

Landscape Evolution by Fluvial Processes and Gravitational Slope Processes in Tectonically Active Mountains in Taiwan

河川プロセスと重力斜面プロセスによる地形発達 －地殻変動が活発な台湾山岳地における例－

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論文要約

Chapter 1 Introduction

In active orogens, mountain landscapes are controlled mainly by tectonic, climatic, fluvial, and gravitational slope processes. Understanding these complex interactions in mountainous watersheds is crucial if we wish to reconstruct and predict landscape evolution. However, this is not an easy task, because the interactions are sensitive to changes in erosion base level, climate and tectonic conditions, and lithological properties. Geomorphic responses of hillslopes to the channel lowering and the relationship between fluvial and gravitational slope processes are important issues that remain to be fully clarified. The main aims of this study are: (i) to reconstruct long-term landscape evolution, (ii) to clarify the driving forcings of river incision, and finally (iii) to understand slope movement distributions in the context of landscape evolution in tectonically active mountainous areas. Study sites were an upstream section of the Dahan River catchment and a middle section of the Chishan River catchment of the Central Range in Taiwan, known as one of the world's most tectonically active belts. Geomorphic analysis was carried out on the river long profiles, hillslopes, deep-seated gravitational slope deformation, and landslide scars to determine the role of fluvial and gravitational slope processes in landscape evolution. These results were correlated with chronological data from several landform surfaces to reconstruct the history of landscape evolution. In addition to the geomorphic analysis outlined above, this study also involved geological investigations, reinterpretation of published geological maps, and clarification of the internal structures of deep-seated gravitational slope deformations.

Chapter 2 Study areas

The upstream section of the Dahan River catchment and the middle section of the Chishan River catchment are located in the north and the south of the Central Range, respectively. These two areas are underlain by Miocene to Pleistocene sedimentary rocks and slate. Both catchments show paleosurface remnants in higher elevations and inner gorges below the paleosurfaces. The current landscape is subjected to slope movement. In the Chishan River catchment, the 2009 Typhoon Morakot induced catastrophic Shiaolin landslide.

Chapter 3 Methods

This chapter details how slope breaks on hillslopes, knickpoints on river profiles, deep-seated gravitational slope deformation, and landslide scars were extracted and analyzed. This chapter also shows how the field investigations and cosmogenic nuclide analysis were conducted.

Chapter 4 Results

This chapter shows that the study areas have strong imprints related to the long-term river incision and slope movement. In the upstream section of the Dahan River catchment, the landscape comprises three levels of knickpoints and corresponding slope breaks. These knickpoints propagated upstream along trunk and tributary rivers, undercutting and destabilizing nearby slopes, of which the oldest is a paleosurface dated to around 150 kyr by cosmogenic nuclide dating. Consequently, three levels of V-shaped inner gorges (up to 600 m deep) are incised into the paleosurface. The inner gorge slopes

have mean inclinations of 35.6°, 37.7°, and 39.8°, and steepen from the higher to the lower inner gorges. These three series of knickpoints and corresponding slope breaks suggest that three phases of river incision took place. In the middle reaches of the Chishan River catchment, distinct knickpoints occur at the margins of a paleosurface. The paleosurface, the age of which remains unknown, has been dissected by the rejuvenation of the Chishan River and its tributaries in response to base level lowering. In contrast, active fluvial processes, as well as gravitational slope processes, were observed in inner gorges below the paleosurface. This chapter also shows the results of probability density analysis of the areas of deep-seated gravitational slope deformation and landslide scars (rock/debris slide avalanches). The results suggest that, many deep-seated gravitational slope deformation and deep-seated rockslide-avalanches are aligned along the higher and middle slope breaks, and debris slide avalanches are concentrated along the middle and lower slope breaks in the upstream section of the Dahan River catchment. In the middle section of the Chishan River catchment, large deep-seated gravitational slope deformation and deep-seated rockslide-avalanches tend to occur along the higher slope break, while many shallow debris avalanches occur most frequently below the slope break. Moreover, geological investigations in the study areas suggest that there are two dominant types of deep-seated gravitational slope deformation: flexural toppling of argillite, slate, and alternating beds of sandstone and mudstone with high-angle cleavage or bedding planes; and buckling of alternating beds of sandstone and mudstone on dip slopes. Buckling of alternating beds of sandstone and mudstone has frequently led to deep-seated rockslide-avalanches, causing widespread damage. The Shiaolin landslide was induced by Typhoon Morakot in 2009, and represents one example of a rockslide-avalanche preceded by the buckling type of gravitational deformation, which occurred on the edge of a paleosurface.

Chapter 5 Discussions

This chapter discusses about the landscape evolution in the study areas from the viewpoint of fluvial and gravitational slope processes. The fact that large deep-seated gravitational slope deformation and deep-seated rockslide-avalanches have occurred along the higher slope breaks is attributed to the destabilization of slopes due to undercutting by the river erosion that formed the slope breaks. The coupling of channels and hillslopes over long timescales creates favorable conditions for slope movement, as convex morphology of slope breaks and increasing relative slope height destabilize the slope stability. The results suggest that the long-term river incision history has controlled the development of gravitational slope deformation and distribution of landslides. This chapter also evaluates the driving force and timing of river incision. Based on the analysis of steepness indices of river long profiles, cosmogenic nuclides dating, and the regional tectonic and climatic history, the drivers behind the river rejuvenation in the Dahan catchment for the first two phases are inferred to have been intermittent uplift and for the last to have been climatic change in addition to uplift. Although the dating data does not relate directly to the timing of river incision, the results show that the rejuvenation of the landscape occurred in the middle to late Pleistocene. Detailed river profile analysis was not performed in the Chishan catchment, but the paleosurface remnants are located as high as 700 m above the current riverbed, suggesting that the driving force was tectonic uplift.

Chapter 6 Conclusions and suggestions for further work

This thesis investigated the landscape evolution in tectonically active mountain ranges; i.e., the Dahan and Chishan catchments in the Central Range of Taiwan, from the viewpoint of fluvial and gravitational slope processes, and has reached the following conclusions.

1. Hillslope morphology and river long profiles in the study areas show that there are remnants of a paleosurface widely distributed at higher elevations, which are incised by rivers with knickpoints accompanying inner gorges downstream. The wide distribution of knickpoints in the catchments of both rivers demonstrates that the landscape in the Central Range of Taiwan remains in a

transitional state, rather than being in a steady state as previously proposed.

2. The driving forces behind river rejuvenation in the Dahan catchment are thought to be intermittent tectonic uplift for the first two phases, and a combination of uplift and climatic effects for the last phase. Cosmogenic nuclide dating suggests that the third phase of river incision occurred before about 14 kyr, which indicates that it could have been affected by increased rainfall after MIS 2. In the Chishan catchment, the paleosurfaces remnants are located as high as 700 m above the current riverbed, suggesting that the driving force was tectonic uplift.
3. There are two dominant forms of deep-seated gravitational slope deformation, which are controlled by the underlying geological conditions, and they are the toppling of argillite and slate with high-angle cleavage, and the buckling of alternating beds of sandstone and mudstone on dip slopes. Buckling of alternating beds of sandstone and mudstone has frequently led to rockslide-avalanches, causing widespread damage. The development of gravitational slope deformation can be controlled by river incision in the long-term.
4. The long-term river incision induced deep-seated gravitational slope deformation and landslides, which has been revealed by the relationship between their distribution and the slope breaks. The power law scaling exponents, obtained from the inverse-gamma function, suggest that deep-seated gravitational slope deformation and landslide scars along higher slope breaks may be biased towards larger sizes. Deep-seated gravitational slope deformation and landslide scars are far less frequent on the paleosurfaces away from the slope breaks than in the surrounding areas. The results indicate that landslide sites can be predicted by understanding the long-term river incision history and distributions of knickpoints and slope breaks, which can be used for the hazard level zoning of landslide.