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Do buried-rupture earthquakes trigger less landslides than surface-rupture earthquakes for reverse faults?

Chong Xu *

Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, #1 Huayanli, Chaoyang District, P.O. Box 9803, Beijing 100029, China

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ABSTRACT

Gorum et al. (2013, *Geomorphology* 184, 127–138) carried out a study on inventory compilation and statistical analyses of landslides triggered by the 2010 *Mw* 7.0 Haiti earthquake. They revealed that spatial distribution patterns of these landslides were mainly controlled by complex rupture mechanism and topography. They also suggested that blind-rupture earthquakes trigger fewer landslides than surface-rupture earthquakes on thrust reverse faults. Although a few lines of evidence indicate that buried-rupture earthquakes might trigger fewer landslides than surface-rupture earthquakes on reverse faults, more careful comparisons and analyses indicate that it is not always true. Instead, some cases show that a buried-rupture earthquake can trigger a larger quantity of landslides that are distributed in a larger area, whereas surface-rupture earthquakes can trigger larger but a fewer landslides distributed in a smaller area.

1. Introduction

Gorum et al. (2013) carried out a study on inventory compilation and statistical analyses of landslides triggered by the 2010 Haiti *Mw* 7.0 earthquake. They revealed that spatial distribution patterns of the co-seismic landslides were mainly controlled by complex rupture mechanism and topography. They also suggested that blind-rupture earthquakes trigger fewer landslides than surface-rupture earthquakes on thrust reverse faults. However, some detailed inventories of co-seismic landslides triggered by either blind-rupture or surface-rupture earthquakes on reverse faults may not agree with the conclusion of Gorum et al. (2013). This paper presents an argument on this issue for further discussion.

2. Co-seismic landslides inventories

Eight inventories of co-seismic landslides were analyzed. They include the four earthquake cases that were used by Gorum et al. (2013): the 1994 Northridge, USA ($Mw = 6.7$); the 1999 Chi-Chi, Taiwan ($Mw = 7.6$); the 2008 Wenchuan, China ($Mw = 7.9$); and the 2010 Port-au-Prince, Haiti ($Mw = 7.0$). The Chi-Chi and Wenchuan are surface-rupture earthquakes on reverse faults, while the others are buried-rupture earthquakes on reverse faults. The four more earthquake events analyzed in this paper are the 2004 Mid Niigata, Japan ($Mw = 6.6$); the 2005 Kashmir ($Mw = 7.6$); the 2008 Iwate–Miyagi Nairiku, Japan ($Mw = 6.9$); and the 2013 Lushan, China ($Mw = 6.6$). Of these, the Lushan earthquake is a buried rupture of a reverse fault, and the other three are with surface ruptures of reverse faults (Table 1). In this paper, two parameters related to co-seismic landslides are used. One is the landslide-distribution area, which represents the approximate extent of a continuous area including all co-seismic landslides. The other is the landslide area, which represents the sum of patchy areas occupied by all co-seismic landslides.

2.1. Buried-rupture earthquakes on reverse faults

2.1.1. 1994 Northridge, USA earthquake

Inventory maps of earthquake-triggered landslides published before 1994 are often uncompleted or paper-based because the use of GIS and remote sensing was limited (Keefer, 2002). Therefore, the 1994 Northridge, USA earthquake is used as the earliest event in this study. This earthquake did not rupture the surface (Hauksson et al., 1995). Although it occurred about 20 years ago, an associated co-seismic landslides inventory completed about one year after the shock (Harp and Jibson, 1995) is fairly comprehensive and detailed. This earthquake triggered about 11,000 landslides, distributed throughout an area of about 10,000 km^2 (Jibson and Harp, 1994; Harp and Jibson, 1995, 1996). The total area of the landslides is 23.8 km^2 according to the co-seismic landslide inventory in vector format prepared by Harp and Jibson (1995).

2.1.2. 2010 Haiti earthquake

This event was caused by a buried reverse fault with left-lateral strike–slip motion (Calais et al., 2010; Hayes et al., 2010; Prentice et al., 2010; de Lépinay et al., 2011; Hashimoto et al., 2011). At least 4492 landslides were triggered by the earthquake, covering an area about 8 km^2, and distributed throughout 2250 km^2 (Gorum et al.,

* Tel./fax: +86 10 62009084.
E-mail address: xc11111111@126.com.

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Table 1
Co-seismic landslides inventory cases.

Earthquakes	Magnitude (*Mw*)	Landslide-distribution area (km^2)	Landslide area (km^2)	Landslide number
Northridge	6.7	10,000	23.8	11,000
Haiti	7.0	3200	8–16	7000–30,000
Haiti*	7.0	6400	16–32	14,000–60,000
Lushan	6.6	2500	No data	10,000
Chi-Chi	7.6	11,000	130	10,000–20,000
Kashmir	7.6	4000	80	3000
Wenchuan	7.9	20,000–44,000	600–1160	80,000–200,000
Iwate–Miyagi Nairiku	6.9	5000	20	8000
Mid Niigata	6.6	600	10	1500

Note: For the case of Haiti, only the landslides on the south wall of the fault were included in the earlier estimation. However, the north wall suffered almost the same ground shaking as shown by the PGA distribution. Therefore all values of landslide parameters were doubled (Haiti*). See text for explanation.

2013). Harp et al. (2013) prepared a point-based co-seismic landslide inventory which registered more than 7000 landslides. Xu et al. (2012, 2014) also prepared a co-seismic landslides inventory map for this event, which shows more than 30,000 landslides covering about 16 km^2 and distributed throughout an area of about 3200 km^2. It should be noted that most affected areas along the north wall of the seismogenic fault for this event are covered by the ocean or a flat plain, which also suffered from strong shaking with high PGA values larger than 200 gal (U.S. Geological Survey, 2010; Xu et al., 2012, 2014). Therefore, the indexes of the Haiti earthquake-triggered landslides may be considered twice the original, i.e. 14,000–60,000 in the landslide number, 16–32 km^2 in the landslide area, and about 6400 km^2 for the landslide-distribution area.

2.1.3. 2013 Lushan, China earthquake

The epicenter of the earthquake was located at about 80 km southwest of that of the 2008 Wenchuan earthquake. Field investigation, spatial distribution of aftershocks, and focal mechanism solutions indicated that the Lushan earthquake is a rupturing event on a blind reverse fault (Xu et al., 2013a; Xu and Xu, 2014). So far no complete co-seismic inventories for these landslides have been prepared. Field investigations (Xu et al., 2013b) and interpretation of high-resolutions satellite images and aerial photographs covering a part of the affected area (Xu, 2013; Xu and Xiao, 2013) suggested that at least 10,000 landslides distributed throughout an area about 2500 km^2.

2.2. Surface-rupture earthquakes on reverse faults

2.2.1. 1999 Chi-Chi earthquake

This reverse-faulting event ruptured the surface over 90 km along the Chelungpu fault (Chen et al., 2001). It triggered about 10,000 landslides (Liao and Lee, 2000; Wang et al., 2003) based on visual interpretation of post-earthquake SPOT images and aerial photographs. These landslides cover about 130 km^2 and distributed in an area of about 11,000 km^2. In addition, Wang et al. (2002) pointed out that at least 20,000 landslides were triggered by the earthquake.

2.2.2. 2005 Kashmir earthquake

Co-seismic surface ruptures triggered by the earthquake were typical pressure ridges and warps extending for a distance about 70 km (Kaneda et al., 2008). Although there were several publications about inventory compiling and spatial distribution of landslides triggered by this earthquake, no one declared their co-seismic landslide inventory maps covering the entire earthquake struck area. By integrating information of crustal deformation (Tobita et al., 2006), surface ruptures (Kaneda et al., 2008), and several published landslide inventory maps (Sato et al., 2007; Kamp et al., 2008; Owen et al., 2008), both the study areas of Sato et al. (2007) and Kamp et al. (2008) cover most of the co-seismic landslide-distribution area. Kamp et al. (2008) delineated 2252 co-seismic landslides, which cover 61 km^2 and are distributed throughout an area of 2550 km^2. Sato et al. (2007) located 2424 co-seismic landslides in an area of 2800 km^2. Because a few landslides may be far away from the co-seismic surface rupture, a landslide number of 3000, a total landslide area of 80 km^2, and a landslide-distribution area of 4000 km^2 are assumed for this earthquake.

2.2.3. 2008 Wenchuan earthquake

The Wenchuan earthquake ruptured two large thrust faults, of 240 and 80 km long, respectively, along the Longmenshan thrust zone on the eastern margin of the Tibetan Plateau (Xu et al., 2009a,b). In addition, a 7-km long surface rupture with reverse and left-slip components almost perpendicular to the Longmenshan thrust belt was also observed (Xu et al., 2009a,b) and is thought to be the frontal reverse fault of the Xiaoyudong stepover on the Beichuan–Yingxiu fault (Tan et al., 2012). A large number of available high-resolutions satellite images and aerial photographs should make it possible to prepare a detailed and comprehensive landslide inventory. However, because of the high density and large distribution area of the co-seismic landslides, such an inventory is actually difficult to compile. So far, the most detailed inventory of the co-seismic landslides of this event was prepared by Xu et al. (2013c), after several earlier versions were released (Xu et al., 2009c; Dai et al., 2011). It contains nearly 200,000 landslides, covering 1160 km^2, with a distribution area of about 44,000 km^2 excluding less abnormal landslides that occurred far away from the epicenter. Parker et al. (2011) also prepared a landslide inventory that registered 73,367 landslides with a total landslide area of 565.8 km^2 and a distribution area of 13,800 km^2. In another landslide inventory of this earthquake, nearly 60,000 landslides were located as points in an area of about 20,000 km^2 (Gorum et al., 2011). It should be noted that there exist significant false negative errors (non-landslide errors, omission) in the point-based landslide inventory, because it is not sure whether a landslide has been pointed or not when facing high density and coalescing of co-seismic landslides. Therefore, for landslides triggered by the Wenchuan earthquake, the author chose 80,000–200,000 as the landslide number, 600–1160 km^2 as the landslide area, and 20,000–44,000 km^2 as the landslide-distribution area.

2.2.4. 2008 Iwate–Miyagi Nairiku earthquake

Although Gorum et al. (2013) have described landslides triggered by this surface-rupture earthquake (Suzuki et al., 2010), there is no complete landslide inventory related to this event ever published. Yagi et al. (2009) delineated 4161 landslides, covering 10.2 km^2, distributed in an area of about 600 km^2. From the PGA map and the presented results (Yagi et al., 2009), the actual number and area of landslides triggered by this earthquake should be doubled, i.e. about 8000 in landslide number, a total landslide area of 20 km^2, and a distribution area of about 5000 km^2.

2.2.5. 2004 Mid Niigata earthquake

This earthquake generated a small thrust surface rupture extending for only about 1 km along a previously unmapped fault with less than 20 cm of vertical displacement (Maruyama et al., 2007). Wang et al. (2007) presented 1212 co-seismic landslides (covering about 8 km^2) distributed in a rectangle area of 275 km^2. By integrating the landslide