days 0 and 1, followed by a swift drop as a function of time, which verifies the exponential decrease and indicates the ignorable effects of precipitation on landslide occurrences on the following days.

Further analysis of Table 1 can be made by means of a two-variable function for the relationships among rainfall amount, landslide time, and RLWC, which are fitted via the Advanced Grapher (version 2.1), as shown below,

$$\alpha(x_1, x_2) = (3.017e^{-0.1009x_2} + 0.2253e^{0.01408x_2}) e^{(-0.00006414x_2^{2.193} - 0.8989)x_1}, \quad (2)$$

where x_1 denotes the i th day after the rainfall ($x_1 = 0$ for the day of precipitation; $x_1=1$ for one day after); x_2 signifies daily precipitation (e.g., $x_2 = 50$ mm); and $\alpha(x_1, x_2)$ is the SPL probability to occur at given x_1 and x_2 . The fit by Eq. (2) reaches the accuracy of 92.78%.

Equation (2) displays a time-dependent decline of the landslide probability at a range of daily rainfall categories.

Equations (1) and (2) exhibit a relationship between the rain water at different-intensity permeating into a sensitive part of mountainous or hilly mass and the SPL time. An examination of the RLWC pattern facilitates the study of the SPL mechanism.

3.2 The “Effective Precipitation”

The above analysis shows that intense rainfall has a remarkable effect on causing landslides on the same day but in a successive span of days it exerts varying-degree impacts upon SPL. Hence, the concept of “effective precipitation amount” (EPA) is developed, which defines a multi-day accumulation of precipitation that contributes to an SPL. Obviously, the nearer the rainfall to a given landslide, the greater the contribution it would be. Therefore, an expression is formulated by using the percentage contribution of the multi-day rainfall to a particular SPL multiplied by the associated precipitation total. Through Eqs. (1) and (2), the EPA for a certain landslide is given as follows,

$$R' = \sum_x R_x \alpha(x), \quad (3)$$

$$R' = \sum_x R_x \alpha(x_1, x_2), \quad (x = x_1) \quad (4)$$

where R' represents the EPA of an SPL; R_x is the rainfall on the x day after the first rainfall, with R_0 being the rainfall on the first rainfall day and R_1 the precipitation one day after the first rainfall. The terms $\alpha(x)$ and $\alpha(x_1, x_2)$ are the RLWC on the same day ($x=0$) or several days ($x \neq 0$) after the first rainfall.

Equation (3) is the EPA that takes into account the daily RLWC in a spell of days related to a given landslide while Eq. (4) is the EPA where both daily rainfall amount and the RLWC are considered for a given SPL. Eq. (4) is employed, generally, when rainfall data are more abundant.

3.3 Comparison of RLWC in different geological hazard vulnerable regions

Because vast differences exist in soil and rock properties, slope and landuse features in the studied region, strong precipitation exerts different impacts on landslides from area to area. According to the GCMGEMA, the Chongqing is region is classified into four areas based on their vulnerability to landslides, i.e., almost impossible, weakly possible, moderately possible, and extremely probable. Zhou et al. (2000) showed the RLWC for each of the four areas, and found

that the RLWC experienced almost no big variations as a function of daily precipitation and the number of days prior to the geological disaster, and the RLWC is larger on days 0–3 after the precipitation, and nearly identical starting from day 4 onward. The difference is only appreciable in the first 4 days after the precipitation between the extremely possible landslide area, and moderately or less vulnerable areas.

3.4 Comparison of RLWC between landslides at different scales

To further investigate the landslide hazards with different intensity, the 1615 rockslide events are classified by volume into the following 5 types: micro event (type I, rockslide volume lower than 10^4 m^3), smaller event (type II, 10^4 – 10^5 m^3), moderate event (type III, 10^5 – 10^6 m^3), large event (type IV, 10^6 – 10^7 m^3), and exceptionally big event (type V, higher than 10^7 m^3). Each type of landslides constitutes, respectively, 47.6%, 31.8%, 16%, 4.3%, and 0.3% of the total. And the sum of types I and II (types I–III) makes up 79.4% (95.4%) of the total. Obviously, the first three and especially the first two types are predominant in Chongqing. Figure 2 gives the weighing coefficients for the first four types of SPLs, indicating that the smaller scale the landslide, the nearer the occurrence of the SPL to intense precipitation, and vice versa. That is to say, smaller scale landslides are marked by more abruptness compared to larger-scale rockslides that need more time for rain water to infiltrate into immense-size rocks, leading to more lagged time for the landslide happening. It is obvious that due to

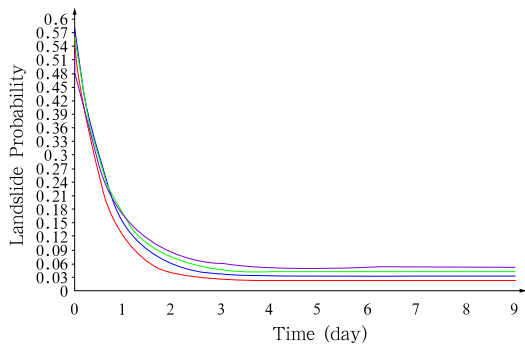


Fig. 2. Weighing coefficients of SPLs at different scales with the microscale in purple, smaller scale in green, moderate scale in yellow, and large scale in blue.

strong rainfall, there is abruptness of landslides at micro, smaller, and moderate scales (particularly the first two types).

4. The SPL prediction model

4.1 The SPL probability category

A categorized probability scheme is used to forecast the SPL in the Chongqing region. According to China Meteorological Administration and Ministry of Land and Resources of China, the probabilistic SPL prediction falls into four levels. But in this study, a 5-level scheme is found appropriate, i.e., category I for landslide probability of 0–10%, II for 10%–25%, III for 25%–50%, IV for 50%–75%, and V for 75%–95%.

4.2 “Effective precipitation” related to SPL

Predicting the SPL probability is based on the EPA calculated from daily rainfall data by using Eq. (3). A statistical relationship is then found between the EPA and SPL. Figure 3 shows a function fit as given in Eq. (5), where $P(R')$ denotes the landslide probability under an EPA of R' . The smooth curve in Fig. 3 exhibits a good fit with observations represented by the black dots. The fit by Eq. (5) arrives at the accuracy of 98.62%. Figure 3 also shows that as the EPA increases, so does the SPL probability, and when the EPA reaches 25 mm, the likelihood is in excess of 50%, and for the EPA of 120 mm, the probability arrives at > 85%.

$$P(R') = 1.348 \times 10^{-4}R'^3 - 0.0334R'^2 + 2.731R' + 6.2. \tag{5}$$

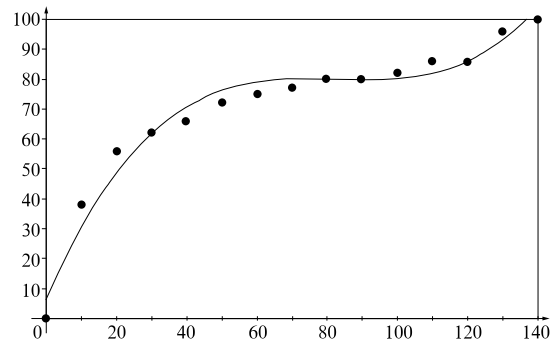


Fig. 3. SPL probability (%) as a function of EPA (mm).

4.3 Construction of the SPL prediction model

The foregoing analysis is employed to construct a categorical model for the SPL prediction. The RLWC is calculated first for each of the four landslide vulnerable regions by Eqs. (1) and (2). Then, the EPA is computed by Eqs. (3) and (4). Further, Eq. (5) is used to get the SPL probability. In line with the Chongqing Municipal Meteorological Bureau, the range of percentage probability is separated into five categories and an SPL model is established for each of the four landslide vulnerable regions. Practice of the SPL model shows that if a rainfall forecast is valid for a longer time, the categorical SPL forecast will cover a longer period as well.

4.4 Validation of the SPL predictions

The disastrous geological events in 2005 were selected to objectively assess the capability of the SPL prediction model.

4.4.1 Procedure

Daily precipitation measurements (0800–2000 BT) at 35 weather stations from April 1 to October 30, 2005 were interpolated onto 890 township-level administrative areas via a distance weighing method, followed by making an SPL categorical forecast out in 24–72 h for each area by using the established SPL prediction model. Afterwards, statistics of 558 landslides was obtained from the Chongqing Regional Department of Land, of which 183 were removed because of no clear records of their time of occurrence. The rest 375 events were put onto corresponding areas for verification of the SPL predictions.

4.4.2 Results

The validation statistics shows that when a lower than category III (exclusive of III) SPL prediction is obtained, practically, no rockslide would occur (1%, see Table 2). At category III, 29.9% of all 890 areas are hit by landslide. The corresponding figures are 75% and 100% for categories IV and V SPL predictions, respectively. These forecasts imply that the category III SPL prediction acts as a reminder, category IV as a warning, and V as an alarm. In comparison, the previously used method of cumulative precipitation gave only the accuracy of 15.6%, invalid rate

of 60.3%, and missing rate of 23.5% for greater than category III SPL predictions out in 24–72 h. This suggests that the introduction of EPA in SPL prediction can improve significantly the forecast accuracy.

Table 2. The SPL categorical predictions in 24–72 h compared with observations

Categorical landslide prediction	Observed percentage of SPL hit areas
<Category III (<25–50%)	1%
Category III (25–50%)	29.9%
Category IV (50–75%)	75%
Category V (75–95%)	100%

4.4.3 Factors influencing the validation

The validation results are affected by the following factors:

- 1) It is hard to get a complete set of SPL areas/times over the studied region. Of the 558 observed events, 183 cases have no happening time. Besides, some SPLs were not reported in dweller-free areas.
- 2) The 35 rain gauge stations are widely scattered over the region of 82,000 km², and for the mountainous and hilly land, each gauge station plays a limited role alone in measuring rainfall for the area, which also affects the validation of the forecast precision.

5. Summary

Based on the above work, the following conclusions are drawn:

- 1) Through a statistical analysis of 1615 SPL events related to strong rainfall happening in a period of 0–9 days in Chongqing, it is discovered that 95.4% of the disasters are medium- and small-scale events marked by strong abruptness. An analysis of the RLWC responsible for SPLs happening on days 0–9 is also undertaken, indicating that 60.96% (75%) of all the rockslides occur on day 0 (days 0–2) after strong precipitation, and as time goes, the SPL frequency decreases rapidly in most cases. In particular, an EPA concept is developed, which is the sum of products of all RLWCs multiplied by rainfall amount before a given SPL.

- 2) Further investigations on the RLWC in relation to stronger precipitation and vulnerable geological environment in the SPL-prone areas show that the heavier the 24-h precipitation, the sooner the rockslide

would be. When the 24-h rainfall is ≥ 100 mm, the SPL happens definitely on day 0 or day 1, illustrating that heavy rainfall is conducive to intensifying the abruptness of landslides.

3) A categorical SPL prediction model is established, which takes into account localized geology and landform, and uses model parameters applicable to local conditions. Validation tests show that the accuracy of landslide predictions at categories III, IV, and V arrives at 29.9%, 75%, and 100%, respectively, thereby indicating a good warning capability of the SPL model in preventing rockslides and minimizing their damage.

4) Variation in RLWC revealed in this study is expected to facilitate the SPL mechanism investigations.

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