Catena 171 (2018) 359–375

Contents lists available at ScienceDirect

Catena

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

Can low-magnitude earthquakes act as a triggering factor for landslide activity? Examples from the Western Carpathian Mts, Poland

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ARTICLE INFO

Keywords:
Landslide
Low-magnitude earthquake
Seismic activity
Triggering factor

ABSTRACT

There are numerous examples of the impact of strong earthquakes on landslide activity. There is however very little information about the ability of low-magnitude earthquakes (M < 5.0) to affect the stability of pre-existing landslide slopes. Two landslides were studied (Hołowiec and Kamień, Western Carpathians, Poland). These are located 20–30 km from seismoactive zones where earthquakes of M ≤ 4.4 occur. We have used tree rings to date past landslide movements possibly caused by earthquakes. We have dated events of tree tilting by landslide activity, after which the trees developed eccentric rings and reaction wood, in a sample of 40 Norway spruces (Hołowiec) and 51 European silver firs (Kamień). The results of dendrochronological dating were compared with the occurrence of earthquakes in the study area (magnitudes, epicentral distance, etc.). We have also analysed precipitation data to help to disentangle the impact of rainfall and earthquakes as triggering factors. We were able to distinguish: earthquake-triggered landsliding with no impact of precipitation, precipitation-triggered landsliding with no seismic impact and landsliding triggered by the overlapping impact of precipitation and earthquakes. The results show that the combination of both triggering factors has the strongest influence on the stability of landslides under study. The study demonstrates the ability of low-magnitude (M < 5.0) earthquakes to trigger landslide activity, even at distances larger than appears from limiting curves published for co-seismic landslides. The results also suggest that the activity of the Kamień landslide can possibly be influenced by the long-distance (over 500 km) influence of strong earthquakes (M 6.8–7.4) from outside of the study area. The study demonstrates that the seismic factor, both local, low-magnitude earthquakes and distant, strong earthquakes, can be an important trigger of landslide activity. Their role may be underestimated in the study area and other areas considered as seismically non-active or of low seismic activity.

1. Introduction

Earthquakes are commonly acknowledged as triggering factors for landsliding. However, this mainly concerns earthquakes of significant magnitude which cause the fast development or reactivation of numerous landslides. A recent and severe example is the 2008 Wenchuan earthquake in China, M 8.0 (e.g. Sato and Harp, 2009). According to Xu et al. (2014b) the earthquake resulted in 197,481 individual coseismic landslides. The 1999 Chi-Chi earthquake in Taiwan, M 7.6, triggered at least 26,000 landslides (Wang et al., 2002). Other strong events causing the occurrence of coseismic landslides are the 2011 Tohoku earthquake in Japan, M 9.0 (Miyagi et al., 2011), the 2002 Alaska, M 7.9 (Gorum et al., 2014), the 2005 Kashmir earthquake, M 7.6 (Owen et al., 2008), and the 2010 Haiti earthquake, M 7.0 (Gorum et al., 2013).

Development of coseismic landslides is also observed during weaker earthquakes with magnitudes between 5.0 and 7.0, such as: the 2004 Mid-Niigata earthquake, Japan, M 6.6 (Sato et al., 2005), the 2003 Lefkada, Greece, M 6.3 (Papathanassiou et al., 2013), the 2007 Aysén Fjord, Chile, M 6.2 (Sepúlveda et al., 2010), the 2013 Minxian, China, M 5.9 (Xu et al., 2014a), and the 2011 Mineral, Virginia, M 5.8 (Jibson and Harp, 2012) earthquakes. Their impact on slopes can also be severe like in case of the 1994 Northridge, USA, M 6.7 earthquake with c 11,000 coseismic landslides observed (Keefer, 2002). Over 15,000 coseismic landslides resulted from the 2013 Lushan, China earthquake of M 6.6 (Xu et al., 2015). A total of 2036 landslides were identified in China after the 2010 Yushu earthquake, M 6.9 (Xu and Xu, 2014).

In the case of strong earthquakes, besides numerous examples of the direct triggering of new coseismic landslides, there is also evidence for

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https://doi.org/10.1016/j.catena.2018.07.028
Received 13 May 2018; Received in revised form 18 July 2018; Accepted 20 July 2018

the reactivation of previously existing landslides (e.g. Martino and Scarascia-Mugnozza, 2005; Šilhán et al., 2012), acceleration of slow-moving landslides (e.g. Lacroix et al., 2015), and the long-term increase of landslide susceptibility and activity (e.g. Lin et al., 2008; Tang et al., 2011). At the same time, examples of landslides triggered by earthquakes of M < 5 (small earthquakes according to "The SHARE European Earthquake Catalogue…" by Stucchi et al., 2013) are scarce and these events seem to have a very small impact on landslide relief. Delgado et al. (2015) described coseismic landslides triggered by an M 4.7 earthquake as being < 2–4 m^3 in volume and occurring more frequently in road cuts than in natural slopes. According to Delgado et al. (2011), events of small magnitude (M < 5.0) can induce small instabilities along areas particularly prone to landsliding, like river banks. The curve of maximum epicentral distance of landslides proposed by Keefer (1984) suggests that an earthquake of M 4.0 (the weakest included on the curve) can influence slopes only within 100 m distance from epicentre. According to the author the most frequent types of mass-movements induced by low-magnitude earthquakes are rock and soil falls and very small disrupted landslides of previously jointed/weathered material (Keefer, 1984). Earthquakes of M < 5.0 are highly unlikely to induce the development of vast and deep landslides but there is also a lack of data on whether low-magnitude earthquakes can cause the reactivation or acceleration of the movement of pre-existing landslides. To the best of our knowledge this has never been described before. Thus the aim of the study was to check if seismic events of M 2.0–5.0 which occurred recently in the study area, the Polish Western Carpathians, were able to influence the stability of adjacent slopes with pre-existing landslides. The analysis was conducted through the dendrochronological reconstruction of landslide activity which is then compared to precipitation and seismic records. We included precipitation data because rainfall is the main triggering factor activating landslides in the study area (Starkel, 1996; Gil, 1997). Precipitation data was thus analysed to facilitate the deciphering of the importance of earthquakes in the activity of the landslides being studied and to exclude landsliding events triggered solely by rainfall.

2. Area of the study

2.1. Seismic activity in the Polish Western Carpathians

Low-magnitude (M 2.0–5.0) and low-intensity (Io ≤ 7 EMS) earthquakes are nowadays observed in the Polish Western Carpathians (Guterch, 2009) (Table 1, Fig. 1(C)). Since the beginning of the 20th century 24 earthquakes of M ≥ 2.0 have occurred in the study area (Guterch et al., 2005; Guterch, 2009). Typically, these earthquakes are shallow and their *hypocenters* do not exceed 5 km depth. Therefore, their macroseismic area may be relatively large. The epicentral intensity Io 4–5 may affect an area of c. 10 km in diameter (Guterch, 2006). The strongest recent earthquakes observed in March 1993 (M 4.4, Io 7), September 1995 (M 3.5, Io 5), and November 2004 (M 4.4, Io 7) were accompanied by series of weaker foreshocks and aftershocks M ≤ 3.5 (Guterch, 2006). No coseismic landsliding was recorded as a result of the recent earthquakes. However, there are reports of landslide activity observed simultaneously with seismic events in 1817 (Io 7) and 1840 (M 5.0, Io 7) (Pagaczewski, 1972; Hojny-Kołoś, 2002; Poprawa and Rączkowski, 2003).

The epicentres of the strongest recently recorded earthquakes are located in two distinctly seismoactive zones: the Podhale Seismic Region at the border between the Inner and Outer Western Carpathians and the Krynica Seismic Region (Fig. 1(C)). For our study we have selected two slopes located close to these zones (Table 2, Figs. 1(B),(C)): the Hołowiec landslide (20–30 km from the 1995 and 2004 epicentres in the Podhale Seismic Region) and the Kamień landslide (c 30 km from the 1993 epicentre in the Krynica Seismic Region).

2.2. Landslides under study

The bedrock of the Hołowiec landslide (Fig. 2) is composed of Podhale flysch dipping in a southern direction, parallel to the slope surface (Fig. 3). The slope that is subject to landsliding is composed of sandstones lying on less resistant, soft mudstones-claystones (Fig. 3), all of Oligocene age and with a dense system of joints. Such bedrock is prone to landsliding and landslides are common in the area (Watycha, 1972). The landslide studied is the largest of these, covering 288 ha (Table 2). The landslide is of a translational type (Rączkowski, 2010) (Figs. 2(A), 3(A)). In addition, it is located 5 km W of an active fault zone where triangle facets have been found in a river valley (Zuchiewicz et al., 2009).

The bedrock of the Kamień landslide (Fig. 2) is composed of Palaeogene Carpathian flysch: mainly shales and sandstones (Fig. 3) with considerable variability in lithology and resistance to weathering. The bedrock is strongly tectonically disturbed (Jankowski and Kopciowski, 2014). It is prone to landsliding and landslides are very common in the study area (Margielewski, 1997). The landslide studied covers 32 ha

Table 1
Earthquakes in the study area since 1950 (data after: * Guterch, 2009, ** Guterch et al., 2005, *** US Geological Survey data after earthquaketrack.com). I–XXI: epicentre location on Fig. 1(C).

No	Date	Epicentral intensity EMS	Depth of the hypocentre (km)	Macroseismic magnitude	Remarks
I*	17. 03. 1966	4–5	3	3.0	3 foreshocks, 5 aftershocks**
II**	24. 10. 1989			2.8	–
III**	15. 11. 1989			2.6	–
IV*	20. 06. 1992	5	3	3.3	foreshocks, aftershocks
V*	01. 03. 1993	7	3	4.4	aftershocks
VI*	11. 09. 1995	5	2	3.5	36 aftershocks M 2.3–3.3**
VII*	13. 10. 1995	4	2	2.9	–
VIII*	13. 10. 1995	4	2	2.9	–
IX**	February 2000	A few local earthquakes in the Podhale Seismic Region, not enough data for accurate location of the epicentre			
X**	07. 07. 2001			2.6	8 aftershocks
XI**	12. 03. 2002			2.6	–
XII**	27. 04. 2002			2.3	–
XIII*	30. 11. 2004	7	3	4.4	aftershocks
XIV*	02. 12. 2004	5	3	3.6	aftershocks
XV*	09. 12. 2004	5	3–5	3.4	aftershocks up to M 2.5***
XVI***	13. 12. 2004		5	2.8	–
XVII*	23. 01. 2005	4–5	3–5	3.1	aftershocks
XVIII*	29. 01. 2005	5	3–5	3.4	aftershocks
XIX*	02. 06. 2005	5	3–5	3.4	aftershocks
XX***	24. 08. 2005		5	2.6	–
XXI***	25. 06. 2006		5	3.1	–