Gravitational slope deformation due to river rejuvenation in the Laonung River catchment, Taiwan

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Abstract

River rejuvenation forms convex, projecting slopes that lead to the development of deep-seated gravitational slope deformations (DGSDs) and in some cases transformed themselves into catastrophic failures. This study analyses these processes in the catchment of the Laonung River, southern Taiwan, where was severely damaged by 2009 Typhoon Morakot. At the study area, the landscape comprises paleosurface remnants with slopes mostly gentler than 30° at higher elevations and separated by convex slope breaks at their peripheries and incised valleys, in which showing a series of terraces. The slope breaks up to about 400 m above the current river bed are inferred to have been formed associated with rejuvenation of river. The lower parts of the DGSDs have many slope failures that are along the rims of the paleosurface and within the incised valleys, showing the toes of the DGSDs are destabilized by slope failures. Many areas of DGSDs tend to occur along the slope breaks, suggesting a common mechanism of slope instability, probably owing to river undercutting.

Keywords: gravitational slope deformation, catastrophic landslide, convex slope break

1. Introduction

Deep-seated gravitational slope deformations (DGSDs) in tectonically active mountain areas typically occur by long-term creep and may fail catastrophically as deep-seated landslides. Such catastrophic landslides usually accompany voluminous rock or debris avalanches, travel rapidly for long runouts, and abruptly bring catastrophe to wide areal extent (Crosta et al., 2006; Tsou et al., 2011; Chigira et al., 2013a). These unstable slopes prior to collapse were inherently controlled by discontinuities such as bedding planes, foliation, or faults and fractures (Chigira, 1992; Nichol et al., 2002). Among these, the number of fractures and/or faults may develop and propagate that play a significant role in formation of the gravitational failure associated with long-term river incision (Chigira et al., 2013b; Hou et al., 2014). Therefore, DGSD may indicate precursory creeping before their final failure and must be interpreted from the view point of geology as well as regional slope development, because which create a topographic setting of these landslides over wide area.

Studies have shown that predicting potential sites of the catastrophic landslides is possible with reference to their geomorphic and geological features. Chigira (2009) and Chigira et al. (2013a) studied catastrophic landslides induced by rainfalls in gravitationally deformed slopes and suggested that the small scarps seen on the deformed slopes become the crowns of subsequent catastrophic landslides, and so could be used as markers to locate potential sites of future catastrophic landslides. Such precursory features are interpreted as exterior expressions related to internal deformational structures (Chigira et al., 2013a; Hou et al., 2014), and however vary in forms depending on subsurface condition in different kinds of geologic and topographic settings.

In order to progress in understanding these issues for the hazard assessment by large, catastrophic landslides, we studied DGSDs and topographic features that might imply the regional slope development in a mountainous catchment of the Laonong River catchment, southern Taiwan (Fig. 1). Geological structures of the DGSDs are not considered here and will be an important part of our future study. A geological map of the study area was compiled from a 1:50,000 geological map (Sung et al., 2000) published by the Central Geological Survey (Ministry of Economic Affairs, Taiwan), a geological map published by the (Central Geological Survey.,

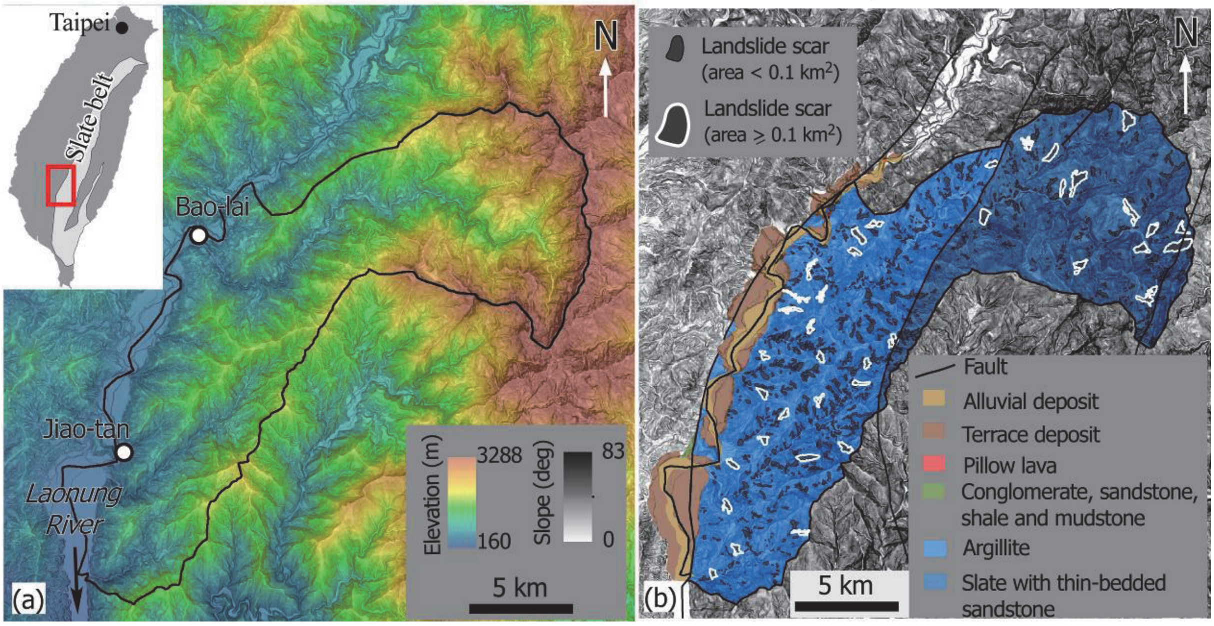

Fig. 1 Map of the study area within the Laonung River catchment. (a) Map showing an elevation image superimposed on a slope inclination map derived from a 20-m mesh DEM. The DEM was created by resampling 5-m mesh DEMs obtained from the Ministry of Interior, Taiwan. (b) Map showing the distribution of landslide scars and geological map superimposed on a slope inclination map.

2010), and additional data obtained from field surveys. The bedrock in the study area is Miocene in age and mainly comprises argillite, slate, and slate with thin-bedded sandstone. These beds are faulted along NNE trending axes. The beds of argillite and slate have well developed cleavage, respectively, that generally trend N31°W and dip SW at 38°. The cleavage plane forming a discontinuity has been known to be susceptible to gravitational slope deformation. Similar geological features could be widely recognized in the Taiwan slate belt (Fig. 1).

2. Landslides in the study area

This area was severally devastated by Typhoon Morakot in 2009, when it caused the worst rain-induced landslides hazards in 50 years (Lin et al., 2011). Four landslide dams were formed when large landslides blocked the rivers. Total casualties by this event in this catchment were 60 people dead and missing (National Disasters Prevention and Protection Commission, 2009).

Figure 2 shows the cumulative number-area distributions for 1257 landslide scars (Fig. 1b), that are identifiable on Google Earth imagery as bare areas, including source and depositional areas. The landslides were thus delineated using Google Earth imagery taken after the Typhoon Morakot in 2009. The landslides indentified here are thus the landslides occurred before and after the Typhoon Morakot. These landslides with areas span three orders of magnitude from 1.9×10^{-4} to 5.0×10^{-1} km^2. Large landslides (i.e. areas larger than 0.1 km^2) account for only 3% of the total number, but for 30% of the total area.

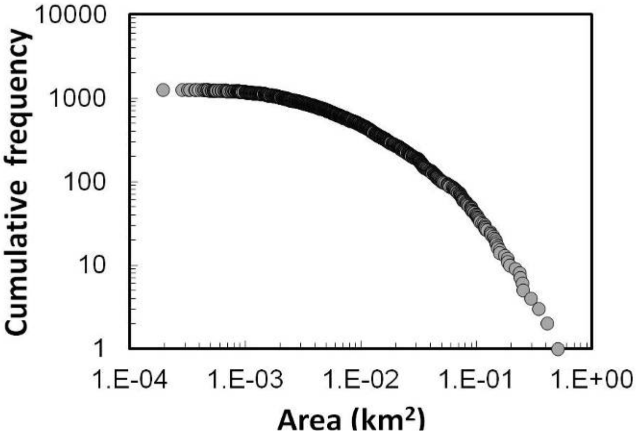

Fig. 2 Analysis of the cumulative-area distribution for the landslide scars.

3. Topographic features and slope movement

3.1 Paleosurface remnants and terraces and slope breaks at their peripheries

Field surveys showed that slopes mostly gentler than 30° are widely distributed at higher elevations and dip into the river valleys, surrounded by steep slopes with convex slope break in many locations (Fig. 3a). These morphological features suggest that the gentler slopes at higher elevations are remnants of a paleosurface which are preserved within the mountain ranges bounded by the slope breaks that up to 400 m above the present river bed. The

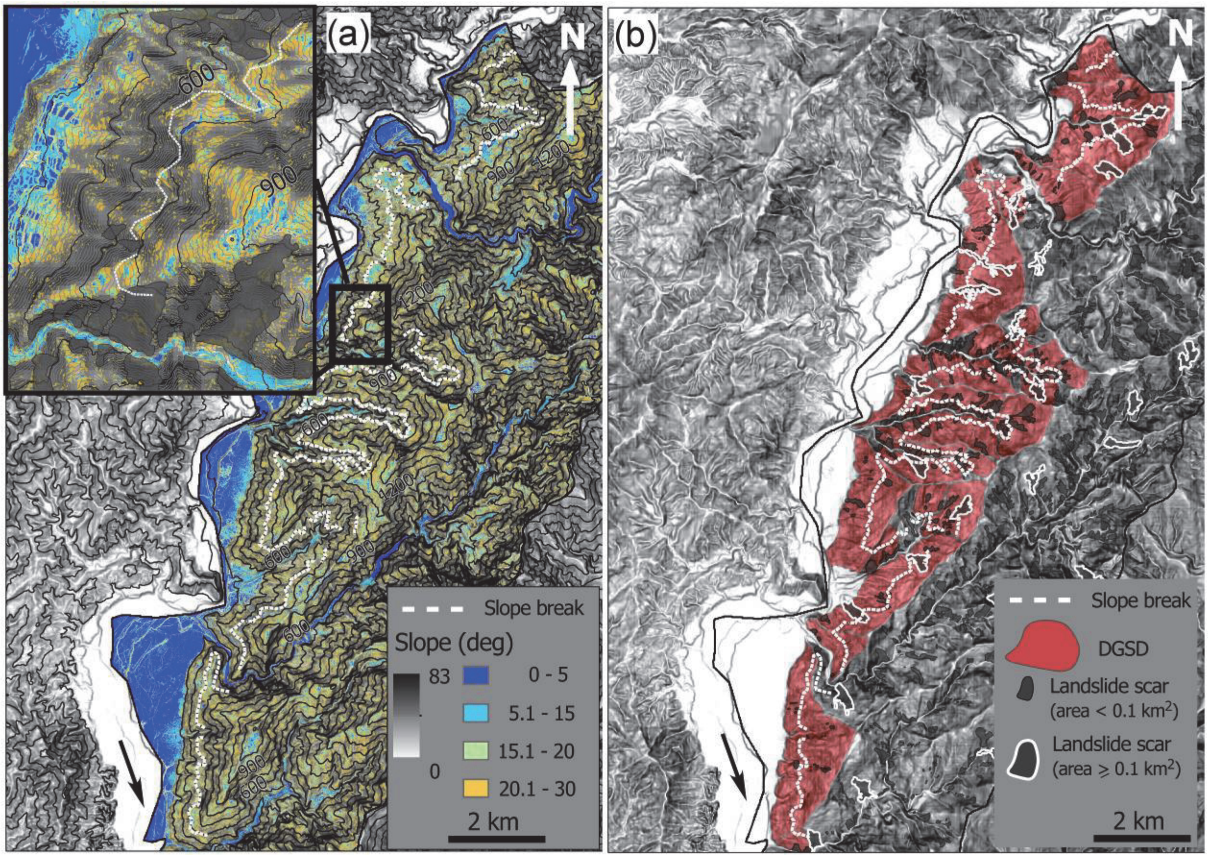

Fig. 3 Examples of distributions of slope breaks and slope movements along the major trunk Laonung River. (a) Superimposed contours and a classified slope gradient image. The image shows an example of delineation of slope breaks based on a slope gradient map with a geomorphic break value of 30° and field checks. Numbers indicate the elevation in meters. An arrow indicates the flow direction of the Laonung River. (b) Distribution of the slope breaks, DGSD, and landslide scars.

paleosurface, the age of which is unknown, has been dissected by the rejuvenation of the trunk river and its tributaries in response to base-level lowering probably associated with tectonic uplift of the area. This relative elevation of about 400 m might act as a proxy for fluvial dissection in the incised valleys.

Hillslopes adjacent to the higher slope break are characterized by incised valleys. The valleys contain subsidiary slope breaks that aligned the treads of a series of terraces. The terraces show flat morphology (with slope < 15°) of various sizes and heights, consisting of fluvial terrace and fan terrace developed where the tributaries join the main river. The contemporary terrace tread slopes are commonly steep showing that they have been enhanced by erosion from shallow soil slips.

The distinct features have been attracted much attention by previous researchers (Tomita, 1972; Hsieh et al., 2013), however, have received insufficient attention in terms of slope movements, in particular the DGSD. We noted that the higher slope breaks are commonly blurry by the DGSDs and disconnected by landslides (Fig. 3b), which might imply that the river rejuvenation controlled the DGSD distribution. To find such a causal relationship, we focused on the spatial relationship between the slope breaks at the rims of the paleosurface and DGSDs (See Section 3.2).

3.2 Distribution of DGSDs

DGSDs, which are characterized by topographic features such as scarps, hummocky surfaces, and linear depressions (Chigira, 1992; Dramis and Sorrisovalvo, 1994; Chigira et al., 2013a), were mapped by visual interpretation of Google Earth imagery and stereo-pair ALOS/PRISM images (Scene IDs: ALPSMW090153135 and ALPSMB090153190) with a resolution of 2.5 m.

The DGSDs were mapped along the major trunk Laonung River posing great size extending from the crests of gentle ridges to the valley floor. The DGSDs are concentrated along the rims of the paleosurface, which is attributable to the undercutting of slopes by river incision. The lower parts of the DGSDs have many slope failures that are along or below the rims of the paleosurface, suggesting the toes of the DGSDs are currently being destabilized by them (Fig. 3b). This relationship might can be observed further upstream since the topography suggests that river incision is propagated upstream along trunk and tributary river. Such relationship is consistent with that seen in other tectonically active mountain basins (Hiraishi and Chigira., 2011; Tsou et al., 2014).

4. Conclusions

We investigated a mountainous catchment of the Laonung River to understand the DGSD process regarding to rive rejuvenation and has reached the following preliminary conclusions. Hillslope morphology shows that there are palrosurface remnants widely distributed at higher elevations and incised valleys below then in which contain a series of terraces. Slope breaks are present at the boundary slopes in contact with the slopes between the paleosurface remnants and the incised valleys and along the terrace treads. The higher slope breaks are up to 400 m above the present river bed, acting as a proxy for fluvial dissection in the incised valleys. The analysis of the spatial relationship between the DGSDs and the higher slope breaks shows that DGSDs tend to occur along the slope break, suggesting a common mechanism of slope instability, probably owing to undercutting by river rejuvenation.

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