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Qualitative and quantitative analysis on landslide influential factors during Wenchuan earthquake: A case study in Wenchuan County

Deping Guo *, Masanori Hamada

Department of Civil and Environmental Engineering, Waseda University, 3-4-1Okubo, Shinjuku-ku, Tokyo 169–8555, Japan

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ABSTRACT

The 2008 Wenchuan earthquake with a surface wave magnitude of 8.0 triggered numerous landslides along the Longmenshan thrust fault belt in Sichuan province of China. The authors investigated various influential factors on the slope stability of 119 landslides in Wenchuan County, such as the horizontal peak ground acceleration, slope angle, slope height, rock type and geological structure. We separately developed acceleration attenuation laws for both the hanging wall and footwall side from 183 seismic stations. These formulae confirmed the hanging-foot wall effect had notable influence on landslide distribution density and occurrence probability. Further, we explored the qualitative tendency of landslide distribution and occurrence probability related with each influential factor. The results from the quantitative analysis by a multivariable method demonstrated that slope height, horizontal peak ground acceleration and geological structure had a stronger effect on the sliding area and volume than slope angle and rock type.

1. Introduction

On May 12th 2008, a disastrous earthquake, Ms = 8.0, with a focal depth of 14 km, occurred at Wenchuan County of Sichuan province in China; the location of the epicenter is 31.0° north latitude, 103.4° east longitude (China earthquake administration, CAE, 2008). Two main surface fault ruptures were generated: the 240 km-long Beichuan surface rupture on the Yingxiu-Beichuan fault and the 72 km-long Hanwang surface rupture on the Penguan fault (Xu et al., 2009a). 190,693 landslides had been induced (Xu and Xu, 2012). It was estimated that the total economic losses exceeded 10 trillion RMB, and a third of the total was accounted for co-seismic geological disasters, especially landslides (Chen et al., 2009); about 20,000 deaths were attributed to landslides (Huang and Li, 2008, 2009a). In many previous studies, the attention was paid to analyze the qualitative relation between landslide spatial distribution pattern and influential factors, such as the seismic factors (distance from epicenter or surface fault rupture, intensity), geomorphologic factors (gradient, elevation, slope orientation and ground surface curvature) and geological factors (lithology and geological structure) (Huang and Li, 2009a, 2009b; Xu et al., 2009b; Yin et al., 2009; Chigira et al., 2010; Qi et al., 2010; Xu et al., 2010; Dai et al., 2011; Gorum et al., 2011; Xu and Xu, 2012). However, most of these researchers used a single factor analysis method to discuss the general tendency. Since there are several influential factors on landslide distribution pattern and slope stability, it is necessary to apply a composite analysis, including as many influential factors as possible, to clarify which factor/factors is/are more important to slope stability for better understanding landslide mechanisms during the earthquake. Here, we firstly discuss the general tendency of landslide distribution related with each influential factor in Wenchuan County, then use a multivariable method to explore the different factors influencing the development of landslide areas and sliding volumes as well as slope stability itself.

2. Data collection

The National Strong-Motion Observation Network System (NSMONS) of China was completely established in March 2008, just before the Wenchuan earthquake (Li et al., 2008). During the main shock, 420 seismic stations were triggered. In order to obtain seismic ground acceleration for each landslide site, the authors selected 183 out of these 420 records to define an acceleration attenuation law, obeying the model as Eq. (1) discussed in Section 3. All of these 183 seismic stations surrounding Wenchuan County are distributed within a square of 900 × 900 km, as shown in Fig. 1(a).

The authors investigated landslides in Wenchuan County, where the seismic intensity was in the range of VII–XI Chinese seismic intensity. Two thrust faults are crossing this County, the N30~45°E trending Wenchuan-Maoxian fault and the N35°E trending Yingxiu-Beichuan fault. The Wenchuan earthquake occurred on the Yingxiu-Beichuan fault. This article pays attention to two kinds of landslide: first, large landslides with a sliding volume bigger than 10^4 m^3; second, landslides that had impacted the infrastructure. When several landslides were located at close distances and their slope angles were almost the same, they were regarded as one landslide zone. 119 landslides are

* Corresponding author.
E-mail address: guodeping99@gmail.com (D. Guo).

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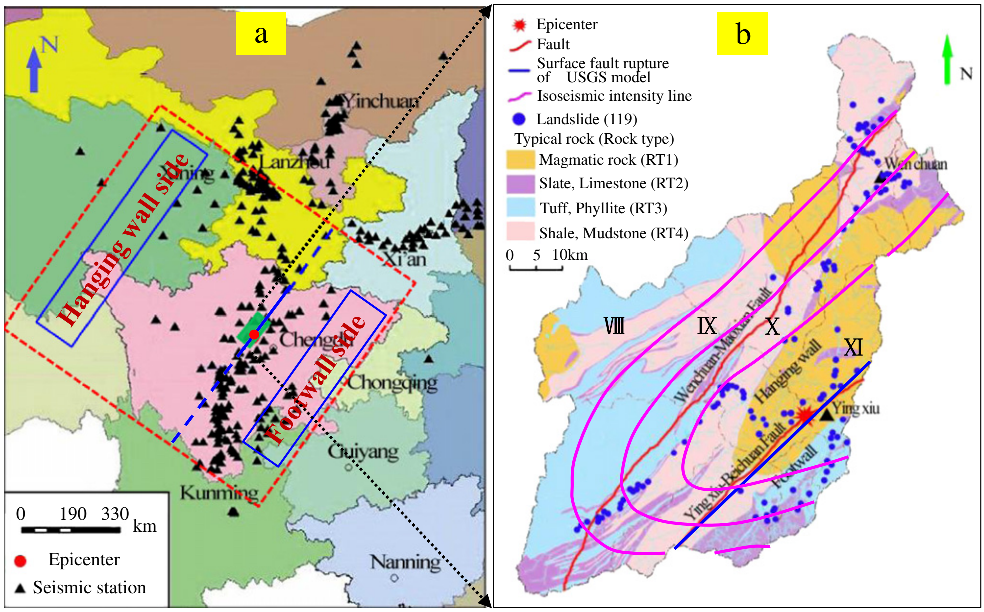

Fig. 1. (a) The distribution of seismic stations around Wenchuan County. (b) The distribution of investigated landslides in Wenchuan County.

distributed over the area shown in Fig. 1(b), where the blue solid line represents the strike of the surface fault rupture of the USGS model by Chen and Hayes (2008).

The sliding area outlined on the map was calculated by using ArcGIS software, and the sliding volume was estimated by multiplying the sliding area by the average collapse depth of the sliding body. The average collapse depth was obtained from the typical longitudinal profile of slope, as shown in Fig. 2.

According to rock strength and the degree of weathering, rock materials were assorted into two types, such as hard rock and soft rock; further, they were divided into two subclasses, respectively, as listed in Table 1.

3. Ground acceleration attenuation regarding hanging-foot wall effect

The Wenchuan earthquake occurred in the Longmenshan thrust fault belt. Such as for other historical earthquakes on thrust faults, the hanging-foot wall effect could also be demonstrated for the Wenchuan earthquake by statistical analysis from field investigation and remote sensing interpretation (Huang and Li, 2008, 2009a; Chigira et al., 2010). Fig. 3 illustrates that a hanging-foot wall effect clearly exists; it shows that much more landslides occurred on the hanging wall side than on the footwall side indicating that the landslide occurrence probability was much higher on the hanging wall side.

Since the hanging-foot wall effect had a significant influence on landslide distribution pattern and occurrence probability, the acceleration attenuation law was respectively regressed on the hanging wall and footwall. Considering that landslides were triggered along the surface fault rupture (Huang and Li, 2008) rather than radial distribution from epicenter, herein, distance from surface fault rupture was employed as regression parameter to obtain acceleration attenuation formulae. Furthermore, the main surface fault rupture was 240 km-long Beichuan surface rupture along Yingiu-Beichuan fault (Xu et al., 2009a) and the USGS finite element model could locate it, as shown in Fig. 1(a), represented by the blue solid line. Therefore, the nearest distances from seismic stations to Yingxiu-Beichuan surface fault rupture were used to get the acceleration attenuation law.

183 seismic stations were assorted into two groups according to their locations. 93 seismic stations locate on the hanging wall side, 90 seismic stations are on the footwall side, as shown in Fig. 1(a).

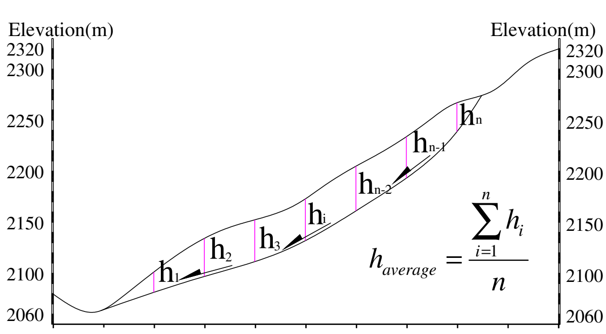

Fig. 2. Typical longitudinal profile of slope.

Table 1
Classification standard of rock type (Chang et al., 2006).

Rock type		Weathered degree and typical rock	Uniaxial compression strength (σ, MPa)
Hard rock	RT1	Non-weathered~slightly weathered magmatic rock, diorite, basalt, andesite, gneiss and quartzite, etc.	$\sigma > 60$
	RT2	1) Non-weathered~slightly weathered marble, slate, limestone, dolomite, metamorphic quartz rock, etc. 2) Moderately weathered magmatic rock, diorite, basalt, andesite, gneiss and quartzite, etc.	$30 < \sigma \leq 60$
Soft rock	RT3	1) Non-weathered or slightly weathered tuff, phyllite, marl, sandy mudstone, etc. 2) Moderately~strongly weathered hard rock	$15 < \sigma \leq 30$
	RT4	1) Non-weathered~slightly weathered shale, mudstone, shaly sand, etc. 2) Strongly weathered hard rock 3) Moderately~strongly weathered tuff, phyllite, marl, sandy mudstone, etc.	$\sigma \leq 15$