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Deep-seated gravitational deformation of mountain slopes caused by river incision in the Central Range, Taiwan: Spatial distribution and geological characteristics

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ABSTRACT

Fluvial undercutting can cause the large-scale destabilization of mountain slopes and induce deep-seated gravitational slope deformation (DGSD) that eventually leads to catastrophic failures. This study analyses these processes in the catchment of the Dahan River, northern Taiwan. The area has experienced phases of river incision of up to 600 m since the middle to late Pleistocene, and middle Pleistocene paleosurfaces at higher elevations were incised to form V-shaped valleys. A DGSD inventory was compiled by visual interpretation of high-resolution images, and field surveys were conducted to clarify the geological structures associated with DGSDs and major rockslide-avalanches. The observed relationships between DGSDs and the topography modified by long-term river incision show that about 53% of all DGSDs occurred on slopes along the rims of paleosurfaces, which is approximately 2 and 2.5 times as many as in the incised valleys and on the paleosurfaces, respectively. A comparison of the power-law scaling exponents of cumulative frequency–area distributions shows that the frequency of DGSDs along the rims of the paleosurfaces decreases less rapidly with DGSD area than for DGSDs on other slopes. Geological investigations suggest that there are two dominant types of DGSD: one is flexural toppling of slate and argillite with high-angle cleavage, and the other is buckling of alternating beds of sandstone and mudstone on parallel or underdip cataclinal slopes. Catastrophic landslides observed along or below the rims of paleosurfaces were preceded by buckling of alternating beds of sandstone and shale. These beds dipped at 50° to 58°, and each bed was 10^{-1}–10^{0} m thick. This study suggests that the peripheral zones of the paleosurfaces may be most susceptible to future catastrophic landslides, particularly on parallel or underdip cataclinal slopes comprising alternating beds of sandstone and mudstone dipping at 50° to 60°. Thus, an understanding of the geological characteristics, spatial distribution of DGSD occurrence, and landscape evolution within a particular area can provide important information for landslide hazard-level zoning.

1. Introduction

Deep-seated gravitational slope deformations, referred to as DGSDs by Dramis and Sorriso-Valvo (1994), DSGSDs by Agliardi et al. (2001), and sackung by Zischinsky (1966) have now been observed in high relief mountain areas worldwide. Furthermore, some of these features have been found to have transformed into catastrophic failures similar to rockslide-avalanches (Mudge, 1965; Chigira and Kiho, 1994; Kilburn and Petley, 2003; Geertsema et al., 2006; Chigira, 2009; Tsou et al., 2011; Chigira et al., 2013). Chigira (2009) and Chigira et al. (2013) suggested that the small scarps seen on gravitationally deformed slopes become the crowns of subsequent catastrophic landslides, and so could be used as markers to locate potential sites of future catastrophic landslides. Therefore, DGSDs may help to identify either specific slopes or wider areas that may be susceptible to catastrophic landslides in the future.

The frequency and distribution of DGSD and landslide sites have been discussed in the context of landscape evolution and the debuttressing effect on slopes caused by glacial erosion and deglaciation (Bovis, 1990; Holm et al., 2004; Ambrosi and Crosta, 2006; Brückl and Brückl, 2006; Agliardi et al., 2009, 2013) and fluvial incision (Chigira, 2009; Hiraishi and Chigira, 2011; Tsou et al., 2011). Agliardi et al. (2013) analyzed 904 DGSDs and suggested that about 5% of alpine slopes are affected by DGSDs predominantly triggered by processes related to valley deglaciation. Ambrosi and Crosta (2006, 2011) argued that relief controls topographic stress field on slopes, and this leads to DGSD clustering in areas conditioned by the depth of glacial scour as well as rock mass strength and pre-existing structures. Holm et al. (2004) used the locations of DGSDs along glacial trimlines to show that recent catastrophic landslides in DGSD areas mainly occurred on valley slopes debuttressed during the glacial retreat following the Little Ice Age. A similar debuttressing effect on slope destabilization has also been reported from non-glaciated areas, where fluvial processes acted to debuttress the slopes (Chigira, 2009; Hiraishi and Chigira, 2011;

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Pánek et al., 2011; Hou et al., 2014). However, the effects of fluvial incision history on DGSDs and landslides have only been reported in a limited number of papers (Chigira, 2009; Hou et al., 2014).

Ongoing tectonic activity and extreme orographic precipitation are the major factors responsible for topographic evolution in the mountains of Taiwan, but slope movements tend to be restricted to high-relief areas. Six recent case histories of catastrophic rockslide-avalanches in Taiwan are shown in Fig. 1a, each having a volume of more than 10^6 m^3, and were reported to be preceded by DGSD (Chigira et al., 2003; Wang et al., 2003; Chen and Lee, 2008; Tsou et al., 2011; Lee et al., 2012; Lo et al., 2014). These landslides are in areas of high local relief (over 500 m). and occurred at sites with specific geological and topographic conditions formed by long-term processes, and were triggered by short-term processes, such as rainfall or seismic events. Using an inventory of landslide scars (but not a detailed geological examination), Tsou et al. (2014) reported that large rockslide-avalanches in the Dahan River catchment, northern Taiwan (Fig. 1), were preceded by DGSD induced by long-term river incision. In this paper, we present a catchment-scale inventory of DGSDs, and describe the geological structures associated with these DGSDs. We use the same study area as Tsou et al. (2014), and discuss the lithological and structural controls on DGSDs and their spatial distribution with reference to long-term river incision.

2. Study area

2.1. Geomorphological setting

In the study area (which covers 503.8 km^2; Fig. 1b), the Dahan River flows north through a mountainous landscape with summit elevations of 1200–3529 m above sea level (a.s.l.). On both sides of the river, Tsou et al. (2014) observed that hillslopes contain three convex slope transitions (i.e., slope breaks; Fig. 2). The slope breaks at higher elevations are distributed along the rims of the widespread paleosurface remnants, but are locally discontinuous due to gravitational slope processes. The exposed bedrock on a ridge top found at the paleosurface have been dated to be 150 kyr by using cosmogenic nuclide, ^{10}Be (Tsou et al., 2014). Hillslopes adjacent to the higher slope break are characterized by deeply incised V-shaped valleys (up to 600 m deep). These inner gorges (Kelsey, 1988) contain two subsidiary slope breaks at around 300 and 100 m above the current riverbed (Tsou et al., 2014). The paleosurface remnants have a moderate relief, with an average slope angle of 32°, whereas the inner gorges have average slope angles of around 36° to 40° (Tsou et al., 2014). It is thought that these geomorphic features have been formed by long-term river incision since the middle to late Pleistocene (Tsou et al., 2014).

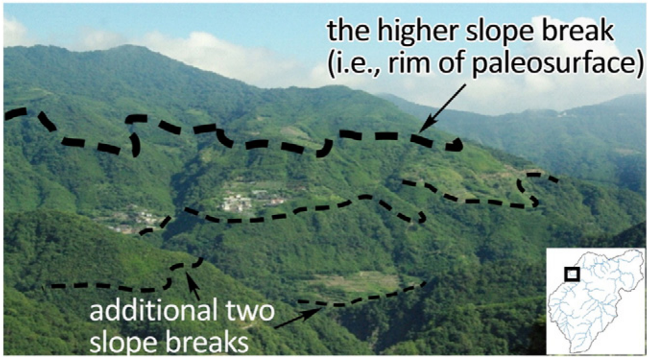

Fig. 2. Photograph of an example of the convex slope breaks (after Tsou et al., 2014). The higher slope break is located at the rim of the paleosurface. The inset shows the location of the photograph.

GPS surveys show that this area, like many other orogens in Taiwan, is experiencing rapid uplift rates of 5–10 mm yr^{-1} (Ching et al., 2011). The Dahan catchment has a subtropical climate and receives annual rainfall of 2500 mm, which comes mainly from the monsoon in winter and typhoons between May and October (Lin et al., 2011). Typhoon-

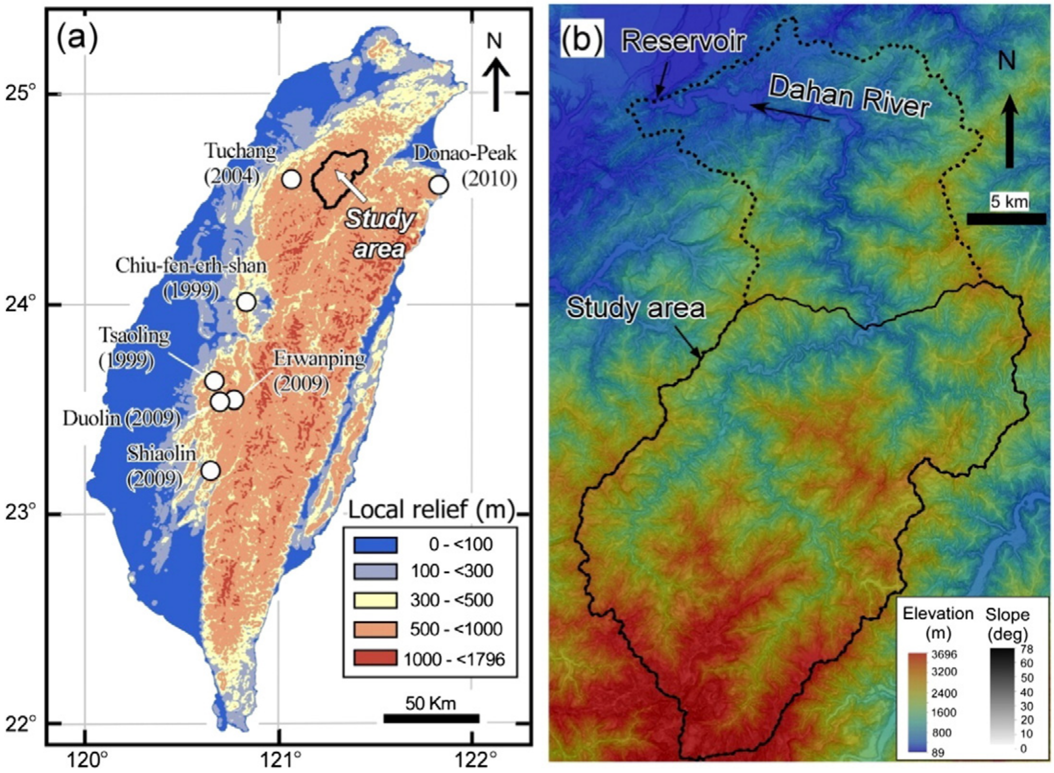

Fig. 1. Six recent case histories of catastrophic rockslide-avalanches in Taiwan and this study area (the upstream Dahan River catchment). (a) Recently reported catastrophic rockslide-avalanches superimposed on a local relief image. The local relief image was derived from an ASTER DEM using a circular 30 × 30 cell moving window. Numbers in brackets indicate the year of landslide occurrence. (b) Map of the upstream Dahan River catchment showing an elevation image superimposed on a slope inclination image.