Topic: **Risk Analysis of Large-Scale Landslides**

The Distribution and Characteristics of Deep-Seated Gravitational Slope Deformation in Active Fluvial Landscapes

Ching-Ying Tsou/
Hirosaki University/
Faculty of Agriculture
and Life Science

Abstract

Huge landslides have been occurring in tectonically active mountains, where uprising and river incision form gravitationally unstable state in mountain slopes. This report aims to provide an overview of distribution and characteristics of deep-seated gravitational slope deformation (DGSD) based on the analysis of topography and catchment-scale inventories of DGSD and relating deep-seated landslide in active fluvial landscapes in the Central Range, Taiwan and the Kii Mountains in Japan. This report discusses the lithological and structural controls on DGSDs and their spatial distribution with reference to long-term river incision. This report uses a case study of DGSD of a shale-dominated dip-slope to numerically simulate the progressive propagation of plastic shear zones and the development of gravitational slope deformation accompanying staged river-bed incision.

Key words: deep-seated gravitational slope deformation, deep-seated landslide, river incision, geological structure.

Author：Ching-Ying Tsou
Contact：Ching-Ying Tsou
TEL：+81-172-39-3842
FAX：+81-172-39-3842
E-mail：tsou.chingying@hirosaki-u.ac.jp
Address：3 Bunkyo-cho, Hirosaki, Aomori 036-8561, Japan

The Distribution and Characteristics of Deep-Seated Gravitational Slope Deformation in Active Fluvial Landscapes

1. Introduction

The slope movements vary significantly over the wide range of spatial and temporal scales over which landscape evolve. Some of the slope movements are deep-seated, long-lasting slow landslides in rock and are associated with deep-seated gravitational slope deformations, referred to as DGSD by Dramis and Sorriso-Valvo (1994) and DSGSD by Agliardi et al. (2001). DGSDs are characterized by various deformational structures, different size, location, sensitivity to external triggering factors, displacement rates. DGSDs often transform into deep-seated landslides, with resulting catastrophic loss of life and extensive property damage. These complications are controlled mainly by the geological structure, lithology, and topography of the rock slopes, and are often triggered by rainstorms or earthquakes (Chigira and Kiho 1994; Nichol et al. 2002). Deep-seated landslides have been observed in tectonically active mountains, where uprising and river incision form gravitationally unstable state in mountain slopes. However, a limited number of studies have discussed the effects fluvial incision on DGSD occurrence. This report briefly summarizes the observations of Tsou et al. (2011), Chigira et al. (2013), Hou et al. (2014), Tsou et al.(2014), Tsou et al. (2015), and Tsou et al. (2017), which deal with the distribution and characteristics of DGSD, with focus on active fluvial landscapes in Taiwan and Japan.

2. Distribution and characteristics of DGSD

Deep-seated gravitational slope deformations (DGSDs) induced by long-term river incision were observed in the Chishan River (Tsou et al. 2011), and Dahan River catchments in the Central Range in Taiwan (Tsou et al. 2014; Tsou et al. 2015) and the upstream area of the Kumano River in the Kii Mountains in the outer belt of Southwest Japan (Chigira et al. 2013; Tsou et al. 2017). These areas show typical fluvial landscape comprising paleosurface remnants with moderate relief at higher elevations and incised V-shaped inner gorges below them, which were made by the recession of knickpoints.

2.1 DGSD in the Central Range, Taiwan

In the Dahan River catchment, rims of paleosurface remnants, which have a minimum age of ca. 150 kyr, are widely distributed up to 600 m above the present river bed, acting as a proxy of fluvial dissection associated with three phases of river incision since the middle to late Pleistocene (Tsou et al. 2014). The observed relationships between slope movements and the topography modified by the long-term river incision show that about 53% of all DGSDs, or all large DGSDs ($>10^6$ m^2) occurred on slopes along the rims of paleosurfaces and catastrophic rockslide-avalanches occurred along or below the rims of paleosurfaces, suggesting they could be fundamentally controlled by long-term river incision (Tsou et al. 2014). Catastrophic landslides observed along or below the rims of paleosurfaces were preceded by buckling of alternating beds of sandstone and mudstone on parallel or underdip cataclinal slopes. These beds dipped at 50° to 58°, and each bed was 10^{-1}–10^0 m thick. This 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° (Tsou et al. 2015).

The 2009 Typhoon Morakot-induced Shiaolin landslide (volume of 25×10^6 m^3) in the Chishan River catchment also occurred on a gravitationally deformed slope along the rim of a paleosurface, suggesting the result of denudation of the paleosurface (Tsou et al. 2011). The slope deformation appeared as a hummocky slope surface before the event and was observed as gravitational buckle folds in the source area after the event, suggesting the landslide can be predicted as a potential site before the event. Moreover, gravitational deformation occurred with a preferable geological structure of wedge-shaped detachments consisting of bedding planes and joints or fault planes (Tsou et al. 2011).

2.2 DGSD in the Kii Mountains, Japan

In the Kumano River catchment, paleosurfaces are widely spread as remnants, being incised by new fluvial incision with two levels of V-shaped inner gorges, which are the result of sequential propagation of two series of knickpoints (Tsou et al. 2017). The slope breaks between the slopes of the higher inner gorges and paleosurfaces are up to 400 m high above the current riverbeds and the slope breaks between the higher and lower inner gorges are up to 100 m above the present riverbed. This study area has experienced severe rain-induced landslide disasters in 1889 and 2011. Slope movements, including 366 and 52 landslides, respectively, induced by the 1889 and 2011 rainstorms, and 1046 DGSDs, were identified. More than 65% of DGSDs and 75% of landslides were found along slope breaks bounding the paleosurfaces and totally in the inner gorges, respectively, which percentages are ~2−3 times as frequent as within the paleosurface. Analysis of the cumulative frequency−area distributions of DGSDs and deep-seated landslides showed DGSDs and landslides associated with the incised inner valley slopes tend to have larger sizes than those within the paleosurface for DGSDs $> 6.8 \times 10^5$ m^2, landslides of the 1889 event $> 1.0 \times 10^5$ m^2, and landslides of the 2011 event $> 1.8 \times 10^4$

m^2 (Tsou et al. 2017). Besides, the average slope angle of the landslides was 32°, whereas the average slope angle on nearby stable paleosurfaces was 33°, suggesting that an angle of around 32° may represent the threshold of long-term slope stability on dip slopes in the context of the geological setting of the study area (Chigira et al. 2013). Geological survey of the 14 major landslides by the 2011 rainstorm suggested all of the surveyed landslides were preceded by DGSD, which appeared as small scarps or linear depressions along their future crowns. There were three types of DGSD that led to the development of landslides: most landslides were preceded by sliding with wedge-shaped discontinuities, one landslide by buckling on a dip slope, and one landslide by flexural toppling on a slope with steeply dipping foliation (Chigira et al. 2013).

3. River incision and DGSD: a numerical case study

On the left bank of the Yoshino River in the Kii Mountains, Japan, Hou et al. (2014) identified the triggering factors, the controlling conditions and evolutionary process of the gravitational deformation of a shale-dominated dip-slope through numerical simulation with FLAC, and to interpret the actual distribution of nontectonic shear zones observed from high-quality drill cores. Numerical study is performed to simulate the progressive propagation of plastic shear zones and the development of gravitational slope deformation accompanying staged river-bed incision. The results suggested that rock mass strength degradation and river incision are the two most important factors for time-dependent deep-seated gravitational deformation development. Without the strength reduction of rock mass, river incision itself may not be enough to develop deep-seated gravitational deformation. Numerical simulation revealed that plastic shear bands within the slope are initiated and developed in a step-wise fashion accompanied by river incision and finally connect with each other. The formation of the lower shear band is related closely to stress relaxation induced by river incision. DGSD in a dip slope involves both shear slip along the bedding planes and brittle fracture of the intact rock mass across the bedding planes. This results in shear zone propagation in a step-wise manner. Bedding planes constitute a structural control on deep-seated gravitational deformation evolution due to their weaker strength. Therefore, DGSD is an integrated process, dependent on slope topography, geological structures and triggering factors. Numerical modeling reproduces very well the weak zone distributions across the slope as recognized from drill cores, and the deformed topographic features. The agreement and constraints from numerical models, boreholes and topography allow a more in-depth understanding of the relationships between the interior deformation of the slope, exterior geomorphology and associated controlling mechanism. The observations also confirm that the topographic features of gravitationally deformed slopes are surface expressions of internal deformational structures of the slope.

4. CONCLUSION

Large-scale destabilization of mountain slopes, which are affected by long-term river incision, give rise to the risk of catastrophic failures in tectonically active orogens. Field geological and geomorphological surveys, mapping of DGSD and landslide scars by visual interpretation of high-resolution images were conducted in the Chishan River, and Dahan River catchments in the Central Range in Taiwan and the upstream area of the Kumano River in the Kii Mountains in the outer belt of Southwest Japan. The results showed that DGSDs have been induced by the undercutting of paleosurface slopes and involve many recent deep-seated landslides. It suggests that landscape evolution history associated with the long-term river incision through river networks gives a background of landslide hazard and could be used as a basis for landslide hazard zonation. Numerical simulation on DGSD in a dip slope in the Yoshino River in the Kii Mountains was also performed to simulate the progressive propagation of plastic shear zones and the development of DGSD accompanying staged river-bed incision. The results show a link between geomorphological development and internal deformation of the slope, which aids in the understanding of relationships between interior deformation of the slope, the exterior geomorphology and related effect factors including river incision and strength degradation.

5. ACKNOWLEDGEMENTS

This report consisted of the results that obtained together with the following researchers: Profs. Masahiro Chigira and Yuki Matsushi and Dr. Yanli Hou of Disaster Prevention Research Institute, Kyoto University and Prof. Su-Chin Chen of Chung Hsing University. For details, readers are suggested to refer to Tsou et al. (2011, Geomorphology), Chigira et al. (2013, Geomorphology), Hou et al. (2014, Engineering geology), Tsou et al. (2014, Geomorphology), Tsou et al. (2015, Engineering geology), and Tsou et al. (2017, Landslides).

6. REFERENCES

Agliardi F, Crosta G, Zanchi A (2001) Structural constraints on deep-seated slope deformation kinematics. Eng Geol 59:83–102

Chigira M, Kiho K (1994) Deep-seated rockslide-avalanches preceded by mass rock creep of sedimentary-rocks in the Akaishi Mountains, Central Japan. Eng Geol 38:221–230

Chigira M, Tsou C-Y, Matsushi Y et al. (2013) Topographic precursors and geological structures of deep-seated catastrophic landslides caused by Typhoon

Talas. Geomorphology 201:479–493

Dramis F, Sorriso-Valvo M (1994) Deep-Seated Gravitational Slope Deformations, Related Landslides and Tectonics. Eng Geol 38:231–243

Hou Y, Chigira M, Tsou C-Y (2014) Numerical study on deep-seated gravitational slope deformation in a shale-dominated dip slope due to river incision. Eng Geol 179:59–75

Nichol SL, Hungr O, Evans SG (2002) Large-scale brittle and ductile toppling of rock slopes. Canadian Geotechnical Journal 39:773–788

Tsou C-Y, Chigira M, Matsushi Y et al. (2014) Fluvial incision history that controlled the distribution of landslides in the Central Range of Taiwan. Geomorphology 226:175–192

Tsou C-Y, Chigira M, Matsushi Y et al. (2015) Deep-seated gravitational deformation of mountain slopes caused by river incision in the Central Range, Taiwan: spatial distribution and geological characteristics. Eng Geol 196:126–138

Tsou C-Y, Chigira M, Matsushi Y et al. (2017) Coupling fluvial processes and landslide distribution toward geomorphological hazard assessment: a case study in a transient landscape in Japan. Landslides

Tsou C-Y, Feng Z-Y, Chigira M (2011) Catastrophic landslide induced by Typhoon Morakot, Shiaolin, Taiwan. Geomorphology 127:166–178