Geomorphology 272 (2016) 102–114

Contents lists available at ScienceDirect

Geomorphology

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

Biographical sketch of a giant: Deciphering recent debris-flow dynamics from the Ohya landslide body (Japanese Alps)

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form 13 November 2015
Accepted 15 November 2015
Available online 18 November 2015

Keywords:
Debris flows
Tree-ring reconstruction
LiDAR DEM
Orthophoto interpretation

ABSTRACT

Debris-flow frequency, discharge, and travel distance are highly catchment dependent and typically controlled by topography, hydrological conditions, and sediment supply. As a consequence, detailed and case-specific investigations are needed to decipher debris-flow histories in order to improve hazard mitigation. This study documents past (ca. 10 years) debris-flow occurrences originating from the Ohya landslide, central Japan, by using a large set of methods including field monitoring, repeat airborne LiDAR, orthophoto interpretation, and tree-ring reconstructions. We demonstrate that the different approaches generally agree on the occurrence of debris flows but that mismatches may exist when it comes to the assessment of areas affected by individual events. These differences may even exceed the usual errors in precision inherent to each of the methods used. In the present case, high-resolution orthophoto interpretation tends to underestimate areas affected by debris flows, especially in the vertical direction, in the absence of lateral movement of the channel bed and as a result of shade and areas under trees. On the other hand, we realize that LiDAR data cannot necessarily be used to distinguish local changes in topography from noise. Tree-ring analyses can help to improve the temporal resolution of the analysis, but may have limitations when it comes to the definition of areas affected by an event because of the point-type nature of data. We conclude that the best and most complete results are obtained by combining multiple methods to improve the spatial and temporal resolution of past debris flows and to delimit areas affected by individual events.

1. Introduction

Debris flows are fast-moving mixtures of water, fines, boulders, vegetation, and air. They often occur in confined channels and have been described as being extremely hazardous as a result of their high velocity, large volumes, and destructive power (Lin et al., 2002; Glade, 2005; Cui et al., 2011). Debris flows are typically initiated through the mobilization of unconsolidated sediment, which is stored in channels, or by shallow landslides through the sudden input of large amounts of water during rainstorms. In addition, rapid snowmelt, rain-on-snow events, or the sudden release of water from glaciers or (landslide) dammed lakes have been identified as triggers of debris flows (Iverson, 1997; Wieczorek and Glade, 2005; Worni et al., 2014; Allen et al., in press). More commonly, however, debris flows were described as being triggered by high-intensity, short-duration downpours or low-intensity, long-duration precipitation events (Stoffel et al., 2011, 2014a,b; Schneuwly-Bollschweiler and Stoffel, 2012).

In addition, debris flow characteristics (such as the frequency, magnitude, and travel distance) differ significantly between catchments as a result of differing catchment topography, hydrological conditions, and/or sediment supply (Fannin and Wise, 2001; Jakob et al., 2005). Detailed knowledge of catchment and debris-flow characteristics are therefore of key importance when it comes to improving site-specific process understanding and appropriate hazard mitigation. Field surveys of debris-flow deposits are one of the possible ways to improve the understanding of debris-flow characteristics (Suwa and Okuda, 1983; Whipple and Dunne, 1992; Cornamusini et al., 2002; Keefer et al., 2003) but will not necessarily provide the temporal resolution needed to understand dynamics, volumes, and return periods of debris-flow events.

Field monitoring has been demonstrated to be one of the best ways to know the timing and flow characteristics of debris flows. Detailed field monitoring has been undertaken in many regions including Europe (March et al., 2002; Hürlimann et al., 2003; Berger et al., 2011a; Arattano et al., 2012) and East Asia (Zhang, 1993; Zhang and

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http://dx.doi.org/10.1016/j.geomorph.2015.11.008
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Cheng, 2003; Hu et al., 2011; Suwa et al., 2011), mostly in torrents with high debris-flow activity. The fact that recurrence intervals of debris flows are often >10 years (e.g., Van Steijn, 1996; Imaizumi and Sidle, 2007) limits the choice of suitable torrents.

LiDAR (light detection and ranging) assessments have become increasingly popular in recent years as they provide detailed information on the evolution and changes in topography and thus allow for a documentation of erosion and deposition processes (Staley et al., 2006; Frankel and Dolan, 2007; Berger et al., 2011b; Bremer and Sass, 2012). Airborne LiDAR is effective for the investigation of larger areas (i.e., >1 km^2), whereas topographic changes in small areas can be detected with high spatial resolution by terrestrial laser scanning (TLS) surveys. The spatial accuracy of the DEM obtained by LiDAR generally ranges from several tens of centimeters to several meters in the horizontal and vertical directions (Bremer and Sass, 2012), which is considered to be sufficient to estimate total volumes of transported sediments as well as areas affected by debris flows. One limitation of LiDAR assessments is the duration covered by a data set, as data only exist since the 1990s. Another weakness of airborne LiDAR assessment is their relatively high cost. Intervals of airborne LiDAR assessment in debris-flow systems are therefore generally in the order of several years.

Aerial photograph interpretation is yet another commonly used method to assess debris-flow histories. Periods that can be assessed with aerial images are generally in the order of several decades and thus (much) longer than those covered by LiDAR data (Crosta and Frattini, 2004; Imaizumi and Sidle, 2007; Brardinoni et al., 2009). Precision of aerial photographs has recently been improved through the orthorectification of images with topographic data from airborne LiDAR (Mackey and Roering, 2011). The approach still has its limitations when it comes to the detection of small mass movements, especially in forested and rugged terrains (Brardinoni et al., 2003; Imaizumi et al., 2008). In addition, the interval between pictures is generally >5 years. Image acquisition by an unmanned aerial vehicle (UAV) has recently been shown to yield good results with respect to changes in topography (de Haas et al., 2014), but the spatial accuracy and breadth of surveyed area still need to be improved for its practical use in debris-flow assessments.

In forested environments, geomorphic processes frequently damage trees and leave evidence of past process activity that can be dated with dendrogeomorphic techniques (Alestalo, 1971; Shroder, 1978; Stoffel et al., 2010). These techniques have been repeatedly applied in the past to reconstruct debris flows on forested cones (Hupp, 1984; Bollschweiler et al., 2007; Stoffel et al., 2008). Debris flows may lead to stem wounding and tilting, root erosion, or stem burial. These disturbances lead to various disturbances such as eccentric growth, abrupt changes in growth rates, or local destruction of the cambium and related anatomical reactions after wounding. These growth disturbances can be dated by visual inspection and/or interpretation of the growth-ring series and enable precise dating of past events (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014). Dendrogeomorphic techniques require intensive fieldwork and laboratory analysis, but recently established guidelines assist in defining sampling positions on debris-flow cones and therefore help in optimizing sample sizes (Schneuwly-Bollschweiler et al., 2013; Stoffel et al., 2013). Dendrogeomorphic analyses of debris flows have predominantly been realized with conifers, but the potential of broadleaved trees has been recently demonstrated as well (Arbellay et al., 2010, 2014a,b). Using dendrogeomorphic techniques, precise (annual to subannual resolution) and century-long, continuous records of debris flow occurrence can be established. Assessments can also yield data on various debris-flow parameters, such as temporal frequency, estimates of event magnitudes, or analysis of triggering conditions. Furthermore, the dendrogeomorphic dating of landforms created by debris flows enables determination of the spread and reach of past events on forested debris-flow cones (Stoffel et al., 2008; Bollschweiler and Stoffel, 2010).

For a better understanding of debris-flow characteristics and process dynamics at a given site, one needs to select the best and most appropriate methods, taking into account debris-flow frequency, flow characteristics, and available data. Advantages and limitations of each method should be known before an appropriate approach is being defined. In the past, however, most research focused just on the evaluation of errors and the description of limitations of single approaches (Brardinoni et al., 2003; Bremer and Sass, 2012). By contrast, a comparison and/or combination of different methods have not been done in sufficient detail.

The purpose of this paper therefore is to compare characteristics, advantages, and limitations of different assessment methods to study debris flows and to apply them to a specific case where process activity has been very high in the recent past. We investigate the debris-flow history out of the Ohya landslide, central Japan, by using field monitoring, airborne LiDAR DEMs, orthophoto interpretation, and tree-ring assessments. The Ohya landslide, one of the largest landslide bodies in Japan, is appropriate for such a comparison because of the very high debris-flow frequency (with 3–4 events per year; Imaizumi et al., 2005). In addition, various kinds of monitoring and surveys aimed at disaster mitigation have been conducted in this area. This study focused on the most recent debris-flow history (approximately a decade) of the site.

2. Study site

The Ohya landslide, in the southern Japanese Alps (Fig. 1), was initiated during an earthquake in A.D. 1707 and has an estimated total volume of 120 million m^3 (Tsuchiya and Imaizumi, 2010). Unstable material has subsequently been supplied into the channels in the old landslide scar and has affected the occurrence of debris flows ever since the original failure.

The climate at the site is characterized by high annual precipitation (about 3400 mm). Heavy rainfall events (defined here as events with total rainfall >100 mm) occur during the Baiu rainy season (June and July) and the autumn typhoon season (August to October). Most debris flows at the Ohya landslide occur during these seasons, and we refer to this time window (from June to October) as the *debris-flow season*. The main geological units at the site are comprised of highly fractured shale and well-jointed sandstones of Tertiary age. The highest point of the landslide is the north peak (2000 m asl), while the lowest point is at the south end of the landslide at an elevation of 1060 m asl.

Most debris flows occur in the Ichinosawa catchment, which is located at the northern end of the Ohya landslide (Fig. 1B; Imaizumi et al., 2005). This catchment is divided into two sections, the upper and lower Ichinosawa subcatchments. The upper Ichinosawa catchment is a debris-flow initiation zone, whereas the lower Ichinosawa catchment represents the transportation and deposition zones.

Total length of the channel in the upper Ichinosawa catchment is ≈650 m and the south-facing catchment has an area of 0.22 km^2. Anthropogenic influence on debris-flow activity is clearly absent in the area because of the steepness of the site and the harsh environmental conditions. Seventy percent of the basin slope is bare (scree and outcrop), whereas the remaining 30% is vegetation-covered (forest, shrubs, and tussocks). Most of the catchment is characterized by rocky sequences with some high, subvertical walls. The typical gradient of hillslopes is 40–50°. Unconsolidated debris, ranging from sand to boulders, is the main source of debris-flow material (Imaizumi et al., 2006). The thickness of debris deposits attains several meters in some sections. Channel gradients range from 16° to 28° between P1 and P3 (Fig. 1), where channel bed is alternatively composed of deposited sediments and bedrock. Sediment infilling of the channels is dominated by freeze-thaw processes that promote dry ravel, the gravitational transport of surface materials by rolling, sliding, and bouncing across the surface, and rockfall because of the steep hillslopes (Imaizumi et al., 2006).

After the initiation in the upper Ichinosawa catchment, debris flows are transported onto the fan, which is in turn located in the lower Ichinosawa catchment. Length and gradient of the channel in the lower catchment are 600 m and 18°, respectively. Rather young (<20 years) pioneer riparian forests (e.g., *Alnus hirsuta*, *Alnus firma*)