Orographic rainfall, deep-seated catastrophic landslides and landscape evolution: geomorphic hazard assessment in active orogens

Yuki MATSUSHI[1,2,*], Masahiro CHIGIRA[1], Ken'ichirou KOSUGI[2,3]
[1] Disaster Prevention Research Institute, Kyoto University, Japan
[2] CREST, JST, Japan
[3] Graduate School of Agriculture, Kyoto University, Japan
*Corresponding author. E-mail: matsushi@slope.dpri.kyoto-u.ac.jp

INTRODUCTION

High-relief steep hillslopes in tectonically active mountainous areas are subjected to risk of deep-seated catastrophic landslides especially where accretionary sedimentary rocks compose the regional bedrock. The high relief hillslopes deform gravitationally as a part of long-term geomorphic process before heavy rainfall eventually triggers landslides. The spatial pattern of landslide-triggering rainfall often exhibits a clear infection by orographic forcing, but landslide locations in some cases shows a different distribution from rainfall amount. This implies existence of a feedback systems between rainfall, deep-seated landslides, and landscape evolution. This study aims to reveal how rainfall, landslides and topography are linked, and discuss to what extent we can make hazard assessment in a geomorphological way.

STUDY AREAS AND METHODS

Study sites are Kii Mts and Hira Range, central Japan. In the Kii Mountains, Typhoon Talas hit the area from 31 Aug to 3 Sep 2011, and caused more than 70 deep-seated catastrophic landslides. We analyzed relationships between spatial pattern of rainfall, topography, and deep-seated landslides in a regional scale in Kii Mts using DEM (Digital Elevation Model), on GIS (Geographic Information Systems). Signals of gravitational slope deformation and slip scars are mapped in a local scale on LiDAR (Light Detection And Ranging)-DEM, and the form of those slid/deformed hillslopes were modeled by a simple formulation of Culmann's wedge failure.

RESULTS AND DISCUSSION

The distribution of landslides at the 2011 event in the Kii Mts are not matched with the spatial pattern of rainfall amount. The landslides occurred north-to-west outer rim of the rainfall center. Instead of the rainfall amount, rainfall anomaly (rainfall amount normalized by local maximum-class daily rainfall) explains well the landslide locations. We hypothesize that hillslopes become insensitive to rainfall to cause deep-seated landslides after they had experienced a number of extreme rainfall events enough to remove weathered bedrock layers capable to be slid. To test this hypothesis, relationships between rainfall and topographic relief or mean hillslope angle were examined by 10-m mesh DEM analyses.

The relief index in Kii Mts increases linearly with increasing rainfall, reflecting interaction between tectonic uplifting and orographic rainfall supply, resulting in formation of deeply incised valley slopes. The mean hillslope angle also increases with rainfall but seem to be saturated to form hillslope around 35 degrees. The topographic condition at locations of deep-seated catastrophic landslides in the 2011 event was not the highest in relief nor steepest

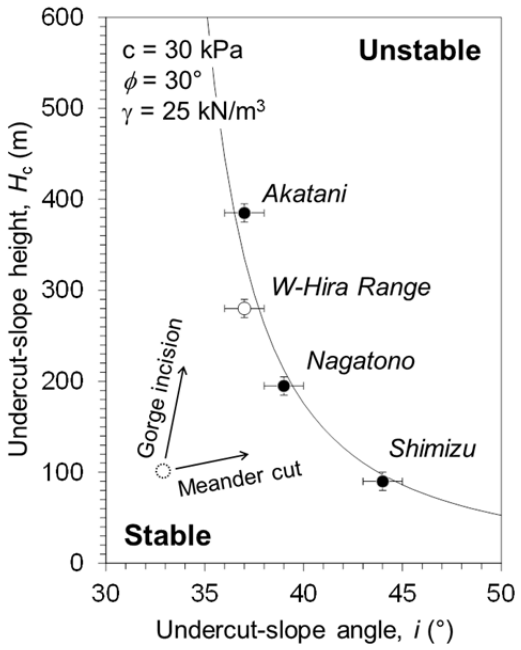

Fig. 1 Relationship between height and angle of undercut slope for several landslides in the Kii Mts and deformed hillslope in the western Hira Range. Curve indicate boundary between stable and unstable conditions by Culmann's model for rock mass strength of c = 30 kPa, ϕ = 30°, and rock mass unit weight γ = 25 kN/m^3. Vertical incision or lateral meander cutting would cause the hillslope destabilization as indicated as dotted open circle moving toward right-up reaching to the critical curve.

in hillslope angle. This finding indicates that deep-seated landslides occur most frequently in the landscape in a pre-mature stage.

Incision of Totsukawa River in central Kii Mts form an inner gorge, cutting the toe of hillslopes . The hillslopes slid along a slip plane connecting to the valley bottom. The formation of inner gorge thus seems to play an important role in the enhancement in susceptibility of deep-seated landslides in the pre-mature, being dissected landscapes. The insight for controlling factors of deep-seated landslides from Kii Mts can be confirmed in another mountainous terrains underlain by accretionary sedimentary rocks: the western part of Hira Range. The LiDAR-based mapping of landslide scars and deformation scarplets demonstrated, as expected, the instability of hillslopes in the major, deeply-incised fault-along valley. The deformed hillslopes in the western Hira Range show striking similarity to the hillslopes in the Kii Mts, slid at the 2011 rainfall event. They exhibit a comparable set of slope break and scarplets. This similarity may attribute to a common mechanism of slope instability, probably owing to undercutting by river incision.

The slope destabilization due to undercutting can be modeled most simply by Culmann's 2D wedge failure analysis [**Fig. 1**]. The relationship between critical height of hillslope undercut (i.e., height of slope break above river bed) and angle of undercut lower part of hillslope is well explained by the model. The most probable strength parameters are comparable to that of highly weathered rock mass, implying importance of discontinuity with weak asperity in the bedrock for initiation of a deep-seated catastrophic landslide.

CONCLUSIONS

The spatial pattern of orographic rainfall is closely related to the topographic relief and mean hillslope angle, and hence occurrence of deep-seated landslides in the Kii Mts, reflecting the stages of landscape evolution. The spatial distribution of 2011 landslides is concordant with rainfall anomaly rather than absolute rainfall amount. The landslide-prone areas are not the most highest-relief nor steepest zones in the Kii Mts, but exhibit a pre-mature landscape characterized by hillslope undercutting by river incision. Similar inner-gorged landscape is also evident in the western Hira Range, along a major active-fault incised-valley. A simple wedge-failure modeling for such undercut hillslope well explains the instability of actual slid/deformed hillslopes, indicating the significance of downward incision of gorge or lateral meander cutting for long-term hillslope destabilization

Keywords: deep-seated catastrophic landslide, orographic rainfall, topographic relief, river incision, landscape evolution