Geomorphology 217 (2014) 15–22

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Critical acceleration as a criterion in seismic landslide susceptibility assessment

Xiao-Li Chen [a,*], Chun-Guo Liu [b], Lu Yu [a], Chuan-Xiang Lin [c]

[a] Key Lab of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing, 100029, China
[b] China Earthquake Networks Center, Beijing, 100045, China
[c] Beijing Institute of Geology, Beijing 100120, China

ARTICLE INFO

Article history:
Received 23 July 2013
Received in revised form 1 April 2014
Accepted 7 April 2014
Available online 18 April 2014

Keywords:
Earthquake-triggered landslides
Newmark's method
Critical acceleration
Potential landslide assessment
The Wenchuan earthquake

ABSTRACT

The 2008 Wenchuan earthquake in China triggered approximately 200,000 landslides. This study examined a detailed landslide inventory for the event. Based on Newmark's method, the correlation between critical acceleration and landslide occurrence was analyzed for the Beichuan region in Sichuan Province, where various kinds of geohazards occurred due to the earthquake. The results indicate that critical acceleration is a good and reliable criterion to assess slope stability, and that slope gradient and material component are important factors influencing landslide occurrences. It was found that external forces behave differently in different directions. Critical acceleration in horizontal direction is more important for assessing the stability of steeper slopes. This knowledge will help in the understanding of the mechanism of earthquake-triggered landslides and facilitate the combined use of critical acceleration and landslide distribution maps for determining peak ground acceleration in a region without abundant seismic instrument records.

1. Introduction

Earthquake-triggered landslides have been a major cause of casualties and damages in recent earthquake events. The 2008 Wenchuan earthquake in China triggered numerous landslides, causing about 20,000 deaths (Yin et al., 2009). Such large and widely distributed landslides can be prevented neither by current mitigating countermeasures nor by regular monitoring to predict rainfall-triggered landslides, although research on the zoning of earthquake-triggered landslides has been conducted in various countries (e.g., Guzzetti et al., 1999; Rodríguez et al., 1999; Miles and Keefer, 2001a, 2001b; Bommer et al., 2002; National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism, 2004; Jibson and Michael, 2009).

Many studies about earthquake-triggered landslides have focused on the relationship between landslide distribution and factors contributing to slope failures, although they are generally complex and difficult to assess with confidence. As a factor of landslides triggered by earthquake, peak ground acceleration (PGA) has been proved to be strongly correlated with landslide density: with the increase of PGA, landslides increase (Keefer, 1984; Harp and Jibson, 1996; Wang et al., 2003, 2007, 2008; Kieffer et al., 2006; Meunier et al., 2007; Chen et al., 2010; Qi et al., 2010).

Many methods have been developed to assess the stability of slopes. Newmark's method is the one that has been widely and successfully applied in seismic landslide hazard assessment (Jibson et al., 2000; Miles and Keefer, 2001a, 2001b; Jibson and Michael, 2009). Wilson and Keefer (1985) used Newmark's method to model the dynamic behavior of landslides on natural slopes and to assess seismic slope stability for a broad region in the Los Angeles area. Based on this physical method, Jibson et al. (2000) proposed a method to map the probabilities of seismic slope failure, which yielded reasonable results for the 1994 Northridge earthquake in Oat Mountain, California. Kaynia et al. (2010) also developed a real-time mapping system for earthquake-triggered landslides based on this method. In the studies above, the permanent-displacements calculated from different empirical prediction models were used to predict the stability of natural slopes during an earthquake event. Nevertheless, the equations used for displacement predictions were calibrated using data from specific regions, and their applications to other regions with different geological or climatic conditions will increase the uncertainty of the results.

The 2008 Wenchuan earthquake, which originated in the Longmen Shan fault zone at the eastern margin of the Tibetan Plateau, was the largest seismic event in China in more than 50 years. The earthquake triggered more than 60,000 destructive landslides that caused about one-third of the total number of fatalities (Huang and Fan, 2013). Many studies so far have dealt with different aspects of the landslides triggered by the event, and the landslide inventory has been gradually improved (Huang and Li, 2009; Yin et al., 2009; Qi et al., 2010; Dai

* Corresponding author. Tel.: +86 10 62009056.
E-mail address: 04chxl@sina.com (X.-L. Chen).

http://dx.doi.org/10.1016/j.geomorph.2014.04.011
0169-555X/

et al., 2011; Xu et al., 2013). However, few studies have related the critical acceleration of slopes to the landslides.

Based on Newmark's method, we have calculated the critical acceleration of the natural slopes in the Beichuan region which suffered severe landslide damage due to the Wenchuan earthquake and correlated the critical acceleration values with the landslide distribution. We propose to use critical acceleration and landslide distribution maps as references to determine peak ground acceleration in a region without abundant seismic instrument records.

2. Geological setting and landslides of the study area

The Wenchuan earthquake triggered numerous landslides from rock falls of a few m^3 to rock avalanches of tens of millions m^3. The most detailed landslide inventory is provided by Xu et al. (2013), who analyzed nearly 200,000 landslides triggered by the earthquake distributed in an area of about 110,000 km^2. This study presents a good data set for deeper and more detailed landslide research.

Landslides triggered by earthquakes are clustered along causative seismic faults (Keefer, 1984, 2002; Khazai and Sitar, 2003; Wang et al., 2003, 2007; Jibson et al., 2004; Wen et al., 2004). This is the case with the Wenchuan earthquake (Huang and Li, 2008, 2009; Chen et al., 2010; Qi et al., 2010; Xu and Li, 2010; Dai et al., 2011). The distribution of the large landslides is particularly correlated with that of the coseismic displacements (Chen et al., 2012). We divided the region where most of the large landslides (≧50,000 m^2 in area) are concentrated into four zones along the Longmen Shan fault: Yingxiu, Gaochuan, Beichuan and Qingchuan from southwest to northeast (Chen et al., 2012). The chosen study area is mainly distributed in the Beichuan zone (Figs. 1 and 2).

The study area is about 40 km long and 16 km wide. The seismogenic Yingxiu–Beichuan fault cuts through the study area from southwest to northeast and forms an obvious rupture zone during the event (Fig. 2). According to the latest landslide inventory provided by Xu et al. (2013), there are more than 7600 landslides with a total affected area around 60 km^2 in the study area. These landslides have different volume sizes in the form of various failure types, and most of them are in a small or moderate scale. Statistics show that more than 70% of the landslides are with an area of < 5000 m^2, and more than 20% of the landslides are with an area of < 1000 m^2. Although there are only 214 landslides greater than 50,000 m^2, they occupy more than 23 km^2, which is 38% of the total affected area.

On the whole, landslides are clustered along the Yingxiu–Beichuan fault, and are distributed unevenly on both sides of the rupture zone (Fig. 2). More than 80% of the landslides are located on the hanging wall, showing sharp effects of the wall. Landslide–area ratio (LAR), which is expressed as a percentage of the area affected by landslide activity, is around 7.9% on the hanging wall side, whereas it is 2.1% on the footwall side. As to the large landslides with a plane area greater than 50,000 m^2, there are 190 landslides on the hanging wall side compared to 24 landslides on the footwall side. Some notable landslides like the Tangjiashan landslide and the Chengxi landslide also occurred in this study region. The Tangjiashan landslide formed the largest landslide-dammed lake which blocked the upper portion of the Jianjiang River, 5 km from Beichuan County Town. The Chengxi landslide is 4.8×10^6 m^3 in volume, which killed 1600 people and destroyed half of the old area of the Beichuan County Town (Yin et al., 2009).

The study region has exposures of the strata from the Sinian to Quaternary periods, while there is a lack of Jurassic to Cretaceous sequences (Fig. 2, Table 1). Almost all bedrocks appearing in this region are weathered and deformed. Rocks found here mainly include sandstone, mudstone, and shale. Alluvial deposits are developed along the river courses. More than 62% of the landslides are present in the Cambrian and Sinian strata, which outcrop along the seismogenic fault (Fig. 2).

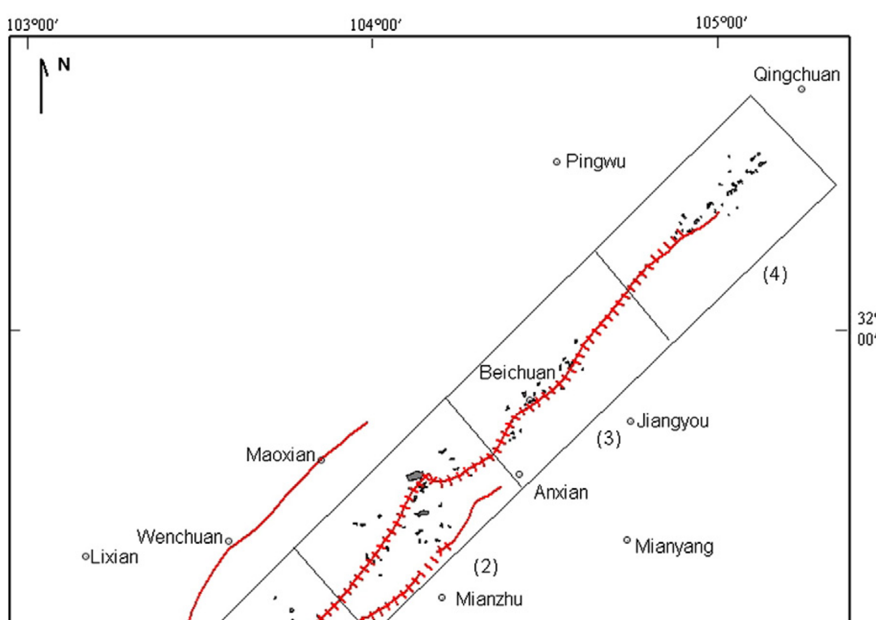

Fig. 1. Distribution of large landslides during the Wenchuan earthquake. F1: Wenchuan–Maowen fault, F2: Yingxiu–Beichuan fault, F3: Guanxian–Anxian fault, (1) Yingxiu segment; (2) Gaochuan segment; (3) Beichuan segment; (4) Qingchuan segment.