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Landslides triggered by the 22 July 2013 Minxian–Zhangxian, China, Mw 5.9 earthquake: Inventory compiling and spatial distribution analysis

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ABSTRACT

On July 22, 2013, an earthquake of Ms. 6.6 occurred at the junction area of Minxian and Zhangxian counties, Gansu Province, China. This earthquake triggered many landslides of various types, dominated by small-scale soil falls, slides, and topples on loess scarps. There were also a few deep-seated landslides, large-scale soil avalanches, and fissure-developing slopes. In this paper, an inventory of landslides triggered by this event is prepared based on field investigations and visual interpretation of high-resolution satellite images. The spatial distribution of the landslides is then analyzed. The inventory indicates that at least 2330 landslides were triggered by the earthquake. A correlation statistics of the landslides with topographic, geologic, and earthquake factors is performed based on the GIS platform. The results show that the largest number of landslides and the highest landslide density are at 2400 m–2600 m of absolute elevation, and 200 m–300 m of relative elevation, respectively. The landslide density does not always increase with slope gradient as previously suggested. The slopes most prone to landslides are in S, SW, W, and NW directions. Concave slopes register higher landslide density and larger number of landslides than convex slopes. The largest number of landslides occurs on topographic position with middle slopes, whereas the highest landslide density corresponds to valleys and lower slopes. The underlying bedrocks consisting of conglomerate and sandstone of Lower Paleogene (E^b) register both the largest number and area of landslides and the highest landslide number and area density values. Correlations of landslide number and landslide density with perpendicular- and along-strike distance from the epicenter show an obvious spatial intensifying character of the co-seismic landslides. The spatial pattern of the co-seismic landslides is strongly controlled by a branch of the Lintan-Dangchang fault, which indicates the effect of seismogenic fault on co-seismic landslides. In addition, the area affected by landslides related to the earthquake is compared to the relationship of “area affected by landslides vs. earthquake magnitude” constructed based on earthquakes worldwide, and it is shown that the area affected by landslides triggered by the Minxian–Zhangxian earthquake is larger than that of almost all other events with similar magnitudes.

1. Introduction

In mountainous areas, major earthquakes can trigger large number of landslides in broad areas with high intensity and large scales (e.g. Keefer, 1984; Xu et al., 2014a), which will further result in serious economic losses and casualties. In recent years, earthquake-triggered landslides receive increasing attention of researchers in fields of active tectonics, geomorphology, engineering geology, hazards and environmental geology, geo-statistics, GIS and remote sensing, as well as other related subjects.

A detailed, comprehensive, and complete landslide inventory is an essential database for subsequent studies (Keefer, 2002; Harp et al., 2011; Guzzetti et al., 2012), such as spatial distribution analysis, susceptibility and hazard assessment (Xu et al., 2012a,b,c,d; Lee et al., 2008; Xu and Xu, 2012a), geomorphologic evolution that controlled by co-seismic landslides (Parker et al., 2011; Hovius et al., 2011), and landslides and debris flows mitigation of the earthquake areas. The early stage of such studies was summarized by Keefer (1984, 2002) and Rodriguez et al. (1999). Later, there were several reports of relatively detailed and comprehensive landslide inventories related to major earthquakes, such as the

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1989 Loma Prieta Mw 6.9 earthquake in the USA (Keefer, 2000), 1994 Northridge earthquake of the USA (Harp and Jibson, 1996), 1999 Chi-Chi, Taiwan, earthquake (Liao and Lee, 2000; Lee et al., 2008; Wang et al., 2002, 2003; Khazai and Sitar, 2004), 2004 Niigata Prefecture Mw 6.6 earthquake of Japan (Yamagishi and Iwahashi, 2007; Chigira and Yagi, 2006; Sato et al., 2005; Wang et al., 2007), 2005 Kashmir Mw 7.6 earthquake in Pakistan (Sato et al., 2007; Owen et al., 2008), 2008 Wenchuan, China, Mw 7.9 earthquake (Xu et al., 2010a, 2014a, and references therein), 2008 Iwate-Miyagi Mw 6.9 earthquake of Japan (Yagi et al., 2009), the 2010 Mw 7.0 Port-au-Prince earthquake in Haiti (Xu et al., 2012a, 2014b; Gorum et al., 2013), 2010 Mw 6.9 Yushu earthquake of China (Xu et al., 2013a; Xu and Xu, 2014a; Yin et al., 2010), 2010 Hejing and Xinyuan, Xinjiang earthquake of China (Li et al., 2012), the 2011 Tohoku-oki Mw 9.0 earthquake of Japan (Wartman et al., 2013), and the 2013 Lushan, Mw 6.6 earthquake (Xu et al., 2013b; Xu and Xu, 2014b; Chen et al., 2014; Wang, 2014).

In particular, a series of new research results of earthquake landslides have been published related to the 2008 Wenchuan, China, earthquake, (Xu et al., 2010a, 2014a, and references therein). This event triggered nearly 200 thousands of landslides, covering about 1160 km^2 throughout a broad area of about 100,000 km^2 (Xu et al., 2014a). The landslide inventory of this event is the most comprehensive and detailed for an individual great shock ever reported so far. This database has been used for subsequent landslide spatial distribution analyses (Xu and Xu, 2012b), hazard evaluations (Xu et al., 2013c,d), as well as seismic intensity inversions (Xu et al., 2013e). These studies not only have provided scientific and technological support for landslide and debris flow disaster prevention and mitigation, engineering site choice, and stability evaluations in the areas with potential seismic hazards, but also are significant for basic studies such as topographic evolution of the earthquake areas (Parker et al., 2011; Xu et al., 2014c), controlling of active faults on landslide spatial distribution patterns (Gorum et al., 2011; Tatard and Grasso, 2013; Xu et al., 2014a; Xu, 2014a), and implications for earthquake rupture processes (Meunier et al., 2013).

According to the China Earthquake Network Center (CENC, www.cenc.ac.cn), an earthquake of *M*s. 6.6 struck between Minxian and Zhangixan of Gansu Province, China, at 07:45 (Beijing Time) on 22 July 2013. Its epicenter is located at 34.5°N, 104.2°E, with a focal depth of 20 km. About one and a half hours later (09:12, Beijing Time), a Ms. 5.6 aftershock (34.6°N, 104.2°E) with focal depth of 14 km occurred. According to USGS (www.usgs.gov), the main shock and the largest aftershock were of Mw 5.9 and Mw 5.6, located at (34.5°N, 104.24°E) and (34.57°N, 104.13°E), respectively, and both had focal depth of 10 km. As of 20:40 (Beijing Time) of 23 July, the earthquakes has caused 95 deaths, 1366 injuries, 69,700 buildings (including houses, farm buildings, barnyards, etc.) of 17,900 families collapsed, 124,300 buildings of 40,400 families seriously damaged, and 269,200 buildings of 82,400 families largely damaged (China Earthquake Administration, http://www.cea.gov.cn/publish/dizhenj/468/553/100500/100502/20130725104839790544691/index.html, 25 July 2013; last accessed October 2013). In total, the earthquake affected the life of about 780.1 thousand people.

Immediately after this event, we arrived at the earthquake area to carry out field investigations of seismotectonics and earthquake-triggered landslides. In this paper, we present the landslide spatial distribution and landslide classification. Then, a comprehensive inventory of landslides triggered by the earthquake is prepared by interpretations of high-resolution satellite images, and selected matching to landslide photos is used to verify the inventory objectivity and accuracy. Next, we correlate the landslides with topographic, geologic, and seismic parameters in a rectangle area. The approximate area affected by landslides, also known as landslide limit area, related to the earthquake was compared to the relationship of "area affected by landslides vs. earthquake magnitude" constructed based on other earthquake events worldwide. According to the main landslide distribution area, correlations of landslides with regional faults were analyzed. Finally, we preliminarily inferred the seismogenic fault based on location correlations of the fault and co-seismic landslides.

2. Geologic setting

The Minxian–Zhangxian earthquake took place on the Lintan-Dangchang fault in the northeastern margin of the Tibetan plateau (Fig. 1). The fault is dominated by thrust with left-lateral slip component (Zheng et al., 2013a,b). This fault has been active since late Pleistocene, and is located between two major sinistral strike-slip faults, i.e., the East Kunlun fault zone (EKFZ) and the northern marginal fault zone of the West Qinling (NMFZWQ). Its activity is obviously different in different segments and uneven within each segment. The area between the two major faults can be considered as a large structural transition zone, with several secondary accommodation structures to absorb and transfer the strain, and the Lintan-Danchang fault is one such structure. These faults mostly show prominent northeast-convex arc-shape. Such a shape suggests that the faults were previously reverse faults that accommodated the transition of motions between the two major faults. More recently, these reverse faults have evolved to also accommodate a significant strike-slip component (Zheng et al., 2007a,b). According to the China Earthquake Data Center (http://data.earthquake.cn/data/), as of 28 July 2013, more than 300 aftershocks occurred, of which one was M 5.0–5.9, three were M 4.0–4.9, and 19 events were M 3.0–3.9. As shown in Fig. 2, except for the Lixian-Luojiabu fault (F8) that strikes southwest-northeast, all other faults strike in northwest-southeast directions. The study area of this work is a rectangle of size 22 km by 15 km (the study/statistical area shown in Figs. 2 and 3), mostly lying in the range of seismic intensity VIII. Before the 2013 event, there were 19 historical $M \geqslant 4.7$ earthquakes ever been recorded in the Minxian–Zhangxian earthquake affected area (Fig. 2). The earthquakes before 1973 A.D. are collected from Disaster Prevention Department of China Earthquake Administration (1999) and Disaster Prevention Department of National Seismological Bureau (1995), whereas others are from USGS (www.usgs.gov). Among the recorded historical earthquakes, only one had magnitude $M \geqslant 7.0$, which is produced by rupture the northern margin fault of the Western Qinling in October 143 A.D. (Yuan et al., 2007). This region has elevations between 2207 m and 3340 m with slope gradients 0–64.6°. The Tao River and several other small rivers run through the study area. Geomorphology of the earthquake-struck area is characterized by severe river incision, frequent slope mass movements, and intermountain basins. This area is dominated by the north subtropical humid to semi-humid climate, with annual rainfall about 550 mm. The vegetation coverage of this area is relatively lower.

3. Data and methods

3.1. Data

In this study, remote sensing images, topographic data, geologic data, and seismic data were collected. Remote sensing images include high-resolution optical satellite images taken both pre-earthquake and post-earthquake. Topographic data include digital elevation model (DEM), slope gradient, slope aspect, slope total curvature, and topographic position information, etc. Geologic data contain regional faults and lithology data. Seismic data include