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Susceptibility Analysis on Landslide Triggering Factors During the 2008 Wenchuan Earthquake

Deping Guo
Waseda University, Japan

Masanori Hamada
Waseda University, Japan

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SUSCEPTIBILITY ANALYSIS ON LANDSLIDE TRIGGERING FACTORS DURING THE 2008 WENCHUAN EARTUQUAKE

Deping Guo
Dept. of Civil and Environmental Eng., Waseda University
3-4-1Okubo, Shinjuku-ku, Tokyo 169-8555, Japan

Masanori Hamada
Dept. of Civil and Environmental Eng., Waseda University
3-4-1Okubo, Shinjuku-ku, Tokyo 169-8555, Japan

ABSTRACT

The 2008 Wenchuan earthquake with M_w7.9 induced numerous landslides along the Longmen Mt. zone in Sichuan Province of China. The authors investigated into various influential factors on the slope stability of 119 landslides in Wenchuan County, such as horizontal peak ground acceleration, slope angle, slope height, rock materials and geological structures. The authors developed hanging wall and footwall's acceleration attenuation formulae from 115 seismic stations and the formulae confirmed hanging-foot wall effect had notable influence on landslide distribution density and occurrence probability. The results of multivariable analysis clarified that slope height, horizontal peak ground acceleration and geological structures were more influential to sliding area and volume than slope angle and rock materials.

INTRODUCTION

A destructive earthquake with moment magnitude M_w7.9 occurred in Sichuan Province of China On May 12th 2008, the location of the epicenter is 30.986°N, 103.364°E, with 19km depth.(USGS, 2008) This catastrophic earthquake triggered unprecedented landslides and a third of economic losses was accounted for co-seismic geological disasters, especially landslides. (Chen *et al*, 2009) According to the latest remote sensing interpretation results, 197,481 landslides were triggered in a range of about 110,000km^2, and sliding area is totally about 1,160 km^2. (Xu, C *et al*, 2012, personal communication) It put forward a great challenge to mitigate geo-hazard caused by co-seismic landslides, meanwhile, a good opportunity to understand causal mechanisms. In order to take effective countermeasures to mitigate the loss caused by co-seismic landslides, it is critical to clarify influential factors on the slope stability during the earthquake.

The authors investigated the landslides in Wenchuan County. This area is a mountainous terrain and the epicenter locates in. It is ranged over with Ⅷ~Ⅺ (CSIS, China Seismic Intensity Scale, GB/T17742-1999). There are two faults going through the investigated County, that is, Wenchuan-Maoxian fault with N30~45^{o}E strike and Yingxiu-Beichuan fault with N35^{o}E strike, as shown in Fig.1. Wenchuan earthquake occurred at Yingxiu-Beichuan fault.

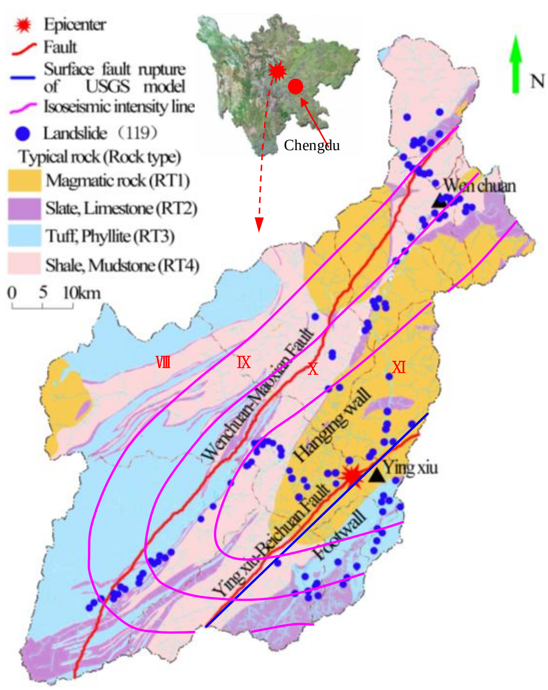

Fig.1. *Landslides distribution in Wenchuan County (Based on geological map by Geological Bureau of Sichuan and seismic intensity map by CEA,2008, China Earthquake Administration)*

DATA COLLECTION

Remote sensing interpretation and field investigation were both adopted to investigate the landslides in Wenchuan County. This article pays attention to two kinds of landslides, the first kind is sliding volume larger than $10^4 m^3$; the second kind is the landslides having destroyed the infrastructure. When several landslides locate closely and their slope angles are almost the same, they were regarded as one sample. The locations of 119 landslides were confirmed by hand-holder GPS and shown in Fig.1, where blue solid line represents the strike of surface fault rupture of USGS model (Ji and Hayes, 2008). Slope height was calculated by the elevation difference between slope top and foot or obtained from hand-holder laser rangefinder. For slope angle, it was measured by geological compass. The sliding area, outlined on the map, was calculated by ArcGIS software, and then, the sliding volume is equal to sliding area multiplied by average collapse depth of sliding body. The average collapse depth was obtained from typical longitudinal profile of slope, shown as in Fig.2.

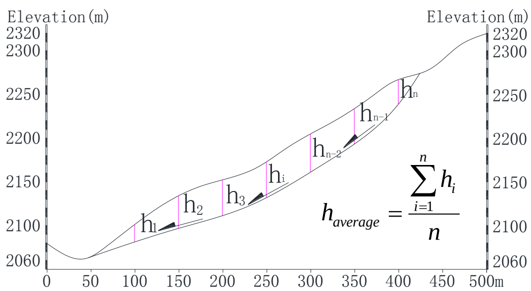

Fig.2. Typical longitudinal profile of slope

Table 1. Landslide rank

Rank	Sliding volume（104m3）
Small(S)	＜10
Medium(M)	10～100
Large(L)	100～1000
Giant(G)	≥1000

Referring to specifications by Chinese Geological Survey Bureau, the landslides were classified into four ranks based on sliding volume, such as small (S), medium (M), large (L) and giant (G), as shown in Table 1. According to rock strength and weathered degree, rock materials were assorted into two types, such as hard rock and soft rock, further, divided into two subclasses, respectively, as listed in Table 2. (Chang, *et al*, 2006)

HANGING-FOOT WALL EFFECT

As mentioned above, there are two faults going through Wenchuan County and Wenchuan earthquake occurred at Yingxiu-Beichuan fault. This fault is a thrust fault, north-western zone from Yingxiu-Beichuan fault is hanging wall side and the south-eastern zone is footwall side. The maximum distances from Yingxiu-Beichuan fault to administrative boundary (footwall side) and to Wenchuan-Maoxian fault (hanging wall side) are about 18km and 20km, respectively. The breadths of these two zones are comparable; therefore, landslide distribution density and landslide area distribution ratio were respectively calculated and compared within these two zones. Landslide area distribution ratio was expressed as the total sliding area of each landslide rank divided by footwall area or area of hanging wall side between two faults, in units of percentage. This ratio represents landslide occurrence probability.

The number of landslides on the footwall side is 22 within $636km^2$; the distribution density is $0.034 landslides/km^2$. The area between the two faults is $1628km^2$ and 79 landslides located in this zone, the distribution density is 0.049 $landslides/km^2$, which is about 1.5 times as large as that on footwall side. Landslide area distribution ratios of hanging wall side between two faults and footwall side are respectively shown in Fig.3. The results show landslide area distribution ratio of small landslide on the footwall side is almost the same as that on hanging wall side between two faults, while landslide area distribution ratios of medium and large landslide on the hanging wall side between two faults are 3.1 and 3.7 times larger than those on the footwall side, respectively. The average landslide area distribution ratio of hanging wall side between two faults is 2.5 times as large as that of footwall.

Table 2 Classification standard of rock type

Rock type		Weathered degree and typical rock	Uniaxial compression strength (σ, MPa)
Hard rock	RT1	Non-weathered or slightly weathered magmatic rock	σ>60
	RT2	1) Non-weathered or slightly weathered slate, limestone, metamorphic quartz rock 2) Moderately or strongly weathered magmatic rock (RT1)	30< σ ≤60
Soft rock	RT3	1) Non-weathered or slightly weathered tuff, phyllite, marl; 2) Moderately or strongly weathered hard rock	15< σ ≤30
	RT4	1) Non-weathered or slightly weathered shale, mudstone, shaly sand 2) Strongly weathered hard rock 3) Moderately or strongly weathered tuff, phyllite (RT3)	σ ≤15

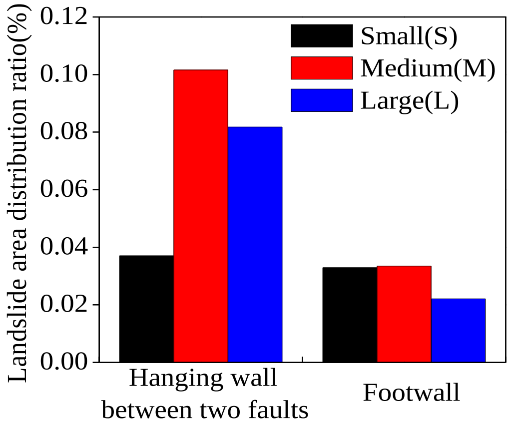

Fig.3. Landslide area distribution ratios of hanging wall side between two faults and footwall side

Comparing landslide distribution density and landslide area distribution ratios of hanging wall side between two faults and footwall side, the results suggest the amount of landslides on different sides of the thrust fault was remarkably affected by the hanging-foot wall effect. The hanging wall side was vulnerable to be triggered more landslides and the occurrence probability of large landslide on the hanging wall was much higher than that on the footwall side.

On account of hanging-foot wall effect, 115 seismic stations were assorted into two groups according to their locations. Among them, 27 seismic stations are on the hanging wall side, while 88 seismic stations are on the footwall side, as shown in Fig.4. , where red solid line stands for Yingxiu-Beichuan fault, yellow dashed line represents the predicted extension of the fault. Horizontal peak ground accelerations of the 115 seismic stations are shown in Fig.5. The authors developed regression formulae for estimating horizontal peak ground acceleration within the hanging wall and footwall, respectively. The formulae are as follows:

Hanging wall:

$$\log_{10}PGA=4.92-1.36\log_{10}(D_{rup}+23.7) \qquad (1)$$

Foot wall:

$$\log_{10}PGA=4.42-1.27\log_{10}(D_{rup}+17.5) \qquad (2)$$

Where PGA denotes horizontal peak ground acceleration (gal); D_{rup} represents nearest horizontal distance from interested site to the surface fault rupture of USGS model (km).

The two regression curves are shown in Fig.5, which reveals that horizontal peak ground acceleration of hanging wall is apparently larger than that of footwall. According to these regression results, it is suggested that hanging-foot wall effect was induced by the difference of seismic ground acceleration between hanging wall and footwall.

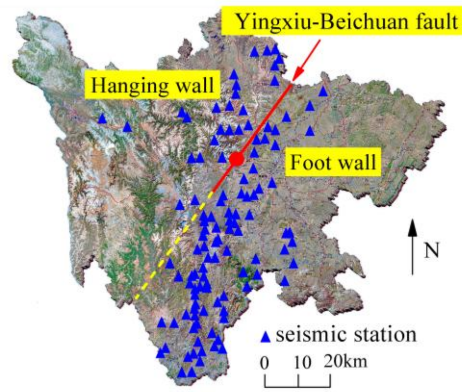

Fig.4. Distribution of seismic stations in Sichuan province

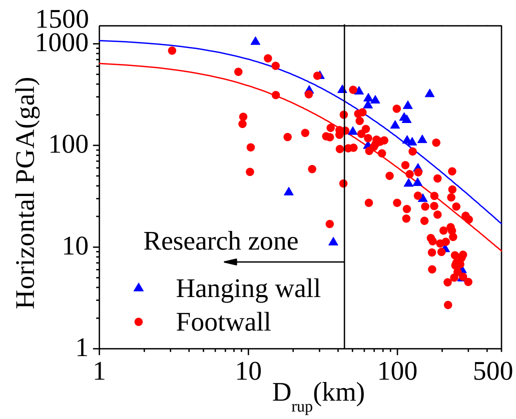

Fig.5. Horizontal peak ground accelerations of seismic stations and regression curves

ANALYSIS OF LANDSLIDE INFLUENTIAL FACTORS

When analyzing influential factors on the slope stability, each factor was divided into several groups. The total area of each group was denoted by TA; correspondingly, the total sliding area within each group was denoted by LA. The following part would apply the landslide area distribution ratio to represent landslide occurrence probability, which was expressed as total sliding area (LA) within each group divided by total area of corresponding group (TA), in percentage.

Effect of horizontal peak ground acceleration

Figure 6 shows landslide area distribution ratios related to the distance from surface fault rupture; it suggests that landslide occurrence probability in the zone of 0~10km is the highest and decreases with the increment of distance. The reason is inferred that horizontal peak ground acceleration decreased with the increase of the distance, as shown in Fig.5.

In order to have insight into the relationship between landslide occurrence probability and horizontal peak ground acceleration, the range of acceleration in Wenchuan County was divided into 6 groups. Landslide area distribution ratio of each group is shown in Fig.7. It suggests landslide occurrence probability increases with the increase of horizontal peak ground acceleration.

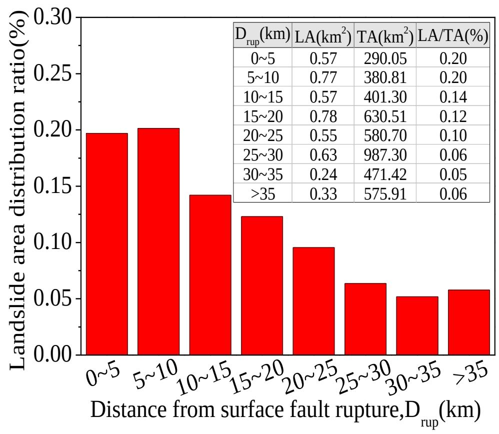

Fig.6. Landslide area distribution ratios related to the distance from surface fault rupture

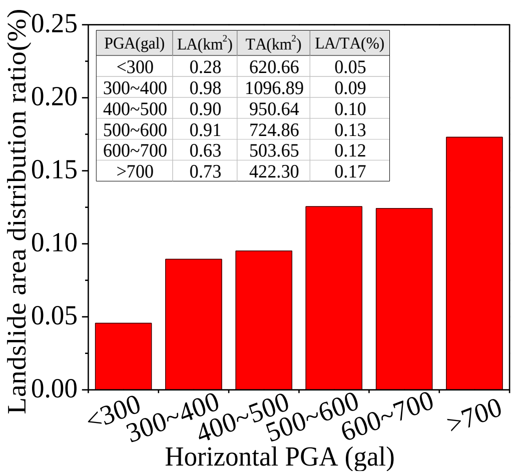

Fig.7. Landslide area distribution ratios related to horizontal peak ground acceleration

Effects of slope angle and height

In order to analyze the effectiveness of slope angle and slope height to landslide occurrence probability, digital elevation model (DEM) with 40m×40m grid spacing produced from topographic map was used to obtain total area (TA) of each divided group. The range of slope angle was classified into 9 groups. Landslide area distribution ratio of each group is shown in Fig.8, which suggests landslide area distribution ratio increases with slope angle, it means landslide occurrence probability increases with the increase of slope angle.

For slope height, the range was divided into 7 groups. Figure 9 shows that landslide area distribution ratio increases with the increase of slope height, which reveals landslide occurrence probability increases with slope height during the earthquake.

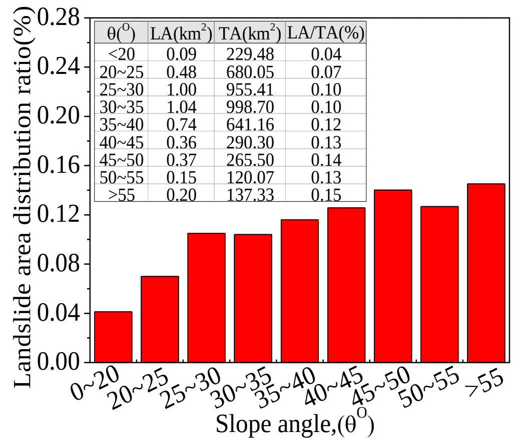

Fig.8. Landslide area distribution ratios related to slope angle

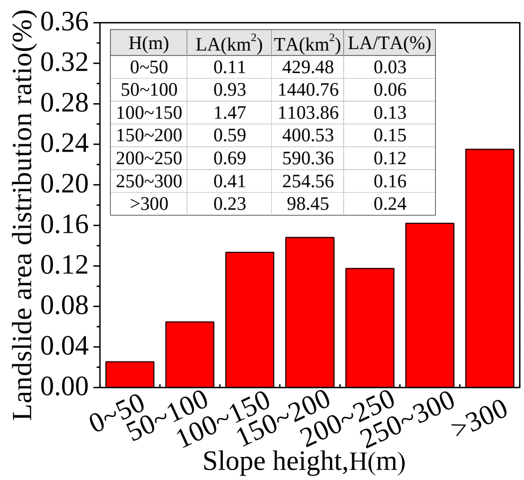

Fig.9. Landslide area distribution ratios related to height group

Effects of rock type and geological structure

Based on classification of rock type, as listed in Table 2, landslide area distribution ratios were respectively calculated in each rock type group. The results are shown in Fig.10. It reveals landslide area distribution ratio increases from hard rock to soft rock and landslide occurrence probability of soft rock slope is much higher than others.

Figure 11 (a) ~ (f) are sketches of geological structures. They are classified into two categories. The first category is that slope has apparent stratigraphic surfaces, namely, rock bedding surfaces, these surfaces are separately continuous and with almost the same inclination direction. This category is defined as ‘bedded-rock structure’, moreover, ‘bedded-rock structure’ is divided into four subclasses based on the relation between rock bedding inclination angle (α) and slope angle (θ), sketches are shown in Fig.11 (a) ~ (d). The secondary category is slope with discontinuous stratigraphic surfaces, such as Fig.11 (e) and (f), which are named as ‘others’.

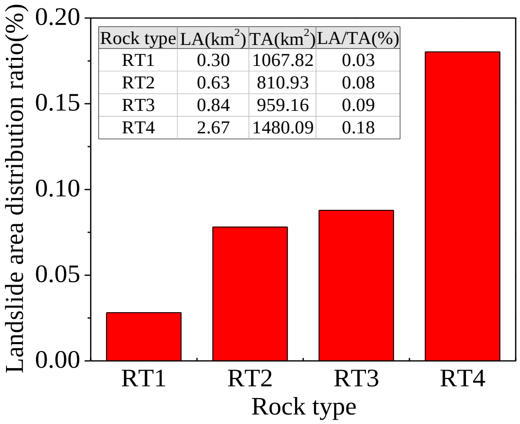

Fig.10. Landslide area distribution ratios related to rock type

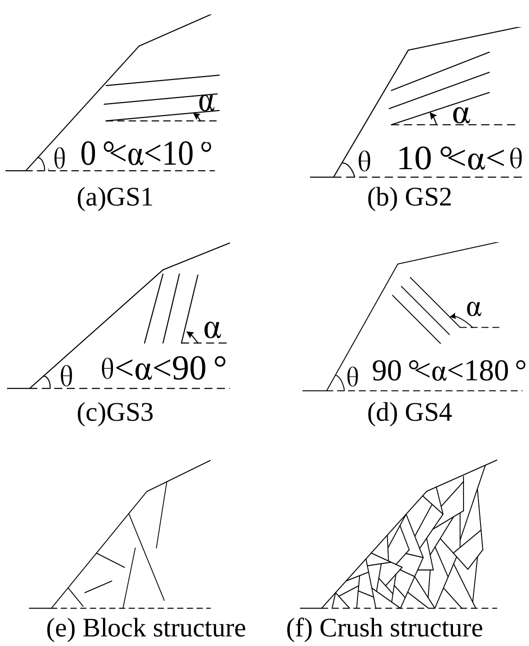

Fig.11. Sketches of geological structures

Figure 12 shows the result of landslide area distribution ratios related to geological structure and reveals slope with GS2 geological structure was more unstable during the earthquake and followed by GS4, which rock bedding has adverse inclination direction to slope inclined surface. When geological structure is GS1 ($0^o < \alpha < 10^o$) or GS3 ($\theta < \alpha < 90^o$), their landslide area distribution ratios are both smaller than ‘others’, it suggests slopes with GS1 or GS3 geological structure were more stable during the earthquake.

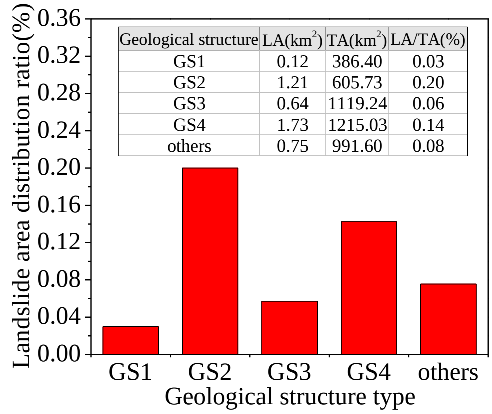

Fig.12. Landslide area distribution ratios related to geological structure

LANDSLIDE SUSCEPTIBILITY ANAYSIS ON TRIGGERING FACTORS

As mentioned above, landslide area distribution ratio is affected by five factors. Sliding area and volume are the two most important outcomes of slope instability; they indicate the affected scope and disaster scale. Therefore, it is necessary to analyze the relationship between sliding area, sliding volume and influential factors.

Horizontal peak ground acceleration, slope angle, slope height, rock type and rock bedding inclination angle were regarded as independent variables to conduct multivariable regression. The parameters of 97 landslides were applied to regress. However, since 22 landslides are lack of rock bedding inclination angle (α), they were excluded from the regression analysis,

Regression results of sliding area and volume are shown as equation (3) and (4), respectively, where *LA* refers to sliding area (m^2), *LV* refers to sliding volume (m^3); *PGA* refers to horizontal peak ground acceleration (m/s^2); H represents slope height (m), θ represents slope angle (^{o}); α denotes rock bedding inclination angle (^{o}). *RT* refers to rock type, which was qualitatively considered; 4, 3, 2, and 1 were assigned to RT1, RT2, RT3 and RT4, respectively.

Since regression coefficients are affected by the independent variables units, therefore, standardized regression coefficients are applied to exclude the effectiveness of units and have insight into the influence of each independent variable to dependent variable. Standardized regression coefficient of each variable is shown in the bracket of equation (3) and (4).

$$LA^{1/2} = 12.04PGA + 0.67H - 19.92\tan\theta + 51.88\sin\alpha - 3.34RT \quad (3)$$
$$(0.22) \quad (0.59) \quad (-0.06) \quad (0.13) \quad (-0.03)$$

$$LV^{1/3} = 3.15PGA + 0.20H - 5.59\tan\theta + 23.90\sin\alpha + 0.67RT \quad (4)$$
$$(0.18) \quad (0.56) \quad (-0.05) \quad (0.18) \quad (0.02)$$

Absolute values of standardized regression coefficients suggest slope height, horizontal peak ground acceleration and geological structure are more influential to sliding area and volume than slope angle and rock type. Because sliding area and sliding volume are the two most important outcomes of slope instability, therefore, it is conjectured that slope height, horizontal peak ground acceleration and geological structure are the most important factors to affect slope stability during the earthquake.

Comparing square root of observed sliding area and cube root of observed sliding volume with predicted results by regression formulae (3) and (4), the results are shown in Fig.13 and Fig.14, respectively.

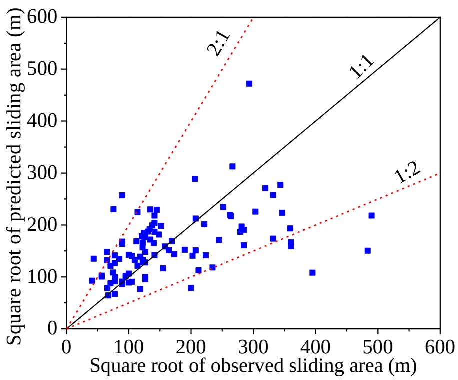

Fig.13. Comparing square root of observed sliding area with square root of predicted sliding area

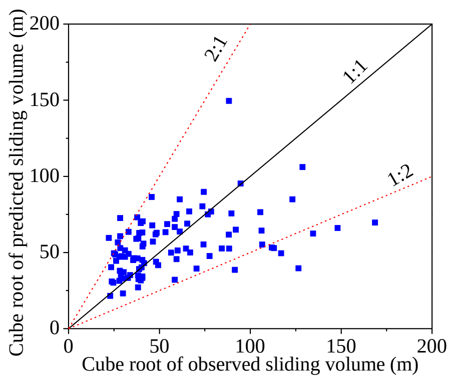

Fig.14. Comparing cube root of observed sliding volume with cube root of predicted sliding volume

Regressive F-values of equations (3) and (4) are 70.38 and 74.09, respectively; they are both bigger than 95% F-test threshold value 2.31, so overall regressions of equations (3) and (4) respectively satisfy significance level. It is inferred that investigation method may cause those points below the 1:2 gradient red dot line. Because several very close landslides were regarded as one landslide during investigation, this investigation method results in subjectively enlarging sliding area and volume. Some points above 2:1 gradient red dot line may be due to regression error.

CONCLUSIONS

Due to vulnerable circumstances and devastating magnitude, Wenchuan earthquake induced lots of landslides and caused enormous casualties and economic losses. In this article, the authors investigated co-seismic landslides in Wenchuan County. The main conclusions are as follows:

(1) The average landslide area distribution ratio of hanging wall side between Yingxiu-Beichuan fault and Wenchuan-Miaoxian fault is 2.5 times as large as that of footwall side. Horizontal peak ground acceleration of hanging wall is distinctly larger than that of footwall; therefore, the authors recommend hanging-foot wall effect had better be considered when projects are nearby the thrust fault.

(2) The result of multivariable regression analysis reveals slope height, horizontal peak ground acceleration and geological structure are more influential to sliding area and volume than slope angle and rock type during the earthquake, which suggests slope height, horizontal peak ground acceleration and geological structure are the most important factors to affect slope stability during the earthquake.

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