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A prediction model for horizontal run-out distance of landslides triggered by Wenchuan earthquake

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Abstract: The peak ground acceleration (PGA), the volume of a sliding mass V, the height of a mountain H_L and the slope angle θ of a mountain are four important parameters affecting the horizontal run-out distance of a landslide L. Correlations among them are studied statistically based on field investigations from 67 landslides triggered by the ground shaking and other factors during the Wenchuan earthquake, and then a prediction model for horizontal run-out distance L is developed in this study. This model gives due consideration to the implications of the above four parameters on the horizontal run-out distance L and the validity of the model is verified by the Donghekou and Magong Woqian landslides. At the same time, the advantages of the model are shown by comparing it with two other common prediction methods. The major findings drawn from the analyses and comparisons are: (1) an exponential relationship exists between L and log V, L and log H_L, L and log PGA separately, but a negative exponential relationship exists between L and log tanθ, which agrees with the statistical results; and (2) according to the analysis results of the relative relationship between the height of a mountain (H) and the place where the landslides occur, the probabilities at distances of 2H/3–H, H/3–2H/3, and 0–H/3 are 70.8%, 15.4%, and 13.8%, respectively, revealing that most landslides occurred at a distance of H/2–H. This prediction model can provide an effective technical support for the prevention and mitigation of landslide hazards.

Keywords: Wenchuan earthquake; landslides; run-out distance; prediction model; relationship

1 Introduction

Earthquake-induced landslides can cause significant damages and losses (Keefer, 1984; Hutchinson, 1987; Sassa, 1996), as seen in many severe earthquakes, such as the 2008 Wenchuan earthquake, the 1999 Chi-Chi earthquake (Khazai and Sitar, 2003), and the 1994 Northbridge earthquake (Jibson *et al*., 2000), etc. In the M_s 8.0 Wenchuan earthquake, thousands of landslides, mudslides and other geological disasters were triggered in Sichuan Province, China. In the 39 severely affected counties only, there were more than 100,000 earthquake-induced geological disasters, covering an area of about 41,750 km^2 (Dai *et al*., 2011), leading to more than 20,000 fatalities (Yin *et al*., 2009), and causing enormous losses.

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In recent years, the prediction of landslides triggered by earthquakes has been a major challenge in the geotechnical community. A variety of prediction models/methods have been proposed, which can be roughly summarized as the following three kinds: (1) empirical statistical prediction models (Sassa,1992; Mankelow and Murphy, 1998; Long, 2008; Huang, 2009), where the statistical formulas, the relationships between the horizontal run-out distance and its influencing factors are deduced from field macroscopic investigations performed following a certain number of landslides; (2) deterministic prediction models (Scheidegger, 1973; Rathje and Antonakos, 2011; Van Westen *et al*., 2008), which are based on the principle of particle dynamics combined with the movement patterns of the sliding mass and the energy conservation law; and (3) numerical simulation prediction models (Jiang and Qiao, 2006; Hungr and McDougall, 2009; Kokusho *et al*., 2011), where the prediction of the horizontal run-out distance, L, is based on numerical simulation using the discrete element method.

Generally speaking, the impacts of the volume of a landslide V, the vertical run-out distance H and the equivalent friction coefficient ($f = H / L$) on horizontal run-out distance L are considered while the effects of the peak ground acceleration (PGA) and the geometric parameters of the mountain are ignored in the prediction models currently used. However, some research results (Wang *et al*., 2010; Jin *et al*., 2011) have shown that the occurrence of landslides is closely related to the PGA and the slope angle. Hence, in this study, the PGA at various landslide hazard points is estimated by a ground motion attenuation model combined with a correction by the measured data from the Wenchuan earthquake, and then a prediction model for horizontal run-out distance is established through nonlinear regression analysis. The prediction model proposed in this study comprehensively considers the impacts of the PGA, the mass volume *V*, the height H_L and the slope angle θ of a mountain, which can provide effective technical support for disaster prevention and mitigation of the landslide hazards.

2 Field investigation of landslide hazards

The field investigation of landslide hazards was conducted mainly in severely afflicted areas, such as Beichuan county town, Wenchuan county town and Qingchuan County in Sichuan Province of China. Sixty-seven typical landslides are selected based on the field investigation, among which 65 landslides are chosen for statistical analysis, and the remaining two, Donghekou and Magong Woqian landslides, are used to verify the prediction model. Among these landslides, the maximum and minimum distances to the fault are 248 km and 1 km, respectively. Correspondingly, the mass volumes are 7.5×10^9m^3 and 2.0×10^3m^3, the slope angles are 57°and 19.3°, the height of the mountain is 1250 m and 40 m, the horizontal run-out distances are 5300 m and 20 m, the equivalent friction coefficients are 1.511 and 0.158, and the estimated values of PGA are 1.015 g and 0.062 g.

3 Influential factors of the horizontal run-out distance and their relationships

There are many factors that affect the horizontal run-out distance *L*, the impacts of the geometric parameters of a mountain (height H_L, slope angel θ), the mass volume *V* and the PGA in terms of the magnitude *M* and epicentral distance *R* on the horizontal run-out distance, which have been widely recognized (Sassa,1992; Mankelow and Murphy, 1998; Miles and Keefer, 2000; Scheidegger, 1973; Rathje and Antonakos, 2011; Kokusho *et al.*, 2011). Figure 3 shows the influential factors of the horizontal run-out distance, where H_L is the height of a mountain, *V* represents the volume of a sliding mass, *L* and *H* are the horizontal and vertical run-out distance of a landslide, respectively, and θ represents the slope angle.

3.1 Relationships between the *V* and the horizontal run-out distance *L*, the vertical sliding distance *H*

Extensive explorations have been done regarding the implications of mass volume on run-out distance. Based on a study of the relationship between *L* and *V* for 25 landslides in Southern Italy, Budetta and De Riso (2004) indicated that there is a positive correlation between the distance *L* and the volume *V*. The study of Zhang (2009) on the equivalent friction coefficient *f* of loess landslides triggered by the Haiyuan earthquake in Southwest China and rainfall-induced landslides in other parts of China showed that there is a negative correlation between mass volume *V* and equivalent friction coefficient *f*, and from statistical analysis of the relationship between *V*, *L* and *H* in the 65 landslides triggered by the Wenchuan earthquake, found that both log*V*-*L* and log*V*-*H* have

Fig. 1 Overview of the Donghekou landslide

Fig. 2 Field investigation

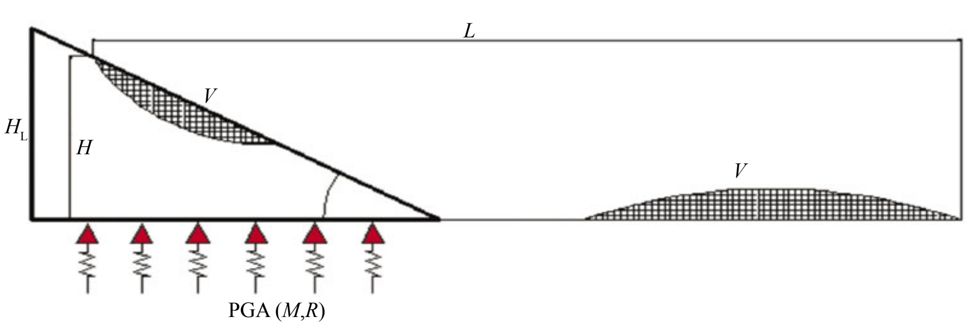

Fig. 3 Influential factors of the horizontal run-out distance

separate exponential relationships. The results are shown in Fig. 4 and Fig. 5.

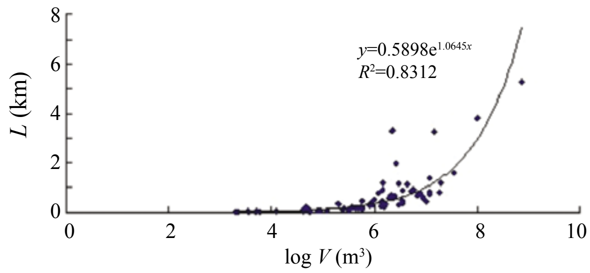

Fig. 4 Relationship between log*V* and *L*

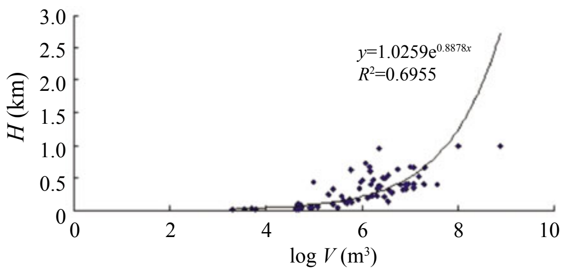

Fig. 5 Relationship between log*V* and *H*

3.2 Relationship between tan *θ* and equivalent friction coefficient *f*

More research has been carried out to investigate the effects of a mountain itself on the horizontal run-out distance *L*. Okura *et al.* (2000) found that there is a positive correlation between the equivalent friction coefficient *f* and the slope angle *θ*, which is consistent with the research results by Li and Kong (2010) through statistical analysis of 46 landslides in the Wenchuan earthquake. At the same time, Li and Kong (2010) also discovered the square of the correlation coefficient is 0.7973. In short, the research above shows that a mountain itself has a significant influence on the horizontal run-out distance *L*. In this research, the relationship between the tangent of the slope angle tan *θ* and the equivalent friction coefficient *f* is studied and a statistical analysis of the 65 landslides triggered by the Wenchuan earthquake is carried out. The results show that there is a linear positive correlation between *f* and tan *θ* and the correlation coefficient is 0.7, which is close to the correlation coefficient obtained by Li and Kong (2010) as shown in Fig. 6.

Meanwhile, the statistical results also show that the probability that landslides will occur in the location of $2H_L/3 - H_L$ of a mountain is 70.8%, for $H_L/3 - 2H_L/3$ it is 15.4%, and for $0 - H_L/3$ it is 13.8%, which illustrates the phenomenon that most landslides occur in the location of $H_L/3 - H_L$ of a mountain, as shown in Fig. 7.

3.3 Ground motion attenuation model

The selection of ground motion is critical to the establishment of an earthquake-induced landslide

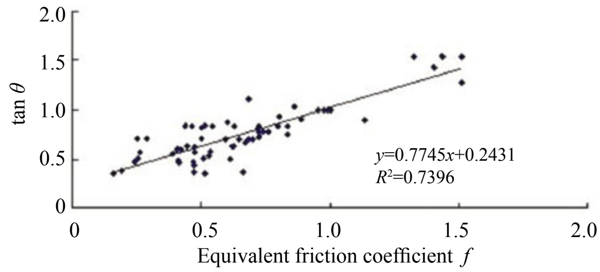

Fig. 6 Relationship between tan *θ* and *f*

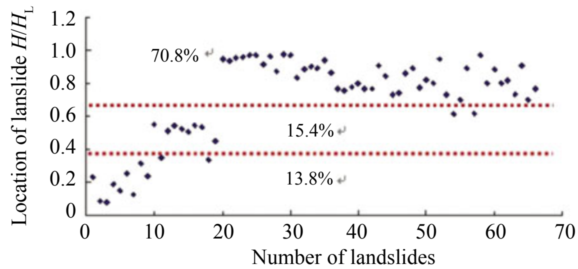

Fig. 7 Location of a landslide in a mountain

prediction model. However, due to the lack of measured ground motions, the impact of ground motion has not been considered in most landslide prediction models. In this study, the PGA at each landslide hazard point is estimated by using the ground motion attenuation model.

Zhao *et al.* (2010) established a spectral acceleration attenuation model based on a large number of earthquake records, as shown in Eq. (1). Lu *et al.* (2010) accomplished a comparative study of the Zhao attenuation model with the Next Generation Attention attenuation model proposed by (Lu *et al.*, 2010; Boore, 1983; Campbell, 1985; School and King, 1984) and found that the former is more accurate in the prediction of PGA and spectral acceleration in the near-field region than the later. Hence, Zhao's attenuation model, corrected by the measured data, is employed in this study to obtain the PGA at each of the landslide hazard points. The procedures are described in the following paragraphs.

First, the predicted value of PGA for 131 seismographic stations located in the Sichuan Province are calculated using the Zhao's attenuation model, and then the residual error is derived by comparing the predicted values with the measured ones. The distribution of the residual error with the distance to the fault is shown in Fig. 8.

Second, a trend line for that distribution is obtained by using the linear regression method, as shown in Eq. (2).

$$\begin{cases} \ln \mathrm{PGA} = \ln(f(M,R)) = aM_{wi} + bx_{i,j} - \ln(r_{i,j}) + \\ \quad e(h-h_c)\delta_h + F_R + S_L + S_S + S_{SL}\ln(x_{i,j}) + C_k + \xi_{i,j} + \eta_i \\ r_{i,j} = x_{i,j} + c\exp(dM_{wi}) \end{cases} \tag{1}$$

$$y = 0.001242x - 0.059721 \quad (2)$$

where the relevant parameters in Eq. (1) are detailed in Zhao *et al.* (2010), x is the distance to the fault (unit: km), and y is the logarithmic residual error of PGA.

Finally, the amended attenuation model can be achieved by adding Eq. (2) to the Zhao's attenuation model.

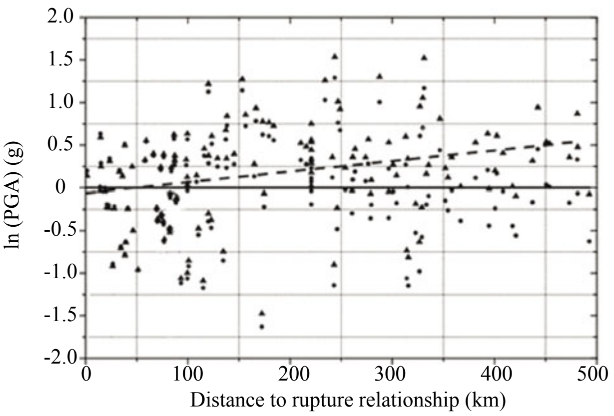

Fig. 8 Logarithmic residual vs. the distance to rupture relationship

3.4 Relationship between the PGA and the horizontal run-out distance *L*

Based on the latitudes and longitudes of each landslide hazard point and the location of the fault, the distances between the fault and the landslide point corresponding to each hazard point can be computed; then, the PGA at each point is available by using the amended attenuation model. The relationship between the PGA and L is shown in Fig. 9.

Note that there is a positive linear relationship (R^2=0.4037) between log L and PGA ; i.e., an exponential relationship between the PGA and L. It is noteworthy that the correlation coefficient R^2 between PGA and L is relatively low, which may be attributed to the small number and extensive distribution of the measuring points. In particular, many other parameters that have a significant influence on L in addition to the PGA can be ignored.

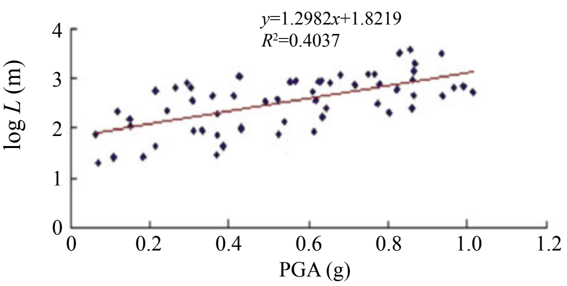

Fig. 9 Relationship between the PGA and the horizontal run-out distance *L*

4 Prediction model of the horizontal run-out distance *L*

From the above correlation analysis, it is known that both L – log$V$ and L –logPGA have separate exponential relationships. Because of the exponential relationship between L and log$H$ and the linear relationship between H and H_L, an exponential relationship exists between L and log (H_L+A), wherein A is a constant (Jiang and Qiao, 2006). Similarly, there is a linear relationship between log L and log (tanθ-B), wherein B is a constant (Sassa, 1992; Mankelow and Murphy, 1998). The prediction model can be derived through multiple linear regression analysis, as shown in Eq. (3).

$$\log L = \alpha \log(H_L + A) + \beta \log V + \delta \log(\tan\theta - B) + \mu f(M, R) + \eta \quad (3)$$

where L is the horizontal run-out distance (m), V is the volume of sliding mass (m^3), H_L is the height of the mountain (m), $f(M,R)$ is the PGA (g), M is the magnitude; R is the epicentral distance (m), θ is the slope angle (°), and η is the constant term.

The solutions can be derived from regression analysis: α=0.2018, β=0.3699, δ=-0.1132, μ=0.3598, η=-0.40922, A=-40, B=0.325, the standard deviation of log$L$ is 0.026, and the residual error plots are shown in Figs.10-13. Consequently, using the prediction model, the horizontal run-out distance of a potential landslide can be predicted and the area that may be affected by the landslide hazards can be determined, which has important practical significance.

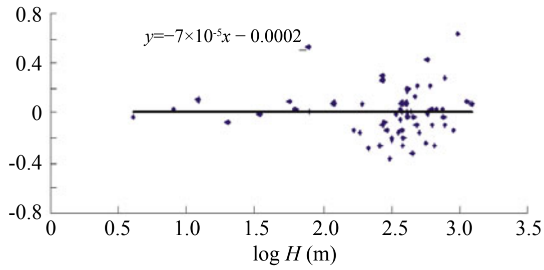

Fig. 10 Distribution of the residual error with log*H*

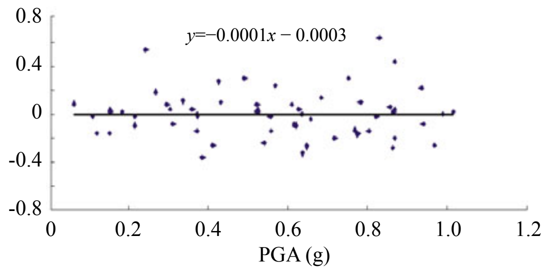

Fig. 11 Distribution of the residual error with PGA

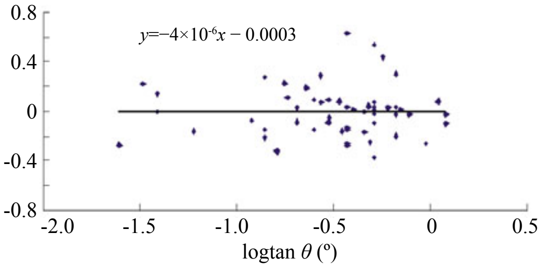

Fig. 12 Distribution of the residual error with log (tan θ)

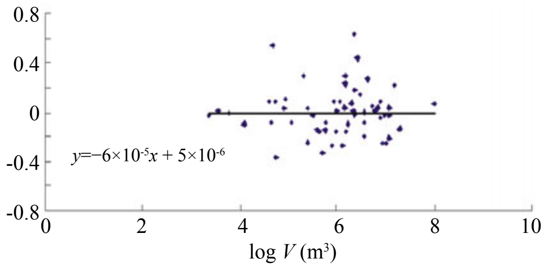

Fig. 13 Distribution of the residual error with log$V$

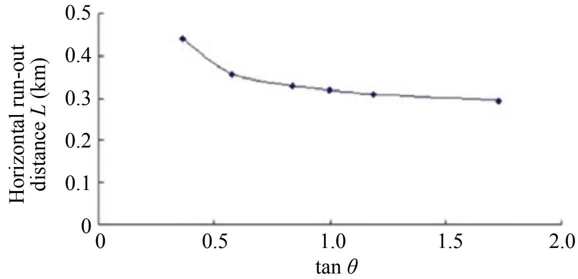

Fig. 14 L vs. tan θ

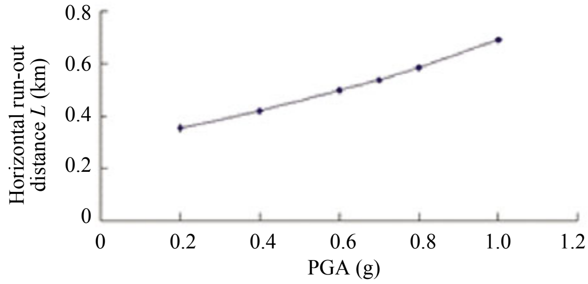

Fig. 15 L vs. PGA

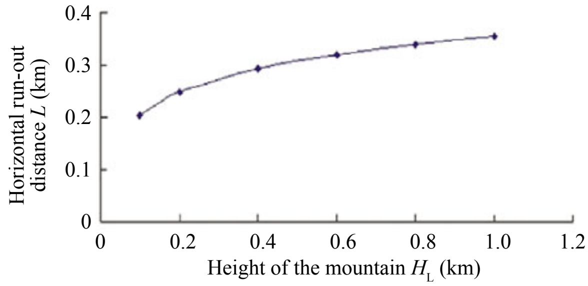

Fig. 16 L vs. H_L

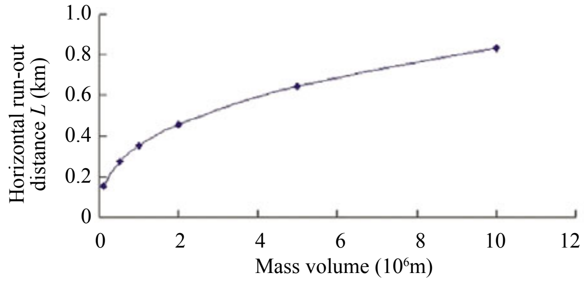

Fig. 17 L vs. V

5 Parametric studies of the prediction model

In order to explore the effects of the four important parameters separately on the horizontal run-out distance L , four groups of parametric studies are conducted based on the prediction model proposed in this paper. The parameter values are as follows:

Group 1: For the effect of the mass volume: V=1000, 500, 200, 100, 50, 20, and 10 (unit: 10,000 m^3), and
θ=30°, H_L=1000 m, and PGA=0.2g;

Group 2: For the effect of the slope angle:θ=20°, 30°, 40°, and 45°, and
V=10^6 m^3, H_L =1000 m, and PGA=0.2g;

Group 3: For the effect of the mountain height: H_L =1000 m, 800 m, 600 m, 400 m, 200 m, and 100 m, and
θ=30°, V=100 (unit: 10,000 m^3), and PGA=0.2g;

Group 4: For the effect of the PGA: PGA=0.2g, 0.4g, 0.6g, 0.7g, 0.8g, and1.0g, and
H_L =1000 m, θ=30°, and V=100 (unit: 10,000 m^3).

The results for the different groups are shown in Figs. 14-17.

Figures 14-17 indicate that the horizontal run-out distance L is positively correlated with all the PGA, H_L and V separately, but negatively correlated with tanθ, which is consistent with the statistical results from the field investigation of the Wenchuan earthquake landslide hazards.

6 Case analysis of the Donghekou and Magong Woqian landslides

In order to verify the prediction model proposed in this study, it is applied to other landslides, i.e., both the Donghekou and Magong Woqian landslides that also occurred during the Wenchuan earthquake and are located within Qingchuan County of Sichuan province, China. The values of the four important parameters measured by different field investigators are listed in Table 1. Note that the values of each of the parameters measured by different field investigators differ slightly. The PGA at the Donghekou and Magong Woqian landslides, estimated by the amended attenuation model, are 0.934g and 0.956g, respectively.

In order to prove the validity of the proposed model, a comparative study was carried out. The results from the proposed model are compared with the measured and predicted values by using the empirical method and the method proposed by Hiromu (1989) as shown in Table 2. Note that the results obtained by the empirical method

Fig. 18 Donghekou landslide (Fu *et al.*, 2012)

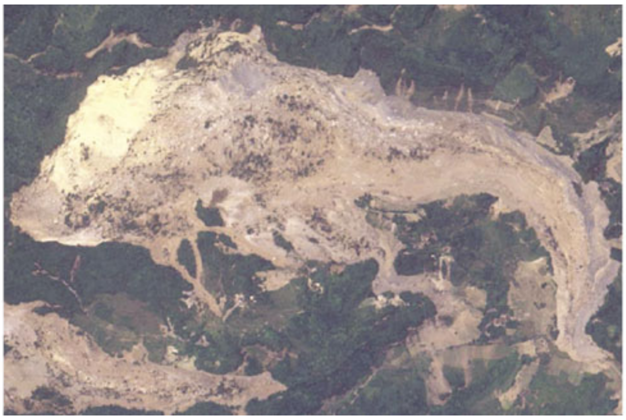

Fig. 19 Magong Woqian landslide (Zhang, 2009)

Table 1 Relevant parameters of the Donghekou and Magong Woqian landslides measured by different field investigators

Parameters	Donghekou landslide			Magong Woqian landslide	
	Authors of this paper	Sun Ping *et al.* (2010)	Fu Rong (2012)	Authors of this paper	Zhang Wei (2009)
Height of the mountain (m)	1610	1500	1330	1950	1870
Average slope angle (°)	41	45	39	38	35
Volume of the sliding mass ($10^6 m^3$)	15	/	15	12.1	12
Horizontal run-out distance (m)	2200	2400	2450	1880	1960

Table 2 Comparison of the measured and predicted horizontal run-out distances of the Donghekou and the Magong Woqian landslides

	Donghekou landslide			
	Measured value	Proposed model	Empirical method	Hiromu Moriwaki method [$(\Delta H_1/L)$=0.73tan α-0.07]
Horizontal run-out distance (m)	2200	2023	960	921.8
Absolute deviation (%)		8.05	56.36	58.1
	Magong Woqian landslide			
	Measured value	Proposed model	Empirical method	Hiromu Moriwaki method [$(\Delta H_1/L)$=0.73tan α-0.07]
Horizontal run-out distance (m)	1880	1960	1400	1469
Absolute deviation (%)		4.26	25.53	21.86

Note: ΔH_1 is the elevation difference between the leading edge and the trailing edge of the landslide; α is the slope angle

and the Hiromu Moriwaki method differ markedly from the measured values, which can be attributed to the large differences between the applicable conditions of these methods from the actual ones in the Wenchuan earthquake. Conversely, the deviation of the proposed model is only 8.05% (Donghekou landslide) and 4.26% (Magong Woqian landslide), which demonstrates a high-precision; therefore, the proposed model can reasonably predict the horizontal run-out distance L.

7 Conclusions

The peak ground acceleration (PGA), the volume of sliding mass V, the height H_L and the slope angle θ of a mountain are four important parameters that affect the horizontal run-out distance of a landslide L. Correlations among them were studied statistically based on field investigations of 67 landslides triggered by the Wenchuan earthquake, and then a prediction model for horizontal run-out distance was developed in this study. This model gives due consideration to the implications of the PGA, the mass volume V, the height H_L and the slope angle θ on the horizontal run-out distance and was verified by the Donghekou landslide event and the two other prediction methods. Finally, a parametric study of the prediction model proposed in this study was carried out. The following conclusions can be drawn:

(1) An exponential relationship exists between L and V, L and H_L, L and PGA separately, but a negative exponential relationship exists between L and tan θ.

(2) The statistical results show that the probability that landslides will occur in the location of $2H_L/3$– H_L of a mountain is 70.8%, and for $H_L/3$–2 $H_L/3$ it is 15.4%, and for 0 – $H_L/3$ it is 13.8%, which illustrates the phenomenon that most landslides occur in the location

of H_L /3 – H_L of a mountain.

(3) The amended attenuation model proposed in this study is able to reasonably estimate the PGA of the landslide hazard point.

Acknowledgement

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