



Empirical prediction for travel distance of channelized rock avalanches in the Wenchuan earthquake area

Weiwei Zhan, Xuanmei Fan, Runqiu Huang, Xiangjun Pei, Qiang Xu, and Weile Li

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, 610059, China

Correspondence to: Xuanmei Fan (fxm_cdut@qq.com)

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Abstract. Rock avalanches are extremely rapid, massive flow-like movements of fragmented rock. The travel path of the rock avalanches may be confined by channels in some cases, which are referred to as channelized rock avalanches. Channelized rock avalanches are potentially dangerous due to their difficult-to-predict travel distance. In this study, we constructed a dataset with detailed characteristic parameters of 38 channelized rock avalanches triggered by the 2008 Wenchuan earthquake using the visual interpretation of remote sensing imagery, field investigation and literature review. Based on this dataset, we assessed the influence of different factors on the runout distance and developed prediction models of the channelized rock avalanches using the multivariate regression method. The results suggested that the movement of channelized rock avalanche was dominated by the landslide volume, total relief and channel gradient. The performance of both models was then tested with an independent validation dataset of eight rock avalanches that were induced by the 2008 Wenchuan earthquake, the M_s 7.0 Lushan earthquake and heavy rainfall in 2013, showing acceptable good prediction results. Therefore, the travel-distance prediction models for channelized rock avalanches constructed in this study are applicable and reliable for predicting the runout of similar rock avalanches in other regions.

Wenchuan earthquake in Sichuan Province (Zhang et al., 2013), with catastrophic consequences for residents in the affected areas. For instance, the $15 \times 10^6 \text{ m}^3$ Donghekou rock avalanche in Qingchuan County, near the seismogenic fault, traveled 2.4 km, killing about 780 people and destroying four villages (Zhang et al., 2013). Rock avalanches can cause incredible damage due to their high-speed and unexpectedly long runout, but their transport mechanisms are still considered to be controversial among many researchers (Hung et al., 2001). Therefore, constructing prediction models for rock avalanche travel distance is meaningful in terms of not only theoretical research on motion mechanisms but also practical application for risk mitigation of rock avalanches.

Methods for determining the travel distance of landslides can be divided into two categories: dynamic modeling (Heim, 1932; Sassa, 1988; Hung and McDougall, 2009; Pastor et al., 2009; Lo et al., 2011) and empirical modeling (Scheidegger, 1973; Lied and Bakkehøi, 1980; Corominas, 1996; Finlay et al., 1999; Van Westen et al., 2006; Guo et al., 2014). The dynamic models are able to provide information on landslide intensity, such as velocity, affected area and deposition depth, in addition to travel distance. Nonetheless, dynamic models with a variety of physical bases require accurately quantified input parameters that are difficult to obtain before the events, and many simplified assumptions that are not applicable to the actual situation. Recently Mergili et al. (2015) developed the multi-functional open-source tool *r.randomwalk* for conceptual modeling of the propagation of mass movements, which can combine the empirical model with the numerical model. Empirical models considering the correlations between observational data provide an effective technique to aid in understanding mech-

1 Introduction

Rock avalanches are extremely rapid, massive flow-like movements of fragmented rock from a very large rockslide or rockfall (Hung et al., 2014). Hundreds of rapid and long runout rock avalanches were triggered by the 2008

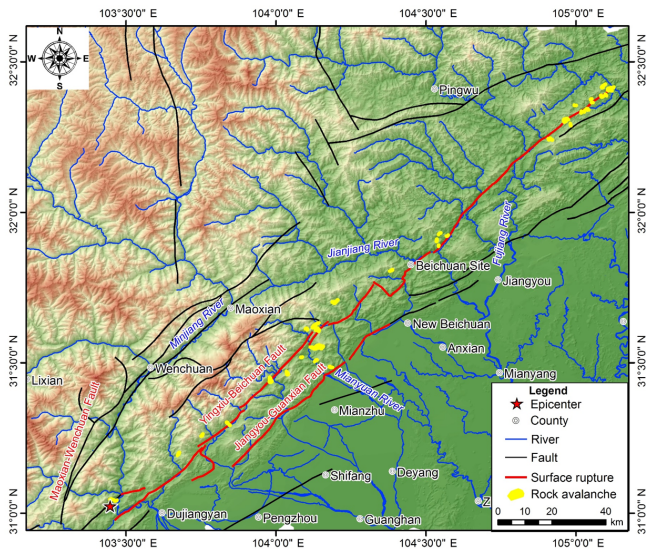


Figure 1. Distribution map of large rock avalanches triggered by the Wenchuan earthquake.

anisms of rock avalanche motion and to develop practical models for predicting rock avalanche travel distance. However, the empirical-statistical models set up from samples with different geomorphological and geological surroundings, trigger conditions or failure modes are not very sufficient to be applied to the Wenchuan earthquake area.

In this study, we compiled a dataset of 38 rock avalanches with flow paths confined by channels (this kind of landslide is hereinafter termed channelized rock avalanche) from interpretation of remote sensing, field investigations and literature review (see Sect. 3.1). Statistical correlations were used to determine the principle factors affecting the mobility of the channelized rock avalanches. Then a stepwise multivariate regression model was developed to build a best-fit empirical model for the travel-distance prediction of this kind of rock avalanches in the Wenchuan earthquake area. A derivative multivariate regression model was also constructed. The performance of both models was then tested with an independent validation dataset of eight rock avalanches in the same area.

2 Rock avalanches in study area

The study area (see Fig. 1) is on the northeast-trending Longmenshan thrust fault zone between the Sichuan basin and the Tibetan plateau. Three major sub-parallel faults are the Wenchuan–Maowen fault, the Yingxiu–Beichuan fault and the Pengguan fault (Fan et al., 2014). With long-term endogenic and exogenic geological process, this region is characterized by high mountains and deep gorges with extreme rates of erosion (Qi et al., 2011).

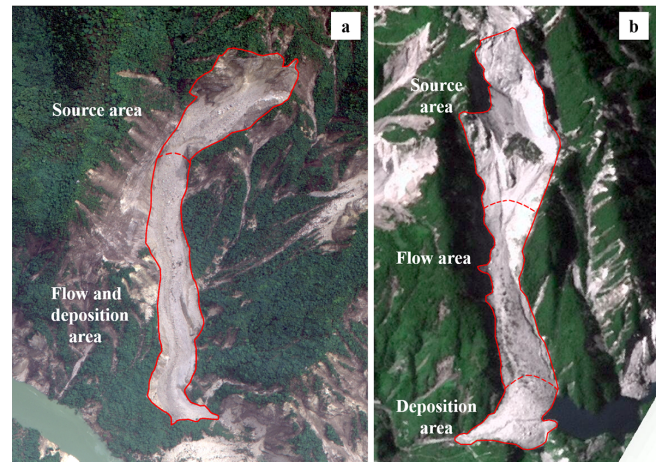


Figure 2. Remote sensing images of two channelized rock avalanches triggered by the Wenchuan earthquake. (a) Changtan rock avalanche (no. 21 in Table 2); (b) Laoyingyan rock avalanche, which is river-blocked.

This study selected 38 channelized rock avalanches induced by the Wenchuan earthquake to study the relations between travel distance and influential factors. These rock avalanches occurred along the seismogenic Yingxiu–Beichuan fault; the distance to the fault ranged from 0 m ~ 21 300 m with a mean value of 3895 m. Another distribution characteristic was that these rock avalanches mainly clustered on the step overs, bends and distal ends of the seismogenic fault. These distribution characteristics of the large rock avalanches suggested that the occurrence of rock avalanches was associated with very strong earthquake ground motion. The Wolong Station recorded the highest seismic acceleration with the peak ground acceleration reaching 0.948 *g* vertically and 0.958 *g* horizontally (Yu et al., 2009). Locally, the ground motion was high enough to throw rocks into the air.

The lithology of outcropping rock in source areas can be divided to four types: carbonate rock, phyllite, igneous rock and sandstone. The deposit of the rock avalanches in the study area was usually debris with mean particle size as tens of centimeters, which suggests that the sliding masses were intensively fragmented during their movement.

The influence of the local geomorphology on the topography of the rock avalanche depositions can be recognized from remote sensing images after the earthquake. The source area and the transition area of channelized rock avalanches in the study area were somehow easy to be differentiated, as the source area are normally located at the top or upper part of slope, while the flow path (flow or transition area) is partially or fully confined by channels (Fig. 2).

Table 1. Summarization of statistical relationships indicating landslide mobility in the literature.

| Approach | Keywords to characterize the methods | Landslide types | Triggers | Main references |
|-----------------|--|---|------------------|--|
| Reach angle | $\log H/L = C_1 \log V + C_0$ | Rockfall/slide/avalanche and flow-like landslides | Unknown | Scheidegger (1973); Corominas (1996) |
| | $H/L = C_1 \tan S + C_0$ | Soil slides, snow avalanches | Non-seismic | Hunter and Fell (2003); Lied and Bakkehøi (1980) |
| Travel distance | $\log L = C_1 Rt + C_2 \log V + C_3 \sin St + C_0$ | Rock/soil slides and rock/debris avalanches, | Seismic | Guo et al. (2014) |
| | $\log L = C_1 \log H + C_2 \log \tan S + C_0$ | Soil landslides on artificial slopes | Human activities | Finlay et al. (1999) |
| | $L = C_1 V^{C_2}$ | Debris slides, debris slides | Rainfall | Jaiswal et al. (2011) |

Note: C_0 , C_1 , C_2 , C_3 are the constants. L is the travel distance. H is the total height. V is the volume. S is the average slope angle while St is the slope transition angle. Rt is the rock type.

3 Data and method

3.1 General consideration

Various statistical methods have been applied to predict travel distance of landslides, and some popular relationships are summarized in Table 1. The most prevalent one is the equivalent friction coefficient model, which only takes account of landslide volume (V) (Scheidegger, 1973). Another well-known model is the statistical α - β model in which the maximum runout distance is solely a function of topographic conditions (Lied and Bakkehøi, 1980; Gauer et al., 2010). Finlay et al. (1999) developed some multiple regression models containing slope geometric parameters like slope height and slope angle for the travel-distance prediction of landslides on the artificial slopes upon the horizontal surface. Based on the data of 54 landslides that were relatively open or confined by gentle lateral slope, Guo et al. (2014) established an empirical model for predicting landslide travel distance in the Wenchuan earthquake area and suggested that rock type, landslide volume and slope transition angle (between the failed upper slope and lower slope) play dominant roles on landslide travel distance. It has been increasingly stated that the prediction models of travel distance should adapt to different types of landslides (Corominas, 1996; Fan et al., 2014).

Moreover, the shape and mobility of rock avalanches are controlled by the local topography. Heim (1932) firstly mentioned the influence of local morphology: the debris masses will undergo different effects with the angle of reach changing, and rock avalanches have to conform to the local morphology regardless of their scale. Abele (1974) summarized four different possibilities of adaptation of the rock avalanche to local morphology. Hsu (1975) noted that a sinuous pathway can reduce runout distance of rock avalanches. Nicoletti and Sorriso-Valvo (1991) inferred that local morphology impacts landslide motion by changing the rate of total

energy dissipation along the travel path. To determine the influence of specific channels on the travel distances of rock avalanches, we consider the impacts of the gradient of the upper slopes and lower channels.

Rock avalanches triggered by the Wenchuan earthquake usually initiated from the top or the higher part of slopes possibly due to the altitude amplification effect of earthquake acceleration; therefore the toes of the rupture surface were commonly found in the source area at the upstream of the pre-existing channel (See Fig. 3). When the slope failed, the failed mass traveled a long distance down the channel. The 38 rock avalanches in this study are selected with the criterion that the flow path is partially or fully confined by channels. The volumes of these rock avalanches ranged from 0.4 to $50 \times 10^6 \text{ m}^3$, with horizontal travel distances between 0.58 and 4.00 km. The volume is prior to the area to be put into the travel-distance prediction model as it had much more physical meanings. We introduced total relief as well as the height of source area to probe the influences of the potential energy difference and altitude difference of source mass on the travel distance of the rock avalanches.

3.2 Data

The terms and notations of a typical channelized rock avalanche are shown in Fig. 3. The local morphology of a rock avalanche can be divided to three sections: initiated slope (source area), channel (main travel path or flow area) and valley floor (deposition area). When the mass moves over the initiated slope section, it is free from lateral constraints, and the moving mass is able to spread laterally. After entering the channel, the flowing mass is constrained by the two lateral slopes. Finally, the mass may reach a wide valley floor, where it spreads laterally and deposits. The average inclination of the source area and travel path is obtained, while the gradient of valley floor (deposition area) is neglected as it has very little variation. Slope angle (α) denotes the average in-

Table 2. Data of various factors for establishment of prediction model of rock avalanche travel distance.

| Code | Landslide name | Longitude, (° E) | Latitude, (° N) | Landslide area, A (m ²) | Landslide volume, V (m ³) | Source area height, H_s (m) | Slope angle, α (°) | Channel angle, β (°) | Total relief, H (m) | Travel distance, L (m) | Reference |
|------|----------------|------------------|-----------------|---------------------------------------|---|-------------------------------|---------------------------|----------------------------|-----------------------|--------------------------|------------------|
| 1 | Wenjia Gully | 104.140 | 31.552 | 3 000 566 | 50 000 000 | 440 | 26 | 7 | 1320 | 4000 | Xu et al. (2009) |
| 2 | Shuimo Gully | 103.981 | 31.442 | 915 608 | 19 960 000 | 490 | 35 | 10 | 860 | 2000 | |
| 3 | Dawuji | 104.196 | 31.702 | 792 190 | 16 330 000 | 540 | 29 | 13 | 880 | 1900 | |
| 4 | Donghekou | 105.113 | 32.410 | 1 283 627 | 15 000 000 | 240 | 25 | 11 | 640 | 2400 | Xu et al. (2009) |
| 5 | Hongshi Gully | 104.130 | 31.624 | 687 520 | 13 410 000 | 290 | 37 | 17 | 1040 | 2700 | |
| 6 | Woqian | 104.964 | 32.308 | 695 672 | 12 000 000 | 330 | 30 | 10 | 560 | 1600 | Xu et al. (2009) |
| 7 | Xiaojiashan | 104.038 | 31.465 | 465 899 | 7 810 000 | 480 | 48 | 24 | 930 | 1350 | |
| 8 | Niumian Gully | 103.456 | 31.044 | 527 700 | 7 500 000 | 320 | 32 | 13 | 800 | 2640 | Xu et al. (2009) |
| 9 | Liqi Gully | 105.207 | 32.169 | 355 113 | 5 360 000 | 360 | 37 | 12 | 650 | 1500 | |
| 10 | Caocaoping | 104.139 | 31.607 | 354 046 | 5 340 000 | 345 | 31 | 17 | 580 | 1340 | |
| 11 | Huoshi Gully | 104.134 | 31.616 | 322 155 | 4 680 000 | 270 | 38 | 17 | 700 | 1320 | |
| 12 | Shibangou | 105.090 | 32.419 | 496 983 | 4 500 000 | 450 | 34 | 9 | 650 | 1800 | Xu et al. (2009) |
| 13 | Xiejadianzi | 103.841 | 31.298 | 294 256 | 4 000 000 | 400 | 34 | 15 | 720 | 1600 | Xu et al. (2009) |
| 14 | Dashui Gully | 103.675 | 31.199 | 241 874 | 3 150 000 | 320 | 30 | 17 | 560 | 1400 | |
| 15 | Changping | 103.754 | 31.259 | 224 645 | 2 840 000 | 290 | 37 | 16 | 500 | 1200 | |
| 16 | Xiaomuling | 104.102 | 31.613 | 218 704 | 2 740 000 | 175 | 45 | 26 | 710 | 1025 | |
| 17 | Baishuling | 104.385 | 31.807 | 208 968 | 2 570 000 | 335 | 36 | 20 | 620 | 1200 | |
| 18 | Dawan | 104.536 | 31.907 | 203 959 | 2 480 000 | 220 | 28 | 20 | 480 | 1000 | |
| 19 | Xiaojiashan | 104.182 | 31.486 | 198 165 | 2 385 499 | 340 | 44 | 20 | 650 | 1135 | |
| 20 | Shicouzi | 104.918 | 32.243 | 169 540 | 1 920 000 | 260 | 30 | 26 | 640 | 1200 | |
| 21 | Changtan | 104.133 | 31.508 | 151 094 | 1 640 000 | 400 | 33 | 25 | 1050 | 1650 | |
| 22 | Hongmagong | 104.962 | 32.301 | 144 683 | 1 540 000 | 195 | 30 | 14 | 330 | 800 | |
| 23 | Baiguocun | 105.088 | 32.385 | 139 800 | 1 470 000 | 165 | 26 | 12 | 260 | 800 | |
| 24 | Qinglongcun | 105.036 | 32.342 | 134 079 | 1 390 000 | 90 | 21 | 11 | 200 | 600 | |
| 25 | Pengjiashan | 104.546 | 31.930 | 127 156 | 1 290 000 | 200 | 33 | 28 | 580 | 1000 | |
| 26 | Longwancun | 104.571 | 31.922 | 99 821 | 920 000 | 205 | 31 | 28 | 460 | 860 | |
| 27 | Zhangzhengbo | 105.017 | 32.333 | 99 726 | 920 000 | 125 | 29 | 15 | 320 | 800 | |
| 28 | Dujiayan | 105.028 | 32.336 | 94 769 | 860 000 | 100 | 33 | 17 | 400 | 880 | |
| 29 | Madiping | 104.996 | 32.355 | 94 632 | 860 000 | 140 | 27 | 31 | 395 | 740 | |
| 30 | Yandiaowo | 105.099 | 32.391 | 92 128 | 820 000 | 145 | 30 | 26 | 390 | 800 | |
| 31 | Chuangzi Gully | 104.085 | 31.518 | 91 717 | 820 000 | 185 | 35 | 15 | 295 | 670 | |
| 32 | Zhaojiashan | 105.041 | 32.342 | 82 329 | 700 000 | 115 | 22 | 16 | 280 | 700 | |
| 33 | Weiziping | 105.083 | 32.387 | 74 661 | 620 000 | 135 | 22 | 18 | 240 | 600 | |
| 34 | Maochongshan 2 | 104.908 | 32.243 | 70 251 | 570 000 | 160 | 38 | 22 | 500 | 740 | |
| 35 | Waqianshan | 105.049 | 32.376 | 70 007 | 560 000 | 135 | 24 | 18 | 250 | 620 | |
| 36 | Muhongping | 104.982 | 32.291 | 68 288 | 540 000 | 175 | 28 | 20 | 420 | 970 | |
| 37 | Dapingshang | 104.542 | 31.889 | 65 700 | 520 000 | 160 | 34 | 29 | 365 | 640 | |
| 38 | Liushuping 2 | 105.054 | 32.365 | 54 810 | 400 000 | 150 | 29 | 16 | 240 | 580 | |

inclination of the initiated slope section. Channel angle (β) denotes the average inclination of the sectional channel. Source area height (H_s) denotes the elevation difference between the crest of the sliding source and the toe of the rupture surface. Total relief (H) is the elevation difference between the crest of the sliding source and the distal end of the debris deposit. Travel distance (L) is the horizontal Euclidean distance between the crest of the sliding source and the distal end of the debris deposit. Landslide area (A) is the source area of the rock avalanche obtained from remote sensing image interpretation. An empirical scaling relationship with different empirical coefficients is frequently used to link the volume and the area of landslides in different areas or with different types, and we chose the one developed by Parker et al. (2011) in the same study area. For some rock avalanches with field measured volume available, we use field measurement data rather than the estimated volume by area. The parameters of 38 rock avalanches are listed in Table 2.

3.3 Method

Travel distance is the most important prediction parameter in rock avalanche hazard evaluation in mountainous areas. Travel-distance prediction of rock avalanche is a complicated issue as it is determined by many different properties of the materials (i.e., grain size distribution and water content), topographical factors, mobility mechanics of failed mass, the confinement attributes of travel path, etc. (Guo et al., 2014). Empirical-statistical methods have long been used as tools to study the mobility of rock avalanche since they are easy to develop and apply, and they are not dependent on knowing the complex physical processes involved in the hypermobility of rock avalanches. Channelized rock avalanches have unique movement paths involving complex, and possibly little-known, physical processes such as grain collisions, fragmentation and entrainment of bed material from the channel sides and bottom. Existing empirical models

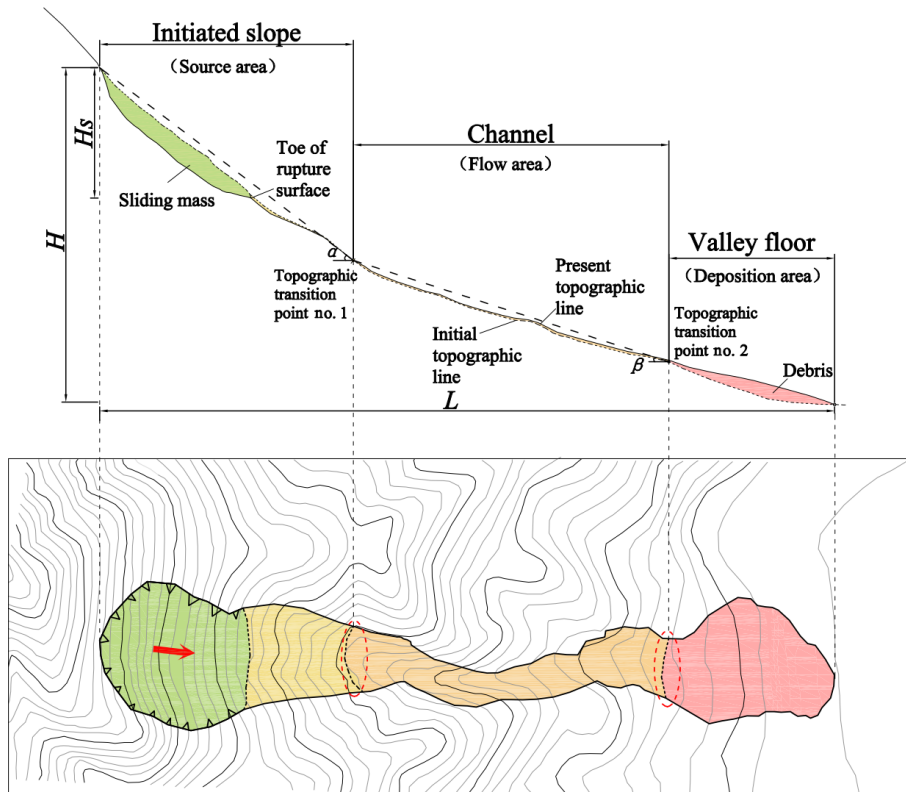


Figure 3. Sketch map of a channelized rock avalanche defining geometric parameters. The red-dashed ellipse indicates the topographic transition dividing the initiated slope, channel and valley floor. The red arrow represents sliding direction of source mass.

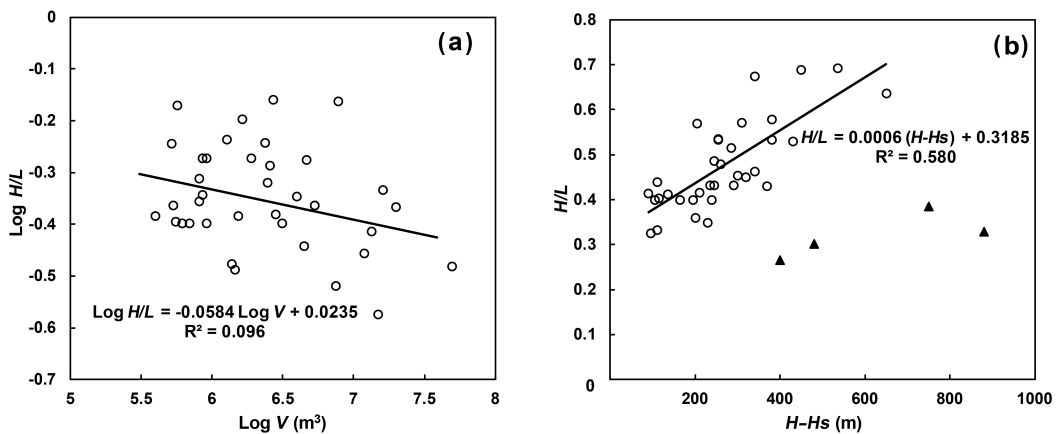


Figure 4. (a) Relationship between reach angle (H/L) and volume (V); (b) relationship between H/L and effective drop height of channelized rock avalanches ($H - H_s$).

have not produced a favorable prediction. The forecasting index system and the prediction model of channelized rock avalanches should be discussed first.

In this paper, we first selected controlling factors on rock avalanche travel distance through correlation analysis. Then we fitted a stepwise multivariate regression model using all significant correlation variables to obtain a best-fit empirical model for landslide travel distance and explored which

factors were statistically significant at the same time, as expressed in Eq. (1).

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \dots + b_nx_n + \varepsilon, \quad (1)$$

where y is the predictand (“dependent variable”), e.g., travel distance of rock avalanche, x_i ($i = 1, 2, \dots, n$) is the predictor (“independent variable”), b_0 is the intercept, b_i ($i = 1, 2, \dots, n$) is the regression coefficient of the corresponding, and

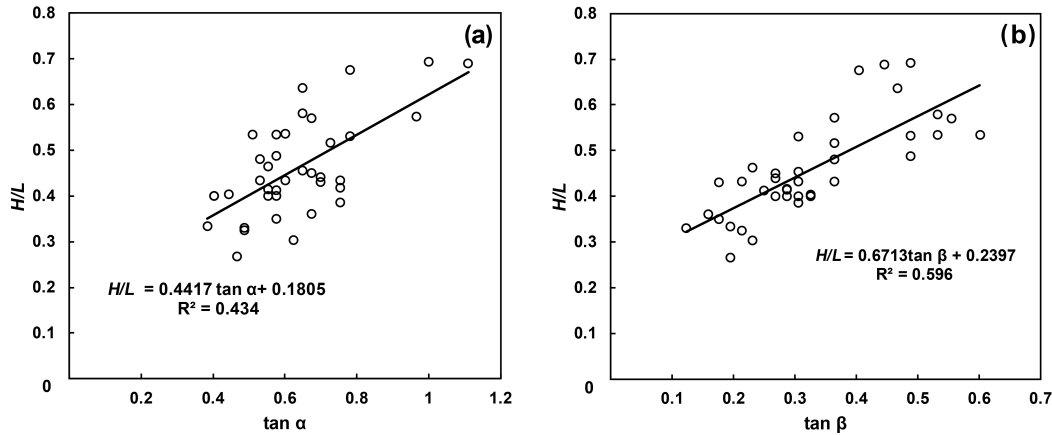


Figure 5. (a) Relationship between reach angle (H/L) and slope angle ($\tan \alpha$); (b) relationship between H/L and the channel gradient ($\tan \beta$) of the rock avalanches.

ε is the residual error, here assumed to be independently and normally distributed. Predictors were added to the regression equation one at a time until there was no significant improvement in parsimonious fit as determined by the adjusted R^2 .

4 Results and validation

4.1 Reach angle of channelized rock avalanches

Reach angle, also called the apparent coefficient of friction, is a well-known index to express the landslide mobility. It is the angle of the line connecting the crown of the landslide source area to the toe of the displaced mass. This angle is firstly conducted by Heim (1992) in the famous energy-line model as the average coefficient of friction of a sliding mass from initiation to rest. The reach angle is supposed to possess the ability of landslide mobility prediction because of its tendency to decrease with the increase of landslide volume as illustrated by many researchers (Scheidegger, 1973; Corominas, 1996).

In this study, the influence of landslide volume, drop height, slope of the source area and flow path (channel) on the reach angle of the channelized rock avalanches are examined (Figs. 4 and 5). Figure 4a presents $\log(\text{volume})$ vs. $\log(\text{reach angle})$, showing a weak correlation probably due to the limited volume range in our dataset, constrained movement in channel and local morphology of channels. In order to analyze the effect of potential energy on the reach angle, the effective drop height (defined as the total height minus the height of source area) is used instead of the total height to exclude the effect of the superposition of source height and total height. That is especially useful for landslides with large-size initiation but limited travel distance. A significant positive correlation is observed between the reach angle and effective drop height, apart from the four lower scatters in Fig. 4b. Figure 5a and b indicate obvious positive correla-

Table 3. Correlation coefficients of continuous variables listed in Table 2.

| | <i>A</i> | <i>V</i> | <i>H</i> | <i>H_s</i> | α | β | <i>L</i> |
|----------------------|----------|----------|----------|----------------------|---------------|---------------|---------------|
| <i>A</i> | 1.000 | 0.982 | 0.674 | 0.521 | <i>-0.119</i> | <i>-0.524</i> | 0.877 |
| <i>V</i> | – | 1.000 | 0.713 | 0.560 | <i>-0.055</i> | <i>-0.492</i> | 0.866 |
| <i>H</i> | – | – | 1.000 | 0.801 | 0.429 | <i>-0.130</i> | 0.857 |
| <i>H_s</i> | – | – | – | 1.000 | 0.399 | <i>-0.323</i> | 0.675 |
| α | – | – | – | – | 1.000 | 0.264 | 0.082 |
| β | – | – | – | – | – | 1.000 | <i>-0.467</i> |
| <i>L</i> | – | – | – | – | – | – | 1.000 |

Note: the number in italics indicates the two variables are not significantly correlated.

tions between the reach angle with both the slope gradient in source area and channel gradient along the flow path. The large scatter in Figs. 4 and 5 suggests that the reach angle of channelized rock avalanches might be controlled by some other factors, such as local topography rather than volume, but this needs to be further studied.

4.2 Relationships between travel distance and volume

Correlation coefficients between different variables and L were calculated first, generating the correlation coefficients matrix shown in Table 3. The significant relevant predictors with the 95 % confidence for travel-distance prediction of channelized rock avalanches are A , V , H , H_s and β , with correlation coefficient of 0.877, 0.866, 0.857, 0.675 and -0.467 , respectively.

Figure 6 illustrates that the travel distance varies exponentially with V of rock avalanche with an exponential exponent of 0.377. Compared with a compilation of worldwide rock avalanche data (Legros, 2002), the mobility of rock avalanches in our study area is stronger than other non-volcanic landslides (power exponent is 0.25) but weaker than volcanic landslides and debris flows (power exponent is 0.39), as shown in Fig. 13. The relation between L and

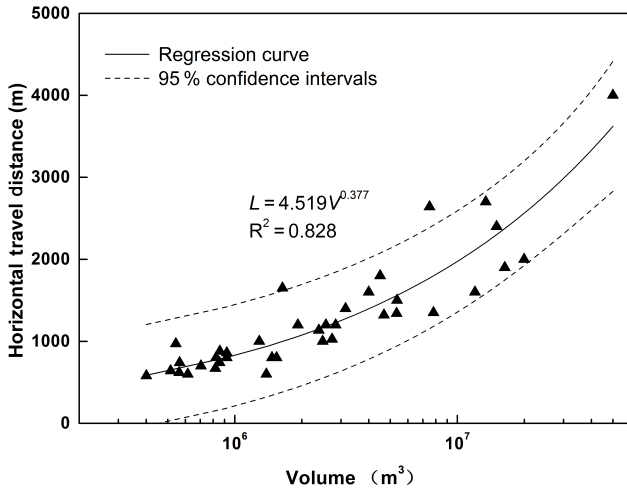


Figure 6. Relationship between horizontal travel distance and volume of channelized rock avalanches.

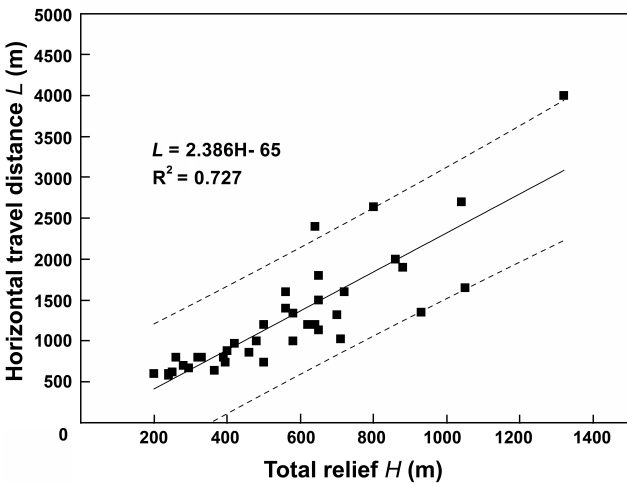


Figure 7. Relationship between horizontal travel distance and total relief of channelized rock avalanches.

H is shown in Fig. 7. The result suggests that the mobility (travel distance) of rock avalanche has a relatively strong linear relationship with H . The scale factor is close to 2.4, which means that the apparent friction coefficient (H/L) for the rock avalanches is approximately 0.42. This is significantly lower than the commonly observed static coefficient of friction of rock material (~ 0.6).

4.3 Multivariate regression model of rock avalanche travel distance

According to the matrix of correlation coefficients (Table 3), α does not have a significant correlation with L at the 95 % confidence level. Thus this variable could be excluded first during development of the best-fit regression model for travel-distance prediction. Prior to A , V has been consid-

ered in the models as it has much more physical meaning. In the end, a stepwise linear multivariate regression technique was applied to find the best-fit travel-distance regression model using the significant relevant predictors including V , H , H_s and β . The best-fit regression equation for travel-distance prediction were derived from the dataset of Table 2 (see Eq. 2), and the coefficient of the variables with 95 % confidence is shown in Table 4.

$$\log(L) = 0.420 + 0.079 \log(V) + 0.718 \log(H) - 0.365 \log(\tan \beta), \quad (2)$$

where \log is the logarithm of 10, L is the predicted travel distance (m), V is the landslide volume (m^3), H is the total relief (m) and β is the mean gradient of the channel ($^\circ$).

Equation (2) can be transformed to Eq. (3):

$$L = 2.630 V^{0.079} H^{0.718} (\tan \beta)^{-0.365}. \quad (3)$$

The best-fit travel-distance regression equation indicates that the travel distance of channelized rock avalanche is positively correlated with landslide scale (landslide volume) and potential energy loss (total relief) and negatively correlated with channel gradient, which is coherent with the results of correlation analysis in Table 3.

While H will be unknown prior to landslide occurrence, the elevation difference of source area will be available through specific field investigation on a potential rock avalanche area. Hence, we introduced H_s and α in replacement of H to the regression model as they have relative high correlation with H (correlation coefficients are 0.801 and 0.429, respectively). The transformed alternative regression equation is given as Eq. (4) with the coefficient of the variables with 95 % confidence in Table 4.

$$L = 3.6V^{0.303} H_s^{0.244} (\tan \alpha)^{-0.115} (\tan \beta)^{0.072}, \quad (4)$$

where L is the predicted travel distance (m), V is the landslide volume (m^3), H_s is the height of source area (m), α is the mean angle of slope segment ($^\circ$) and β is the mean gradient of the channel segment ($^\circ$).

The validity of these two models was evaluated through the significance test leading to the highest R^2 value and the lowest residual standard error. Table 4 shows the significance values for the prediction model equations. Adjusted R^2 means adjusted multiple correlation coefficient, which represents the correlation level between the dependent variable and the independent variables. The calculation of adjusted R^2 considers the number of variables and can be used to compare goodness of fit of different regression models. Adjusted R^2 of the two regression equations is high, suggesting that the constructed regression models are reliable. The adjusted R^2 of Eq. (2) is higher than Eq. (4), implying a higher precision for the best-fit regression model. The significance test results on the regression equation suggest the significance of multiple regression equations ($F = 173.5 > F_{0.05}(2.883)$) for

Table 4. The regression coefficients and results of significance tests of two multivariate regression models.

| Equations | Coefficients* | Intercept | Coefficient of log(V) | Coefficient of log(H) | Coefficient of log(tanβ) | Coefficient of log(Hs) | Coefficient of log(tanβ) | Adjusted R ² | F _{stat} | F _{0.05} |
|-------------|---------------|-----------|-----------------------|-----------------------|--------------------------|------------------------|--------------------------|-------------------------|-------------------|-------------------|
| Best-fit | LCI | 0.175 | -0.013 | 0.521 | -0.548 | - | - | | | |
| Regression | Mean | 0.420 | 0.079 | 0.718 | -0.365 | - | - | 0.933 | 173.5 | 2.883 |
| Equation | UCI | 0.665 | 0.171 | 0.914 | -0.182 | - | - | | | |
| Alternative | LCI | 0.110 | 0.199 | - | -0.165 | -0.002 | -0.464 | | | |
| Regression | Mean | 0.561 | 0.303 | - | 0.072 | 0.244 | -0.115 | 0.840 | 49.5 | 2.659 |
| Equation | UCI | 1.012 | 0.407 | - | 0.308 | 0.489 | 0.233 | | | |

Coefficients of each variable has three kinds: LCI is the lower bound of the coefficients with 95 % confidence; mean is the mean value of the coefficients; UCI is the upper bound of the coefficients with 95 % confidence.

Table 5. Background parameters and predicted values of eight rock avalanches in the same area used for validation.

| Landslide name | Longitude | Latitude | Triggers* | V (10 ⁴ m ³) | α (°) | B (°) | Hs (m) | H (m) | L (m) | L' (3) ** (m) | Error (%) | L' (4) *** (m) | Error (%) |
|----------------|-----------|----------|-----------|-------------------------------------|-------|-------|--------|-------|-------|---------------|-----------|----------------|-----------|
| Pianqiaozi | 104.370 | 31.822 | WCEQ | 8.8 | 35 | 19 | 153 | 205 | 372 | 436 | 17.2 | 373 | 0.3 |
| Yangjiayan | 104.328 | 31.755 | WCEQ | 25.4 | 41 | 23 | 164 | 304 | 518 | 583 | 12.5 | 518 | 0.1 |
| Shanshulin | 103.508 | 31.181 | WCEQ | 27.9 | 34 | 25 | 340 | 433 | 715 | 731 | 2.3 | 660 | -7.6 |
| Fuyangou | 103.501 | 31.422 | WCEQ | 71.9 | 38 | 28 | 385 | 530 | 763 | 869 | 13.8 | 900 | 17.9 |
| Dayanbeng 1 | 102.762 | 30.179 | LSEQ | 100 | 53 | 10 | 254 | 424 | 1267 | 1136 | -10.3 | 781 | -38.4 |
| Dayanbeng 2 | 102.761 | 30.178 | LSEQ | 110 | 50 | 8 | 237 | 407 | 1372 | 1208 | -12.0 | 787 | -42.6 |
| Ermanshan | 102.739 | 29.322 | RF | 100 | 33 | 15 | 148 | 635 | 1370 | 1303 | -4.9 | 767 | -44.0 |
| Wulipo | 103.567 | 30.919 | RF | 150 | 30 | 10 | 135 | 377 | 1260 | 1078 | -14.4 | 833 | -33.9 |

Triggers is the triggering condition of rock avalanches: WCEQ represents the 2008 Wenchuan M_s 8.0 earthquake; LSEQ represents the 2013 Lushan M_s 7.0 earthquake; RF represents the rock avalanche induced by heavy rainfall. L' (3) and L' (4) indicate the predicted travel distance estimated by Eqs. (3) and (4), respectively.

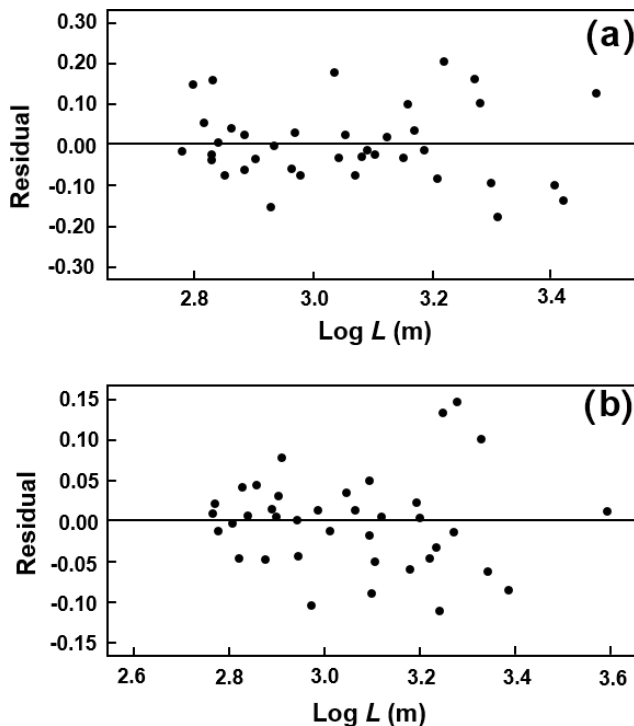


Figure 8. Residual plots for the two multivariate regression models: Fig. 9a is for Eq. (2) and Fig. 9b is for Eq. (4).

Eq. 2; $F = 49.5 > F_{0.05}(2.659)$ for Eq. 4). Figure 8a and b show the distributions of the residuals in relation to the observed travel distance estimated by using Eqs. (2) and (4). Both plots illustrate normality, constant variance and absence of trends in the residuals.

Figure 9 compares the predicted travel distances estimated by using Eqs. (2) and (4) with the observed ones. It suggests that the predicted values of the samples are close to the observed ones. Where L exceeds 2000 m, the predicted travel distance calculated by using two models are lower than actual one, with relatively large residual error.

4.4 Validation

The regression equations were tested using an independent sample validation dataset of eight rock avalanches in the same area induced by three different kinds of triggers: 2008 M_s 8.0 Wenchuan earthquake, 2013 M_s 7.0 Lushan earthquake and heavy rainfall (Table 5). The volume of these samples ranged from 88×10^3 to 1.5×10^6 m³ and travel distance from 372 to 1372 m. The background parameters and the predicted values of each avalanche are listed in Table 5. The relative errors between the predicted values estimated by using Eq. (3) and observed values of the travel distance of the rock avalanches, $|L_{\text{predicted}} - L_{\text{observed}}| / L_{\text{observed}} \times 100 \%$, are between -14.4 and 17.2 %, while the relative errors are -44.0 and 17.9 % for Eq. (4). On the whole, these two regression models achieved acceptable

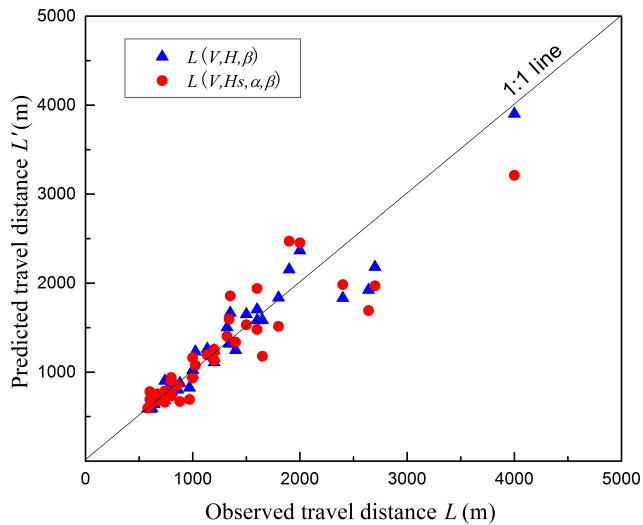


Figure 9. The comparison between observed and predicted travel distance for the two multivariate regression models.

prediction accuracy for preliminary forecasting of travel distance of rock avalanches in rugged mountainous areas. The best-fit regression model appeared to provide greater precision than the alternative model. Regarding the influence of triggers on the travel distance of the channelized rock avalanches, those triggered by rainfall and the Lushan earthquake seemed to be more mobile. It is inferred that the former difference is due to the high water content in failed mass induced by rainfall. A possible reason why two rock avalanches triggered in the Lushan earthquake traveled farther may be the structural weakening of slope rock mass during the 2008 Wenchuan earthquake in the study area.

5 Discussion

5.1 Prediction for travel distance of channelized rock avalanche

The results of our analysis of the dataset indicate that the mobility (travel distance) of channelized rock avalanche is positively correlated with landslide volume and total relief but negatively correlated with channel gradient. As Fig. 6 shows, the travel distance of channelized rock avalanche would rapidly increase with volume of rock avalanche enlarged. Such a high correlation between landslide volume and travel distance implies that the travel distance of channelized rock avalanche is dominated by the spreading of the slide mass (Davies et al., 1999; Staron and Lajeunesse, 2009). The high positive correlation between total relief and travel distance is for two reasons: the larger the total relief is, the more kinetic energy the slide mass could obtain and the further it could travel (Legros, 2002). The channel gradient is highly correlated with the H/L ratio as shown in



Figure 10. Sketch map of flow capacity of channel affecting on the travel distance of the Wenjia Gully channelized rock avalanche: (a) before the earthquake; (b) after the earthquake; (c) photo taken on deposition platform after the earthquake. The red arrow shows the sliding direction of source mass. The red dotted line in (a) indicates the original depression on the travel path of the rock avalanche, where debris deposition of about 30 million m^3 was stored after the earthquake (shown in b); more detailed information is shown in (c).

Fig. 5b, which actually represents the apparent friction coefficient along the flow path similar to the definition of angle of reach by Heim (1992). This is probably the reason for the negative correlation between travel distance and channel gradient, as the decrease of channel gradient means the decrease of static friction coefficient and the increase of landslide volume and mobility (Figs. 4a and 12).

The residual analysis result demonstrates that the projection process in the early motion stage will significantly enlarge the travel distance of rock avalanches. The projection phenomenon was observed in the Wenchuan earthquake region by Huang et al. (2011), defined as the thrown out or projectile motion of slope material due to site amplification effect of seismic wave causing the peak ground acceleration

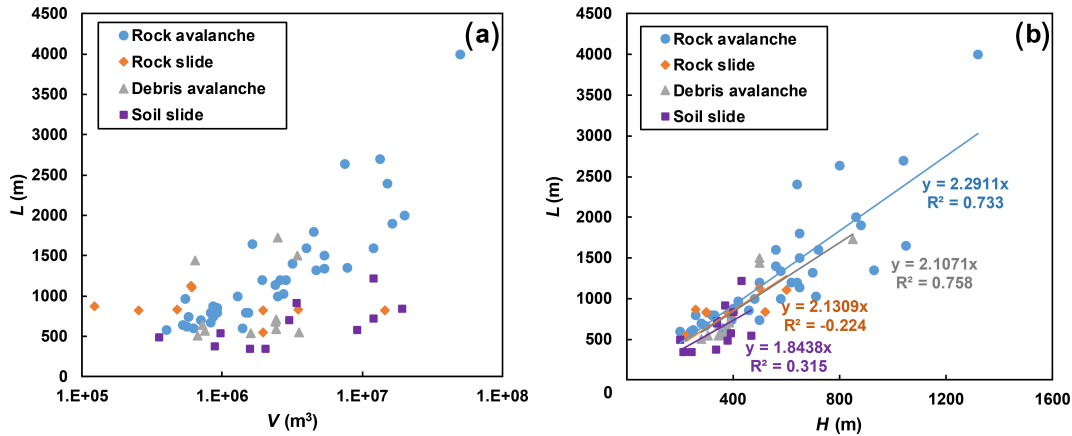


Figure 11. Relationship between the volume and travel distance (a) and between the total height and travel distance (b) of different-type landslides triggered by the Wenchuan earthquake (rockslide, debris avalanche and soil slide data are from Guo et al., 2014).

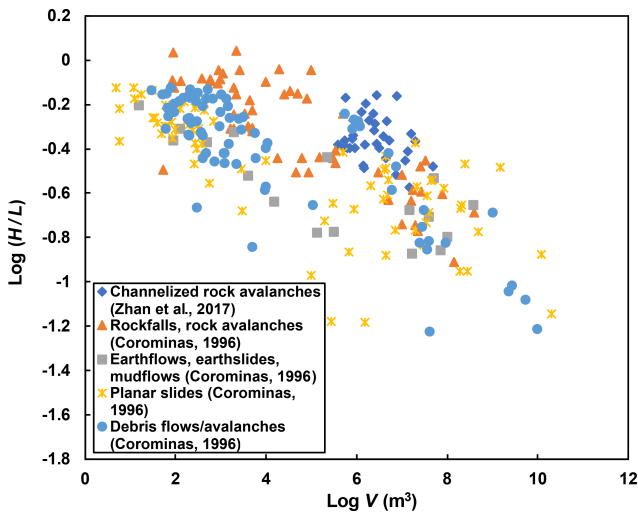


Figure 12. Relationship between the volume and H/L ratio of different-type landslides from the worldwide dataset (Corominas, 1996).

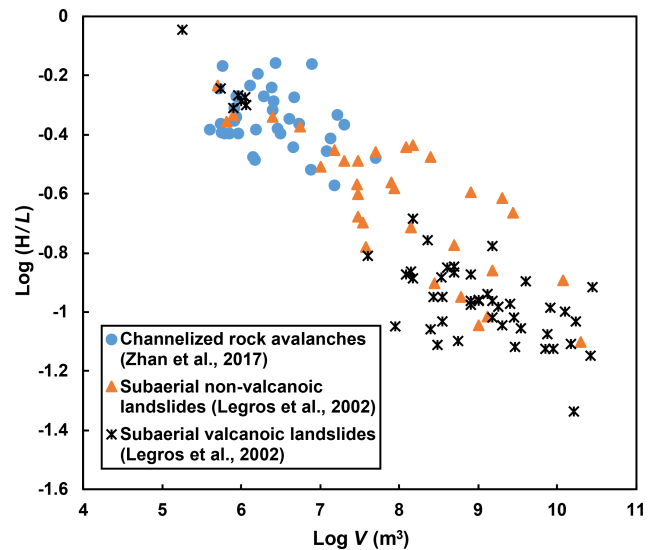


Figure 13. Relationship between the volume and H/L ratio of different-type landslides from the worldwide dataset (Legros, 2002).

to be larger than 9.8 m s^{-2} . The nature of this phenomenon is suggested to be involved with transformation of motion mode from sliding to flowing due to collision and fragmentation effects after the projection (Davies et al., 1999). Furthermore, the degree of fragmentation of failed mass should have remarkable influence on the travel distance of rock avalanche, and other factors changing the fragmentation degree should be further studied, such as earthquake effect, geologic structure and rock type.

5.2 The mobility of channelized rock avalanches

The mobility of landslides is influenced by a variety of factors, such as topography, landslide size, material type, landslide type and water content. The important role of topographical constrains on the landslide mobility can be indi-

cated from the high positive correlation of reach angle with effective drop height, slope gradient and channel gradient (see Figs. 4 and 5). Besides, some microtopography like turns (changes of channel flow direction), drop cliff and broad depression along the landslide travel path will influence the motion and deposition of rock avalanches remarkably. The rock avalanches corresponding with the four large bias scatter in Fig. 4b are the Wenjia Gully, Hongshi Gully, Niumian Gully and Donghekou rock avalanche, whose flow paths have cliffs in the upper end of channels with notable drop heights of 260, 150, 60 and 160 m, respectively, according to field investigations. Moreover, fluidization characteristics such as superelevation near curve transitions can be found in the channel section of these four rock avalanches. This steep microtopogra-

phy will enlarge the mobility of rock avalanches because the sliding mass will undergo the drop, collision and fragmentation effects in the early motion stage, which will facilitate motion-mode transformation from sliding to flowing. This transformation will enhance the mobility of rock avalanches traveling a much longer distance than predicted. Attention also must be paid to the broad depression along the channel, which can contain a large amount of debris mass and therefore curb the travel distance of channelized rock avalanches. For example, in the Wenjia Gully almost half of the total volume of the rock avalanche was deposited at the beginning of the channel (see Fig. 10c), leading to a shorter travel distance than expected.

To investigate the influence of landslide types on the landslide mobility, we compile our dataset with the dataset created by Guo et al. (2014), as it contains the data of 32 landslides with other types (debris avalanches, rockslides, soil slides) triggered by the Wenchuan earthquake. We plot the relationship between L with V and H , respectively, for different landslide types (see Fig. 11a and b). As shown in Fig. 11, rock avalanches have the strongest mobility while soil slides show the weakest one, and the mobility of rockslides is approximate to the mobility of debris avalanches. Through comparison with the worldwide datasets by using the reach angle as the mobility index (see Figs. 12 and 13), our dataset shows a consistent tendency with the worldwide datasets presented by Corominas (1996) and Legros (2002). Our dataset could contribute to the worldwide database by filling the gap of rock avalanches.

The common triggers of landslides are earthquakes and rainfall. The influence of triggers on landslide distribution has been well studied, but the effect of triggers on the landslide mobility still constitutes a gap in scientific knowledge. Zhang et al. (2013) indicated that rock avalanches triggered by earthquakes have a slightly lower mobility than those not triggered by earthquakes, and rock avalanches close to the seismic fault do not always have a higher mobility even when a rock avalanche near the seismic fault is subjected to higher ground accelerations. Guo et al. (2014) also mentioned that the seismic acceleration has less influence than rock type, sliding volume, slope transition angle and slope height on landslide travel distance. According to Table 5, two rainfall-induced rock avalanches show stronger mobility than earthquake-induced ones. The rock avalanches induced by rainfall express a stronger mobility than the earthquake-induced ones may due to lubrication effect of water. However, a detailed study on the influence of triggers on the landslide mobility is required.

6 Conclusions

A channelized rock avalanche refers to a rock avalanche with a flow path confined between valley walls. Relevant detailed data on 38 channelized rock avalanches triggered

by Wenchuan earthquake were collected by remote sensing, field investigation and literature review. The results of correlation and regression analysis revealed that the movement of channelized rock avalanches is dominated by the spreading of the failed mass. Landslide volume, total relief and channel angle had predominant effects, playing a dominating role in the on travel distance of channelized rock avalanches. Stepwise multivariate regression was used to develop a non-linear best-fit travel-distance prediction model for the channelized rock avalanches. An alternative multivariate regression model was also built. The reliability of the two models was tested by an independent validation dataset of eight rock avalanches in the same area and produced good results, meeting the requirements for preliminary evaluation of travel distance for channelized rock avalanches in the Wenchuan earthquake area.

Data availability. Data from Guo et al. (2014) in Fig. 11 are available at <https://doi.org/10.1007/s10346-013-0444-y>. Data from Corominas (1996) in Fig. 12 are available at <https://doi.org/10.1139/t96-005>. Data from Legros (2002) in Fig. 13 are available at [https://doi.org/10.1016/S0013-7952\(01\)00090-4](https://doi.org/10.1016/S0013-7952(01)00090-4). Data used for constructing the runout regression models are available in the Supplement.

The Supplement related to this article is available online at <https://doi.org/10.5194/nhess-17-833-2017-supplement>.

Competing interests. The authors declare that they have no conflict of interest.

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