Examining the Controlling Factors of Landslide Sediment Connectivity by Flume Experiment

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1. INTRODUCTION

Sediment connectivity is defined as the linkage and transfer of sediment from sources to deposits within a catchment system (Bracken et al., 2015). Sediment connectivity implies how sediment can mobilize from one zone to another (e.g. Cavalli et al., 2013) which depends on the geomorphic and hydrologic process of the system (Di Stefano and Ferro, 2018). Connectivity of landslide sediment to and within catchment systems is a key factor affecting the mobilization of landslide material. When the landslide sediments are less mobilized and poorly connected to downstream, most of sediments remain at the hillslopes foot or within the channel and often formed landslide dam (Imaizumi and Sidle, 2007). Meanwhile, when landslide sediments closely connect to downstream, they often transform into debris flows due to their highly liquefied nature (Dade and Huppert, 1998). Although numerous studies examined factors that control the mobility of debris flows and landslide dams, most of these studies only examined individual factors related to hydrologic and geomorphologic conditions. To better understand sediment connectivity related to the mobility of landslide sediments, interactions among multiple hydrogeomorphic factors need to be considered. Therefore, we identify the key factors that control the mobility of sediment using flume experiment and introduced new index of sediment connectivity. We then examined the landslide dam formation and the occurrence of debris flows based on different condition of sediment connectivity.

2. METHOD

We constructed a flume (10 cm wide and 15 cm high) using 1-cm thick acrylic material, consisting of an inflow segment and main channel segment. The inflow segment was 50 cm long with a 45° gradient, while main channel segment was 150 cm in length. We examined the mobility of sediment on four inflow angles (0°, 30°, 60°, and 90°) and two channel gradients (10° and 15°). Four types of sediment originating from different geology were used: sand and shale (SS) from Nigoridani, Nara Prefecture; pyroclastic sediment (PS) from Izu Oshima Island; Tokyo Prefecture; weathered granite (WG) and weathered sedimentary rock (WS) from Asaminami Wards, Hiroshima City. The D_{50} for SS, PS, WG, and WS were 7.5, 0.2, 1.3, and 2.2 mm respectively. For all types of sediment, we used samples of 400 cm^3 and applied six gravimetric water contents (0% to 100% in 20% increments) in all experiments. The channel width and sample volume were approximately 1/2000 of an actual deep-seated landslide (Kharismalatri et al., 2017; 3.3×10^6 m^3 for a mean channel width of 199 m). After the experimental flushing, the amounts of sediment deposition were measured in the flume's junction and outlet.

To evaluate the mobility of sediment, we developed a sediment connectivity index (*SCI*). The Sediment Connectivity Index (*SCI*) represents the potential connection between up and downstream parts of a catchment (Borselli et al., 2008). We assumed the sediment deposition at the junction and the outlet for differentiating between the formation of landslide dam and transformation into debris flows. Our *SCI* is expressed by the following equation:

$$SCI = \frac{W_O - W_J}{W_O + W_J} \tag{1}$$

where W_J and W_O are the dry weights of sediment in the junction and outlet, respectively. Positive *SCI* values indicate that the sediment sources and downstream are closely connected, i.e., landslide material transformed into debris flows. In contrast, negative *SCI* values are associated with the formation of landslide dams because the sediment source is poorly connected with downstream.

3. RESULTS AND DISCUSSION

Assessment of material mobility shows that *SCI* values change with respect to channel gradient and inflow angle, in association with water content and sediment type (Figure 1). For the 10° channel gradient, *SCI* elevated from negative to positive values at high water content condition. *SCI* values with inflow angles of 0° and 30° also significantly differed to ones with inflow angles of 60° and 90°. Such characteristics agreed to GIS analysis of 33 rainfall-induced deep-seated landslides (Kharismalatri et al., 2017). They showed landslide dams formed with inflow angles >60° and channel gradients <10°, while landslide materials with inflow angles <60° and channel gradients >10° were transported as debris flows.

By comparing 10° and 15° channel gradient, water content acted differently for the mobility of sediment. *SCI* values in 15° channel gradient elevated much greatest toward positive values. Such threshold behavior in 10° channel gradient was associated with the deposition process of sediments. A study on debris flow sites in Austria, Japan, New Zealand, Switzerland, and United States showed that debris flows generally initiated on channel gradient >25°, transported on >15°, and deposition occurs on <10° (VanDine, 1996). Decrease in channel gradient leads to separation of water from the sediment and increasing of internal friction angle (Takahashi, 1983). Such conditions ultimately lead to decreasing of velocity and deposition of sediment, particularly in channel gradient <10°.

Among different sediment types, mobility of sediment much differs in 10° channel gradient. In contrast, *SCI* values with 15° channel gradient were similar among different soil types. In steep channel gradient, sediment mobilized in high velocity without water separation from sediment mixture (VanDine, 1996; Takahashi, 2009). In this condition, water content has significant influence on sediment mobility. Contrastingly, soil properties control the sediment mobility in 10° channel gradient, particularly the combined effect of density, porosity, and particle size distribution. For instance, laboratory experiment indicated that sediment with smaller D_{50} values generated rapid sediment flow due to abrupt increase in pore water pressure (Hayashi and Self, 1992; Wang and Sassa, 2003).

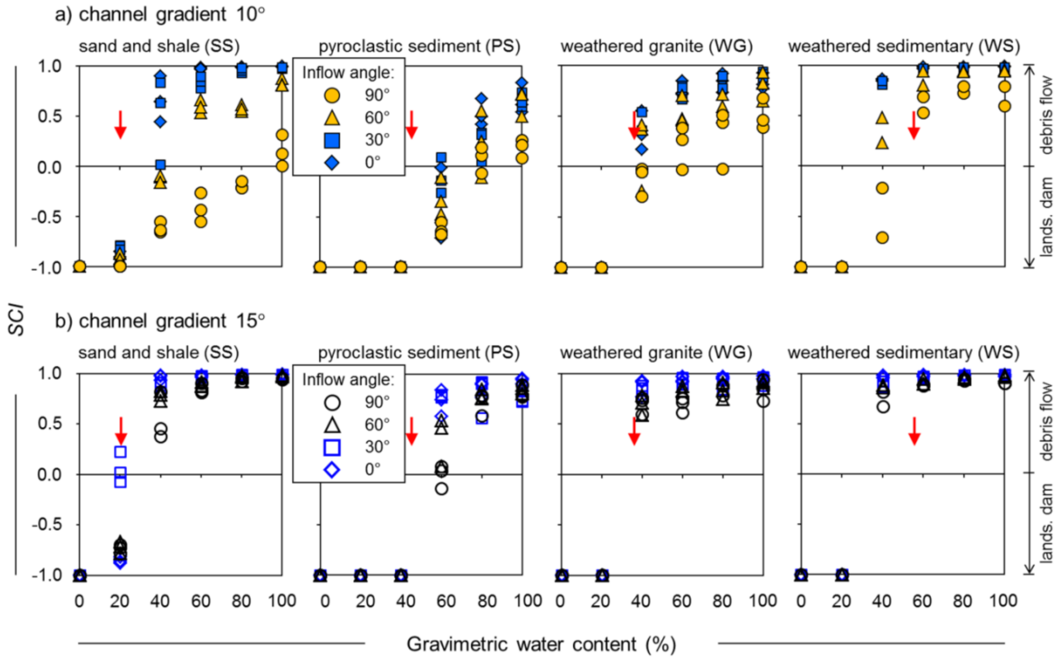

Figure 1. Sediment Connectivity Index (*SCI*) for the classification of landslide dams and debris flows. The arrows represent the different saturated water contents of sediments.

4. CONCLUSION

Our results highlight how topographic characteristics with different sediment and water content affect the sediment connectivity, i.e., formation of landslide dam and mobility of debris flow. Assessment of sediment connectivity is crucial for hazard risk analysis by providing knowledge on possible end members of landslide material mobility on-site and off-site. Because comprehensive spatial planning and land use strategies are keys to ecosystem-based disaster risk reduction and are more cost-effective than conventional structural countermeasures, identification of sediment connectivity is an important aspect for disaster risk reduction.

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