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High-resolution DEMs in the study of rainfall- and earthquake-induced landslides: Use of a variable window size method in digital terrain analysis

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ABSTRACT

We undertake digital terrain analyses of rainfall- and earthquake-induced landslides in Japan, using high-resolution orthoimagery and Light Detection and Ranging (LiDAR) DEMs. Our aims are twofold: to demonstrate an effective method for dealing with high-resolution DEMs, which are often too detailed for landslide assessments, and to evaluate the topographic differences between rainfall- and earthquake-induced landslides. The study areas include the Izumozaki (1961 and 2004 heavy rainfalls), Niihama (2004 heavy rainfalls), Houfu (2009 heavy rainfalls), and Hanokidachi/Kurikoma-dam regions (the 2008 M 7.2 Iwate–Miyagi Nairiku earthquake). The study areas include 7,106 landslides in these five regions. We use two topographic attributes (the slope gradient and the Laplacian) calculated from DEMs in varying window sizes. The hit rates for statistical prediction of landslide cells through discriminant analyses are calculated using the two topographic attributes as explanatory variables, and the landslide inventory data as the dependent variable. In cases of surface failure, the hit rates are found to diminish when the window size of the topographic attributes is too large or too small, indicating that an optimal scale factor is key in assessing shallow landslides. The representative window sizes are approximately 30 m for shallow landslides; the optimal window size may be directly related to the average size of landslides in each region. We also find a stark contrast between rainfall- and earthquake-induced landslides. Rainfall-induced landslides are always most common at a slope gradient of 30°, but the frequency of earthquake-induced landslides increases exponentially with slope gradient. We find that the Laplacian, i.e., the attributes of surface convexity and concavity, and the slope gradient are both important factors for rainfall-induced landslides, whereas earthquake-induced landslides are influenced mainly by slope steepness.

1. Introduction

For decades, most digital terrain analyses of landslide susceptibility have used a medium-resolution Digital Elevation Model (DEM), involving typically 30–50 m square grids, and digitized landslide inventory maps created from paper maps (Iwahashi et al., 2001, 2003; Dai and Lee, 2002; Ayalew and Yamagishi, 2005; Colombo et al., 2005; Havenith et al., 2005; Sato et al., 2005). In the last several years, terrain analysis has begun using high-resolution data, especially using Light Detection and Ranging (LiDAR; airborne laser scanner) DEMs (e.g., McKean and Roering, 2004; Sato and Sekiguchi, 2005; Glenn et al., 2006; Nichol et al., 2006; Ardizzone et al., 2007; Chang et al., 2007). In Japan, Chigira et al. (2004) proposed the use of LiDAR DEMs for landslide research. Unlike traditional DEMs created by airphoto-measurements, LiDAR DEMs are capable of showing small differences in height in residential areas or terrains under forest, after appropriate filtering. Consequently, in Japan, where mountains covered by forests occupy 70% of the land area and lowlands are often covered by buildings, LiDAR DEMs are in growing demand. Malamud et al. (2004) and Galli et al. (2008) have suggested that it is important to use high-resolution and accurate landslide inventory maps.

Sørensen and Seibert (2007) stated, however, that topographic indices change with DEM resolution, and that the highest resolution DEM is not necessarily the most useful. Also, some authors (Armstrong and Martz, 2003; Deng et al., 2007; Wu et al., 2007) stated that if resolutions of source DEMs differ, then values of terrain attributes or their spatial contrast, and results of hydrological analysis, will vary. The authors give a reason: usually a terrain attribute of a cell is calculated using only the elevations of immediately neighboring cells. For landslide risk assessments, a high-resolution DEM, such as a LiDAR DEM, is often too detailed to facilitate the calculation of topographic attributes in ordinary 3×3 cell windows. Although scale issues have been discussed in relation to terrain analysis (Zhang and Montgomery, 1994; Evans, 2003; Claessens et al., 2005; Tarolli and Tarboton, 2006; Sørensen and Seibert, 2007), no method

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of dealing with very high-resolution DEMs, such as LiDAR DEMs, has been established for landslide risk assessments.

Many topographic analyses have been made of earthquake- or rainfall-induced landslides (e.g., Malamud et al., 2004; Sassa, 2005; Chang et al., 2007). However, there is still little comparative research into triggering based on quantitative analysis deriving from large numbers of samples and high-resolution data. In the present study we first consider the scaling problems caused by high-resolution DEMs. The main method is calculation of the gradient of the slope and the Laplacian (relating to curvature of the surface; see Section 3), by expanding window sizes and calculating an optimal window size for each region. Our second objective is to evaluate the risk of landslides, using this method. Accordingly, we compared quantitatively the topographic characteristics of sites where rainfall- or earthquake-induced landslides had occurred, using the previously calculated regionally optimal window sizes. This study has two goals. The first is to demonstrate an effective method for dealing with high-resolution DEMs. The second is to evaluate topographic differences between rainfall- and earthquake-induced landslides. This study should clarify the topographic difference between rainfall- and earthquake-induced landslides.

2. Study areas and data

Fig. 1a shows the study areas. Fig. 1b shows an example of landslide inventory and LiDAR DEM. Table 1 includes descriptions of events, regional lithologies, and specifications of the data. The study areas include 7,106 landslides in five regions (six events). These study areas meet the requirements that LiDAR DEMs had been prepared, many landslides had occurred, and aerial photographs had been taken shortly after the events (Table 1).

Japan is located in the Asian monsoonal region. The Izumozaki region has suffered from two large torrential rainfall events during the Japanese rainy season, in 1961 and 2004. The 1961 event involved two deluges within 2 weeks (250 and 126 mm in daily precipitation), and the 2004 rainfall occurred on a single day, but the precipitation was heavier (360 mm; Kawashima et al., 2005; Yamagishi and Iwahashi, 2007). The 1961 event caused more than twice the number of landslides as in 2004, and there are some differences in the susceptibilities and lithological conditions (Iwahashi and Yamagishi, 2010). The 2004 heavy rainfall in Niihama was caused by typhoons. An hourly rainfall exceeding 50 mm and a total rainfall of more than 400 mm were recorded at many stations (Dahal et al., 2008). The 2009 heavy rainfall in Houfu was caused by torrential rains in the rainy season, and the daily precipitation reached 275 mm (Misumi, 2010). The Kurikoma-dam region lies on the southern flank of the Kurikoma volcano. It is close to the worst-hit area of the 2008 M 7.2 Iwate–Miyagi Nairiku earthquake (Yagi et al., 2009), and suffered many rock failures in a narrow region. The Iwate–Miyagi Nairiku earthquake occurred in inland crust at a depth of 8 km. It has a different mechanism from megathrust earthquakes, such as the 2011 Tohoku earthquake (M 9.0) which occurred along plate boundaries of an ocean trench. The Hanokidachi region lies at the foot of the Kurikoma volcano. The geology of the Hanokidachi region comprises Tertiary sedimentary rocks, and is similar lithologically to the Izumozaki region. The Hanokidachi region suffered fewer landslides than the Kurikoma-dam region, although clear surface ruptures had been investigated (Tsutsumi et al., 2010).

We used 2 m LiDAR DEMs for overlay on the high-resolution landslide inventory data. DEMs surveyed before the events were used for the Houfu region and the regions affected by the Iwate–Miyagi Nairiku earthquake, which caused significant changes in terrain. There are no pre-event DEMs for the Izumozaki and Niihama regions, but post-event DEMs might be reasonably equivalent because most of the landslides in these regions were surface failures (Matsuzawa, 2007; Saito, 2007).

We used 20–60 cm digital orthoimageries to obtain accurate landslide inventory polygons. It was possible to characterize slope failures as small as several meters in width. We employed landslide scars as landslide polygons. Landslides were field-verified in several parts of the study area. The landslide polygons were finally transformed to 2 m grid data, which is the same resolution as the DEMs.

3. Method

We compared high-resolution landslide inventory data and two topographic attributes (slope gradient and the Laplacian) calculated from 2 m DEMs generated from LiDAR data. The landslide inventory data were derived from 20–60 cm orthoimageries, and include 7,106 landslides. We conducted some analyses using the two topographic attributes and compared their statistical characteristics. In this section we describe some methods of data analysis which are rather complicated. Other simple schemes are explained in context.

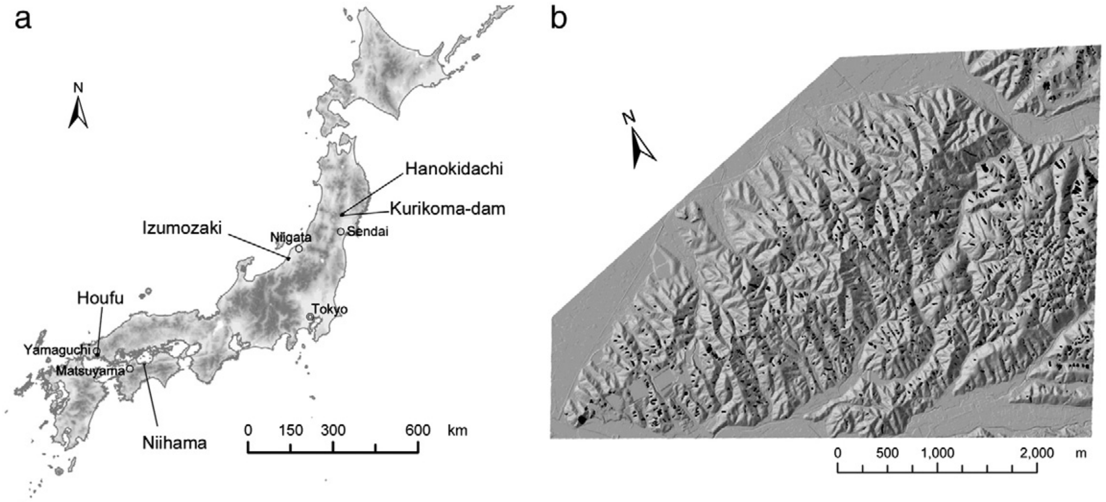

Fig. 1. Locations of the study areas (a) and an image of the Niihama region (b). The shaded relief image in (b) was created from the 2 m DEM, and black dots show the polygons of landslides.