Possible Mechanisms of Cascading Hillslope Mass Movements Induced by Earthquake and Heavy Rainfall in The Noto Peninsula, Japan

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Abstract: This report presents preliminary insights into mechanisms of cascading mass movements induced by the earthquake and subsequent heavy rainfall with special focus on the diversity of phenomena dependent on geological conditions observed during the 2024 Noto Peninsula disaster. The strong seismic shaking altered the structural and physical characteristics of weathered bedrock across different lithologies. This hydrogeological regime shift influenced the behavior of infiltrating rainwater, resulting in a variety of landslides triggered by the subsequent heavy rainfall. Modeling of the subsurface critical zone is key to quantitative landslide hazard assessment.

Keywords: ***Threshold peak ground acceleration, Weathering zone structure, Geo-structural seismic damping, Hazard assessment, Cascading disaster.***

Introduction

The Noto Peninsula, located in central Japan, was severely impacted by an earthquake on January 1, 2024, and was subsequently struck by a record-breaking heavy rainfall from September 20 to 23, 2024, resulting in another devastating disaster. The intense rain bands brought over 500 mm of total rainfall, with intensity exceeding 100 mm/h. In mountainous watersheds, this rainfall caused numerous mass movements, yielding large amounts of sediment and driftwood flowing into river systems, especially in the northern part of the peninsula.

The subsequent heavy rainfall triggered many new landslides particularly in areas underlain by alternating beds of sandstone and mudstone, which was contrasting with active erosion of landslide scars and reworking of debris in the areas of pyroclastic rocks, and with landslide enlargement in the siliceous siltstone dominant areas. The geologically dependent nature of earthquake–rainfall composite triggering for the varying types of landslides should be explained by the bedrock response characteristics to seismic motion and the changes in hydro-geological structures and properties of the subsurface weathering zone. Hence, hillslope hazard assessment for such cascading phenomena requires theoretical and/or semi-empirical modeling for subsurface critical zone development.

Modeling Subsurface Weathering Zone for Hazard Assessment

A probabilistic evaluation of mechanical hillslope properties

In the preceding earthquake, the areal ratio of the coseismic landslides decreased exponentially with distance from the seismogenic fault (Figure 1A), with a steeper decline compared to the modeled peak ground acceleration (PGA) based on Morikawa and Fujiwara (2013). The spatial distribution of coseismic landslides can be explained by incorporating a log-normal probability density function for the threshold PGA required to initiate landslides (Figure 1B).

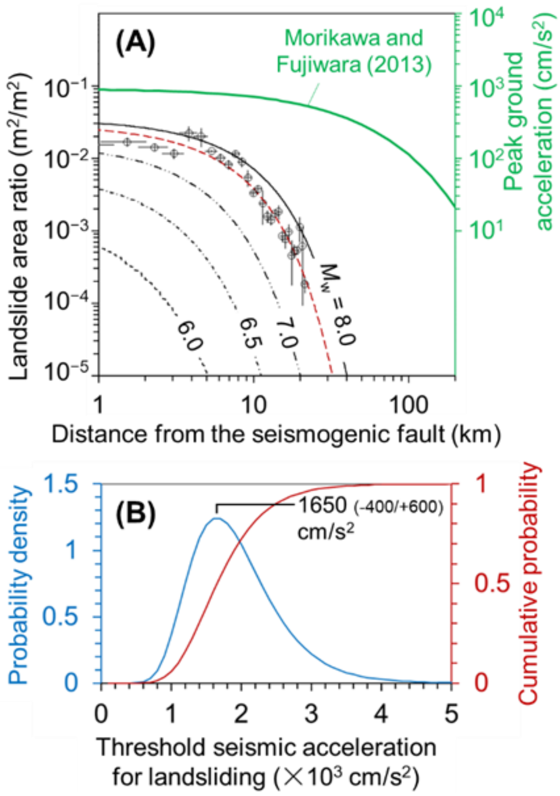

Figure 1, (A) Declining trends of landslide areal ratio and peak ground acceleration. (B) Optimal probability functions of PGA threshold for landslide triggering (adopted from Matsushi, 2025).

This conceptual modeling approach allows us to evaluate landslide susceptibility regulated by geological factors and the topographic amplification of seismic shaking. The probabilistic evaluation of mechanical strength of hillslopes will then provide a clue to calibrate a theoretical model of weathering zone development as well as changes in hydro-geological conditions of the earthquake-affected hillslopes.

Hydro-geological regime in each lithology leads to landslides

The structural and physical characteristics of the weathered zone significantly influenced hillslope behavior in response to sequential seismic impacts and rainwater infiltration. Figure 2 illustrates conceptual mechanisms of typical cascading landslides triggered by the earthquake and heavy rainfall across the major lithologies in the Noto Peninsula.

In areas composed of pyroclastic rocks, topographically elevated terrain with steep, high-relief hillslopes are highly susceptible to earthquake-induced landsliding (Figure 2A). The weathered bedrock exhibits a distinct strength contrast at shallow depth due to a sharp chemical weathering front. Combined with the topographic amplification of seismic motion, this led to widespread shallow shear failures during the earthquake, followed by active sediment reworking during the subsequent heavy rainfall.

In regions underlain by siliceous mudstone, the weathered bedrock has undergone substantial disintegration due to intensive slaking and iron hydroxide precipitation. This has resulted in a thicker weathering zone in dip slopes for the beddings compared to anti-dip slopes (Figure 2B). Coseismic landslides of varying magnitudes appear to reflect these contrasting subsurface structures. Strong seismic shaking likely enhanced fracture networks, potentially improving the slope drainage capability. As a result, cascading mass movements during the subsequent rainfall were likely suppressed, except for sediment yield from existing landslide scars or retreat of steep scarps.

The alternating beds of sandstone and mudstone form a complex weathering zone characterized by impermeable, plastic weathered sandy parts, and fractured muddy strata that retain fragment-scale elasticity but behave as a brittle and permeable zone at a bedrock scale (Figure 2C). The strong seismic shaking for this stratified subsurface structure likely caused energy dissipation via partial bedrock breakdown. This geo-structural seismic damping may have altered subsurface hydrological conditions, creating predispositions prone to slide by rainwater infiltration. Although the whole slope avoided failing during the earthquake, the buildup of pore-water pressure at the interface between fractured mudstone and massive sandstone likely triggered numerous landslides during the subsequent rainfall.

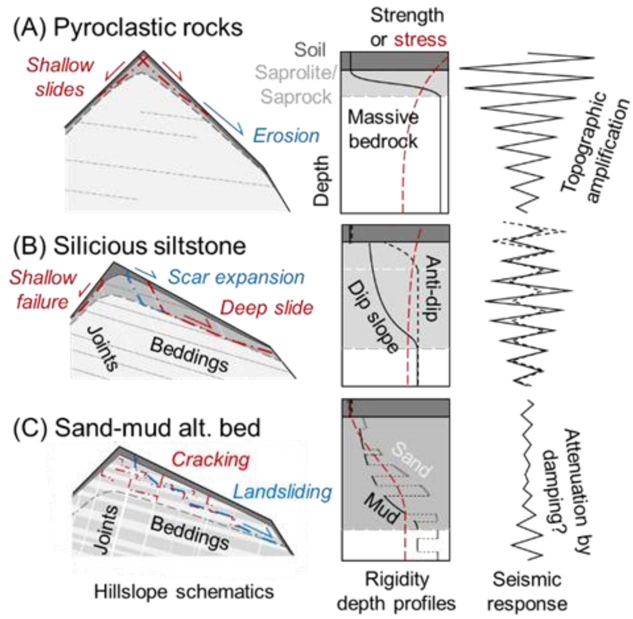

Figure 2, Conceptual schematics illustrating hypothetical mechanisms of cascading mass movements by earthquake (drawn by red) and heavy rainfall (blue) under varying geological conditions (adopted from Matsushi, 2025).

Conclusion

The cascading nature of hillslope mass movements induced by earthquake–rainfall interactions vary significantly with geological conditions. The mechanical strength of weathered bedrock, particularly the threshold for failure, can be statistically evaluated through geospatial analysis of coseismic landslide inventory. Quantitative modeling of the subsurface structure and depth-profiles of physical properties is essential for understanding the dynamic response to seismic shaking and for improving hazard assessments of cascading landslides.

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