Geological structural control on landslide and gravitational slope deformation in response to fluvial incision along the eastern margin of the Tibetan Plateau, China
河川侵食によって生じる地すべりと重力斜面変形：中国チベット高原東縁部における地質構造規制

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論文要約

Chapter 1 Introduction

Rock slope instabilities, such as rockslides and deep-seated gravitational slope deformations, commonly occur in humid and tectonically active areas. These hillslope phenomena are the response of rock slopes to river incision, and thus, the hillslopes are expected to be controlled by the relationship between geological structures and river incision. However, the systematic linkage of geological rock structures and river incision associated with slope instabilities keeps unclear. To explore slope destabilizing mechanisms under different intersection settings of rock structural orientations and rivers, landslides and deep-seated gravitational slope deformations (DGSDs) were investigated in terms of geology and geomorphology along the two major rivers (Minjiang River and its major tributary, the Heishuihe River) in the eastern margin of the Tibetan Plateau. The main targets of this study are 1) identifying and characterizing the geomorphological and geological features of DGSDs and large catastrophic landslides in the eastern margin of the Tibetan Plateau, which is one of the most prominent continental escarpments in the world; 2) characterizing key morphological features on riverbeds (knickpoints) and hillslopes (convex slope breaks and inner gorges) that mark fluvial phases and clarify the effects of these features on DGSDs and landslides in areas with two different intersection angles between a geological trend and river: one parallel and one normal; and 3) discussing the response of valleyside slopes with different structural orientations to fluvial incision. The findings in this study strongly suggest that research of slope development by river incision must consider geological structures, and an understanding of geological structures and river incision history can provide a conceptual model for natural slope destabilizations in high-relief mountainous regions being incised by rivers.

Chapter 2 Study area

The study area, the Minjiang catchment, is located along the eastern margin of the Tibetan Plateau bounded by the Longmengshan fault belt and is adjacent to the western Sichuan Basin, southwest China. The Longmenshan fault belt, which characterizes the transitional terrain of the abrupt change from the Qinghai-Tibet Plateau to the Sichuan Basin, forms among the world’s most remarkable continental escarpments resulting from neotectonic activity and is an area of intense river incision. This mountainous region is underlain by rocks ranging from Precambrian to Triassic in age, which mainly comprise granite, phyllite, dolomite, limestone, sandstone, shale, and other types of metamorphic rocks. The steep topographic escarpment adjacent to the Sichuan Basin has been deeply dissected by rivers, which produced favorable conditions for slope movement along the plateau margin.

Chapter 3 Methods

In this study, topographic investigations were conducted using DEMs (digital elevation models) and satellite images. I particularly focused on the mapping of landslides and deep-seated gravitational slope deformations (DGSDs) and GIS-based analysis of landscape evolution. Field investigations were also conducted for over 30 days using 1:25,000 scale topographic maps. Attitudes of bedding and foliation were specifically investigated from outcrops in the field for the study of hillslope stability along the two major rivers, the Minjiang and Heishuihe Rivers. In addition, discontinuity analysis using the software COTOP-3D was completed to determine the geological structural features.

Chapter 4 Results

This chapter shows the geomorphological and geological characteristics of landslides and DGSDs widely distributed along the Minjiang and Heishuihe Rivers. Topographic analysis suggested that in both rivers, there are major knickpoints that formed as a result of tectonic activity and propagated upstream. Such fluvial behavior produced an inner gorge and undercut and destabilized nearby slopes. There are two slope breaks as high as ~1200 ± 300 m and ~300 ± 150 m from the current riverbeds in the Minjiang River and ~800 ± 200 m and ~400 ± 150 m from the current riverbeds in the Heishuihe River. The slopes above the higher slope break are remnants of the paleosurface. Landslide dams create another type of knickpoint in the river channel, especially along the Minjiang River.

When the geological trend is normal or highly oblique to the trend of the Minjiang River, DGSDs generally do not occur, but gigantic rockslides have occurred on one side of the Minjiang valley, which can be attributed to a wedge structure consisting of bedding planes and joints with intersections dipping valleyward and tight folds with hinges plunging valleyward.

When the planar beds moderately dip and strike nearly parallel to the Songpinggou River (a smaller tributary of the Minjiang River), buckling deformation commonly occurs on cataclinal slopes, often transforming into catastrophic failure. The 2017 Xinmo landslide, which occurred along this river and resulted in 102 fatalities, provided an adequate setting for transformation of the gravitational slope deformation into catastrophic failure. Satellite image analysis and field observations of the landslide scar slope before and after the landslide strongly suggest that buckling gravitational deformation had already started in the alternating beds of pelitic and psammitic schists in the source area prior to the 2017 landslide.

When the geological planar structures strike parallel or slightly oblique to the trend of the Heishuihe River, DGSDs with the types of buckling and toppling occurred along the river. In particular, the buckling slopes always occur on the left bank, while the toppling slopes occur on both banks of the river. The majority of prehistoric rockslides were induced on the hillslopes where buckling and toppling structures developed along the major river. Scarps created by landslides or DGSDs widely distributed above the gravitationally deformed portions of hillslopes.

Chapter 5 Discussion

This chapter discusses about the effects of knickpoint propagation and inner gorge formation on slope stability. Its effects are completely different according to the relationships between the geological trend and river trend. When the geological trend is normal or highly oblique to a river, very few DGSDs occur, but a number of large rockslides occur if geological structures are in adverse conditions such as wedge-shaped discontinuities and valleyward-plunging folds along the Minjiang River. Due to these geological defects, at least 5 large rockslides occurred sequentially by the upstream migration of the knickpoint. When the geological planar structures strike parallel or slightly oblique to the river, DGSDs including buckling and toppling commonly occurred along the Heishuihe River. Buckling only occurred on the cataclinal slope, whereas toppling occurred on both sides of the river. The difference in slope response to river incision as mentioned above is mainly because the gravitational deformation of rocks with planar structures, such as foliation and bedding, occurs principally through shearing along these discontinuities. It suggests the relationship between slope surface and geological structure strongly controls the types of slope instabilities in the mountainous area along the plateau margin. In addition, investigation of the landslides evolved from gravitational slope deformations, such as the Xinmo landslide and the Xinmo east slope, provides a good way for the predictability of potential landslide sites. The irregular hillslope shape, the well-developed open cracks and buckle folds on the Xinmo east slope indicate that this hillslope could transform into a catastrophic landslide during future earthquake or rainfall events. The detailed geological structures and relief also provides a way to assess the risk of landslide or DGSD. The rock slopes usually prepare to fail downstream of the knickpoint and slope destabilization is more prone to occur in the higher-relief valley.

Chapter 6 Conclusions and perspectives

In this thesis, landslides and DGSDs along two major rivers in the eastern margin of the Tibetan Plateau, one of the highest relief areas in the world, were investigated in regards to the relationships between rock planar structures and river incision through both geological and geomorphological investigations. I chose the Minjiang River as a river in which geological trend and river trend are normal and one of the major tributaries, the Heishuihe River, in which the geological trend and river trend are parallel. The most important findings are as follows:

1. The Minjiang and Heishuihe Rivers drain the eastern margin of the Tibetan Plateau, where was confirmed that knickpoint migration and inner gorge formation played an important role for the slope development. Rock slope responses to river incision are completely different according to the relationship between the geological trend and river trend.
2. There are two major knickpoints and two slope breaks in the catchment, and the formation of the lower slope breaks as high as ~300 ± 150 m (Minjinag) and ~400 ± 150 m (Heishuihe) above the current riverbeds are most significant to destabilize the slopes. Landslide dams create another type of knickpoint in the river channel, but these dams gradually disappear from downstream to upstream as a result of river erosion.
3. When the geological trend is normal to the river trend, very few DGSDs occur, but a number of large rockslides occur if geological structures are in adverse conditions along the eastern margin of the Tibetan Plateau. The Manaoding and Dragon landslides were controlled by tight folds, which plunge valleyward at 10–30°. The Diexi and Yinpingya landslides were multiple wedge failures with bedding planes and joint discontinuities; the intersections dip valleyward 30–50°.
4. When the geological trend is parallel to the river trend, gravitational slope deformations of flexural toppling or buckling occurred along the river, and some of the deformations transformed into landslides. Buckling deformations occurred only on the left bank of the river where the slopes are mostly classified as underdip cataclinal slopes, whereas toppling deformations developed on both sides of the river on anaclinal slopes and underdip cataclinal slopes. Differential deformations observed above and below Sb2 (the lower slope break) are probably because of the different exposure times and weathering extents of the middle and late fluvial stages.
5. The Xinmo landslide and DGSDs nearby along the Songpinggou River suggest that gravitational buckling deformation and transformation into catastrophic failure are typical slope processes on dip slopes and probably on underdip cataclinal slopes.