# Small Flume Experiment on Deep-seated Landslide Collapsed Material Movement

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Previous researches revealed that inflow angle and stream gradient are two major factors that distinguish the formation of landslide dam and debris flow from collapsed material of deep-seated landslide. Yet their significance mobilization of landslide material has yet to be clarified. This research aimed to clarify the influence of inflow angle and stream gradient on rapid deep-seated landslide collapsed material movement and the possibility of landslide dam formation by using small flume apparatus. The small flume consisted of inflow segment and main channel where the junction angle between them were modified into 0°, 30°, 60°, and 90°, while the gradient of the inflow segment and main channel was fixed on 45° and 10° respectively. Experiment was conducted on 6 classes of water content, namely from 0% to 100% with 20% increment. Soil samples from Nigoridani, Nara Prefecture where deep-seated landslide occurred in 2011 due to Typhoon Talas, with $D_{50}$ of 7 mm and saturated water content of 21% was used in the experiment. The result revealed that on its saturated water content, collapsed material formed deposition at junction area of 11%, 14%, 32%, and 49% on inflow angle of 0°, 30°, 60°, and 90° respectively. The deposition on inflow angle of 60° and 90° was relatively significant and possibly forming landslide dam. In contrast, the material was mainly transported to the lowest part of the flume as debris flow on inflow angle of 0° and 30°. The experiment result confirmed that collapsed material of DSL that encountered large inflow angle will experience large collision with the opposite slope which cost a large amount of energy and thus the material deposited at or near the junction area. Water content also has an important role in determining the mobilization of landslide material.

**Key words:** small flume, landslide dam, inflow angle, saturated water content

## 1. INTRODUCTION

Collapsed material of rapid deep-seated landslides (hereafter noted as DSL) mainly mobilizes in two main types: debris flow and landslide dam. Debris flow is known as the most powerful mechanism for transporting landslide sediment far downslope [*Bathurst et al.*, 1997] and holds serious impact on human life and infrastructures since it moves rapidly, large in volume, destroys object without warning, and often occurs without warning [e.g., *Nishiguchi et al.*, 2012; *Highland et al.*, 1997]. While landslide dam defined as natural blockage of river channel caused by landslide, having significant height and potentially causing inundation of water behind it [*Canuti et al.*, 1998; *MLIT*, 2006]. Landslide dam holds further threats than debris flow; upon the dam creation, back-flooding threaten upstream area; and when the dam breaks, which commonly due to overflowing of inundated water, large surges and debris flow threaten downstream area [e.g., *Ermini and Casagli*, 2003; *Inoue et al.*, 2012].

Severe rainfall brought by Typhoon Talas in 2011 catastrophically damaged Kii Peninsula including Mie, Nara, and Wakayama Prefectures. The heavy rainfall induced many sediment disasters including 33 DSL, 30 rock falls, and 21 stream blockages, with total sediment amount of approximately $1\times10^8$ $m^3$ [*MLIT*, 2011; *MLIT*, 2013]. From 33 DSL found in Kii Peninsula, 30% of them mobilized downstream as debris flow and deposited far from the failure area, while the 64% of them formed landslide dam in the adjacent stream of the failure area [*Kharismalatri et al.*, 2017]. Based on investigation of these DSL, stream gradient and inflow angle are the major factors which established a boundary between landslide dam and debris flow formation. The collapsed material of DSL which mobilized as debris flow were occurred in stream with gradient of >10° and inflow angle of <60°. While on stream gradient of <10° and inflow angle of >60°, the collapsed material of rapid DSL were likely to form landslide dam.

Yet, very few researches discussed the interaction between landslide, junction/merging/inflow angle, and the gradient of receiving stream. *Benda and Cundy* [1990] developed an empirical model of channel slope (<3.5°) and tributary junction angle (>70°) and found out that deposition of material started at gradient less than 3.5°. While *Takahashi* [2007], focusing on the travel distance of debris flow, constructed an experiment apparatus of 500-m-long slope and 200-m-long river channel (with two types of channel spanning angle: 100° and 140°) where the merging angle between them was 45° and 90°. The experiment revealed that the behaviors of material flow intricately vary depending on the combinations of merging angle, channel gradient, and the opening angle of cross-section.

However, to date, the significance of these topographic characteristics (i.e. stream gradient and inflow angle) to collapsed material movement has yet to be clarified and the possibility of landslide dam formation need to be analyzed further. Additionally, the boundary of whether collapsed material of DSL will mobilize as landslide dam or debris flow has yet to be determined. In this research, small flume experiment was conducted to analyze the mobilization and separate the phenomena of soil deposition by using collapsed material from DSL as soil sample. A small flume of 10 cm wide and 15 cm high was developed to represent the slope where the landslide occurs and the stream where the collapsed material mobilize into. Small flume is easy to develop and the amount of material needed for the experiment also smaller, yet it can give general description of the collapsed material movement and considered more efficient rather than large flume of several meters size. Since inflow angle and stream gradient are the major factors on landslide dam formation, variation of inflow angle and stream gradient were applied on the small flume apparatus. The aim of this experiment is to clarify the significance of inflow angle to the movement and deposition of DSL material and to examine the possibility of landslide dam formation.

## 2. METHODOLOGY

A small flume consisted of a main channel and an inflow segment was developed for the experiment (**Fig. 1**). Both segments were 10 cm wide and 15 cm high by 1-cm thick acrylic material. The gradient of the inflow segment was 45°. The length of the main channel was 130 cm and a bucket was placed at the end of it to capture transported soil sample. Since inflow angle and stream gradient were the major factors for material movement, experiment was applied on four different inflow angles (90°, 60°, 30°, and 0°) and stream gradient of 10°. The authors used 6 classes of water content (0%, 20%, 40%, 60%, 80%, and 100%) because water content of collapsed material also alter the mobility of soil.

Soil mixture was placed in 10 cm upstream from the junction area, and then the lid was opened manually to let the soil mixture flows. After the experimental flushing, percentages of material deposition were measured in 5 sections (**Fig. 2**). Each experiment was conducted 3 times. This flume experiment was not a scale down from an actual landslide event and was not intended as a model of the DSL in Nigoridani, but to describe the general tendency and features of material movement under several conditions. By flume experiment, the principle of material movement which is important to understand the mobilization and deposition of material can be obtained.

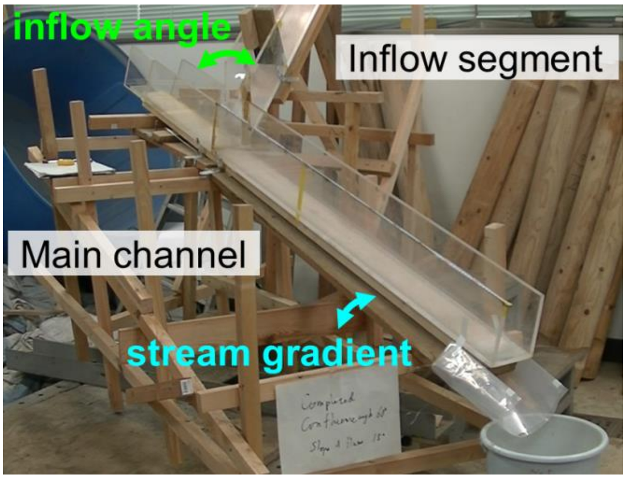


**Fig. 1** Small flume apparatus

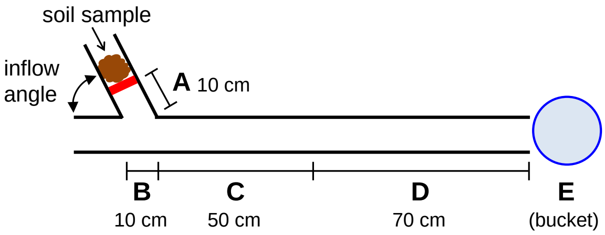


**Fig. 2** Sections division of the small flume

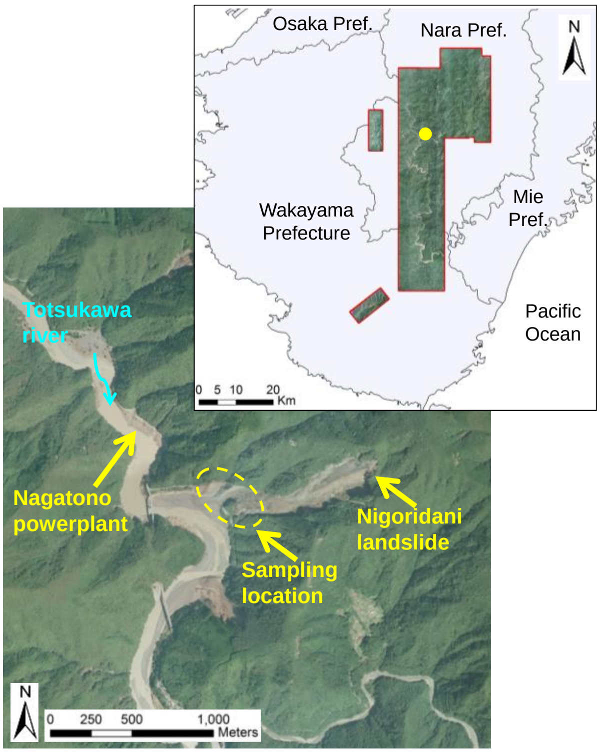


**Fig. 3** Location of soil sampling

## 3. SOIL SAMPLES

Soil samples were taken from Nigoridani, Totsukawa Village, Nara Prefecture, where rapid DSL occurred due to Typhoon Talas in September 2011 (**Fig. 3**). A short-term landslide dam was formed at stream gradient of 0.8° and inflow angle of 121° [*Kharismalatri et al.*, 2017]. The main collapsed area was about 30 m depth [*Chigira et al.*, 2012] and located at the upper part of the slope for about 950 m above the sea level. The amount of collapsed material was increased as it flows to the Totsukawa River for about 650 m below. According to *IEA Hydropower Implementation Agreement* [2016], the total amount of material was estimated for about 4 million ton which rushed at about 200 km/h, creating a mountain tsunami upstream and downstream. Nagatono hydropower plant, located about a kilometer upstream from the failure area, was completely destroyed as the impact of the >10 m mountain tsunami wave [*IEA Hydropower Implementation Agreement*, 2016]. The main failure area consists of well-fractured muddy alternation of sand and shale of Cretaceous Miyama Formation, with a large dense block of felsic tuff intercalated beneath the lower part of the slope, thus groundwater is easily backed up in the mass at the upper part of the slope [*Mitamura et al.*, 2014].

Soil samples were taken at the lower part of the slope due to difficulties to reach the main failure zone at the top of the slope. Soil properties tests were conducted to the disturbed samples, i.e. soil density, particle size analysis, and Atterberg limits tests. From the tests, the author obtained water content at saturated condition of 21%, plastic limit of 14%, and liquid limit of 19%. The plastic limit test was conducted based on Test Method for Liquid Limit and Plastic Limit of Soils (JIS A 1205:2009), while the liquid limit test was conducted based on Test Method for Liquid Limit of Soils by the Fall Cone (JGS 0142-2009). Based on the particle size analysis, the $D_{50}$ of the soil sample was 7 mm.

## 4. RESULT AND DISCUSSION

### 4.1 Influence of inflow angle to material deposition

The result of flume experiment is summarized in **Table 1**. Material deposition at section A was increased with larger inflow angle, but the increasing became less significant as the water content increased. The largest material deposition was on 90° inflow angle with 0% water content, and in contrast, very few material were deposited at section A on water content of more than 40% in all inflow angle cases. At section B, the largest material deposition by trend was 64% which was generated on 90° inflow angle with 0% water content. Whereas the smallest material deposition of 0.3% was generated on 0° inflow angle with 80% and 100% water content.

Section C was the deposition zone for 0% water content and the transportation zone for other water contents. A clear correlation between deposition percentage, inflow angle, and water content was not found at this section. Further, material deposition at section D was zero for 0% water content since the fluidization was stopped at section C. Material deposition at section D tended to be small on inflow angle of 60° and 90° rather than on inflow angle of 0° and 30°. Lastly, the largest material deposition at section E was found on inflow angle of 0°, followed by 30°, 60° and 90° for all water contents. Since the movement of material with 0% water content was stopped at section C, thus the deposition at section E was zero.

**Table 1** Summary of soil deposition percentage on each section

| Flume section | Water content | Inflow angle | | | |
|---|---|---|---|---|---|
| | | 0° | 30° | 60° | 90° |
| A | 0% | 4% | 21% | 12% | 34% |
| | 20% | 1% | 11% | 3% | 20% |
| | 40% | 1% | 3% | 1% | 2% |
| | 60% | 0.4% | 1% | 1% | 2% |
| | 80% | 0.3% | 1% | 0.3% | 1% |
| | 100% | 0.4% | 1% | 0.3% | 1% |
| B | 0% | 56% | 41% | 71% | 64% |
| | 20% | 19% | 27% | 37% | 50% |
| | 40% | 2% | 5% | 16% | 39% |
| | 60% | 0.4% | 2% | 6% | 30% |
| | 80% | 0.3% | 1% | 7% | 31% |
| | 100% | 0.3% | 1% | 4% | 22% |
| C | 0% | 40% | 38% | 17% | 2% |
| | 20% | 67% | 57% | 57% | 30% |
| | 40% | 43% | 60% | 57% | 45% |
| | 60% | 10% | 60% | 46% | 44% |
| | 80% | 5% | 54% | 47% | 33% |
| | 100% | 1% | 19% | 26% | 38% |
| D | 0% | 0% | 0% | 0% | 0% |
| | 20% | 12% | 1% | 1% | 0.2% |
| | 40% | 41% | 19% | 14% | 6% |
| | 60% | 56% | 17% | 25% | 11% |
| | 80% | 56% | 15% | 19% | 14% |
| | 100% | 29% | 27% | 24% | 11% |
| E | 0% | 0% | 0% | 0% | 0% |
| | 20% | 1% | 3% | 2% | 0.1% |
| | 40% | 13% | 13% | 13% | 9% |
| | 60% | 32% | 20% | 22% | 12% |
| | 80% | 38% | 29% | 27% | 21% |
| | 100% | 69% | 52% | 45% | 29% |

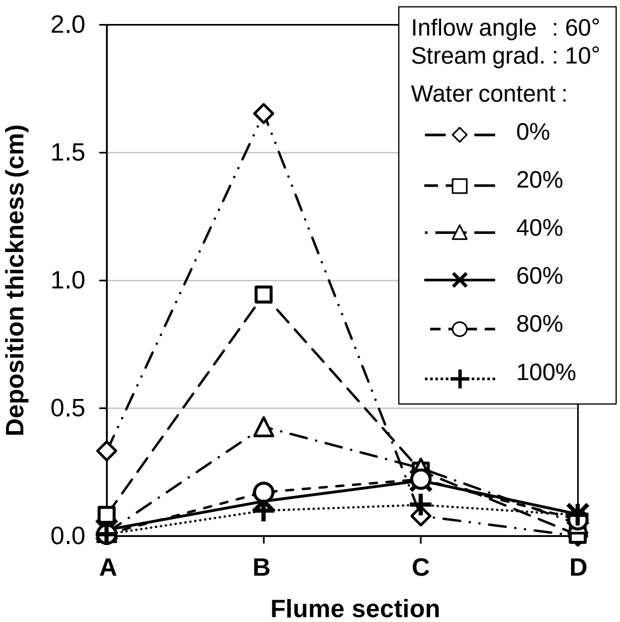


**Fig. 4** Average material deposition thickness on 60° inflow angle

## 4.2 Possibility of landslide dam formation

Among 5 flume sections, the thickest material deposition was generally found at section B (**Fig. 4**) particularly on low water content. Average material deposition thickness was obtained by dividing volume of material deposited on each section with the section area. The inflow angle of 90°, 30°, and 0° has the similar pattern of deposition thickness with 60° inflow angle. Among 4 inflow angles, the thickest deposition at section B was found on 90° inflow angle in all water content classes. At the same water content, inflow angle of 60° and 90° generally generated material deposition of about 0.4 cm thicker than those on 0° and 30° inflow angle. The thickest deposition at section B was generated on 60° and 90° inflow angle on 0% water content which was 1.6 and 1.5 cm respectively. Water content of ≤40% and inflow angle of 60° and 90° generated a thick material deposition at section B. Deposition thickness at section E was not included in **Fig. 4** because the length was unknown and the soil deposited at section E was actually still have potential to mobilize further to downstream if the flume being extended.

By the material deposition thickness, it can be assumed that landslide dam possibly formed at section B, since it generally has the thickest material deposition among other sections and thus has the possibility of blocking the river flow. In addition, section B is the junction area between the contributing slope and receiving channel where the collision between the collapsed material and the opposite slope occurs, possibly knocked down trees and scrapped the soil on the opposite slope, and loss some energy.

**Fig. 5** describes the material deposition formed at section B in accordance with inflow angle modification. By trend, 90° inflow angle generated the largest material deposition in all water content classes, while the smallest material deposition was generated by 0° inflow angle. *Yamamoto et al.* [1999] stated that heavy rainfall-induced DSL are commonly occurred on soil's saturated water content condition. The bold dash line on **Fig. 5** represents the saturated water content of Nigoridani soil sample (21%). Following *Yamamoto et al.* [1999] if DSL occurred on Nigoridani soil samples at their saturated water content, inflow angle of 90° and 60° formed material deposition at section B of 49% and 32% respectively. While only 14% on 30° inflow angle and 11% on 0° inflow angle. In accordance with *Kharismalatri et al.* [2017] that landslide dam possibly formed on inflow angle of more than 60°, the material deposition on 90° and 60° inflow angle in this flume experiment possibly formed landslide dam. Yet the boundary of how much material deposition at the junction area can be considered as landslide dam is uncertain.

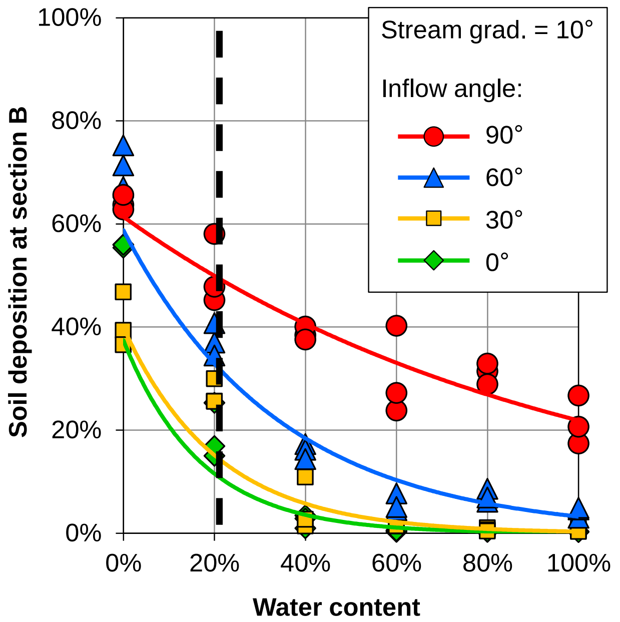


**Fig. 5** Material deposition at section B

### 4.3 Discussion

Inflow angle defined as the upstream junction/merging angle between contributing slope with the stream channel which strongly influenced the mobilization of rapid DSL collapsed material on the stream (e.g. *Benda and Cundy*, 1990; *Ishikawa*, 1999; *Kimura et al.*, 2016; *Takahashi*, 2007). The inflow angle contributed to material deposition at flume sections and possibility of landslide dam formation. *Benda and Cundy* [1990] remarked that material movement with junction angle of less than 70° predicted to be mobilize downstream as debris flow. In accordance, most of the collapsed material movements change into debris flows when the inflow angle of earthquake-triggered DSL is less than 70° [*Ishikawa*, 1999]. From 13 rainfall-triggered DSL, the inflow angle which induced debris flow ranges from 10° to 62° with the stream gradient ranges from 6° to 25° [*Yamada et al.*, 2000]. While from 77 DSL induced by snowmelt, *Kimura et al.* [2016] found that steep valley of more than 9° and sharp inflow angle of less than 70° induced long-travelling landslides which traveled longer than their slope lengths.

Collapsed material of DSL tends to travel in long distance as debris flow when the DSL occurs on slope with pre-existing landslide, sharp inflow angle, and coupling with steep valley topography [*Kimura et al.*, 2016; *Yamada et al.*, 2000]. In contrast, collapsed material of DSL that encountered large inflow angle will experience large collision with the opposite slope which cost a large amount of energy and thus the material deposited on or near the collision/junction area [*Ishikawa*, 1999]. Additionally, *Kharismalatri et al.* [2017] remarked that the threshold between landslide and debris flow is 60° inflow angle and 10° stream gradient. Experiment on this research revealed that inflow angle of 90° and 60° formed large material deposition at the junction area which possibly forming landslide dam. This research agreeing with previous researches that landslides with <60° inflow angle are likely to mobilize to lower stream/channel, while those with >60° inflow angle are likely to be deposited at junction area and has high possibility of forming landslide dam.

DSL' collapsed material movement and landslide dam formation is not solely depends on the topographic characteristics. The natural conditions (e.g. the stream bed and slope soil layer, stream flow, slope and stream soil layers, fallen trees, stream flows, and the condition of the opposite slope) are the factors that also influence the mobilization of collapsed material. On the actual DSL event, these factors will affect the mobilization of DSL' collapsed material. As the collapsed material sliding downwards along the slope, the motion involves not only the material from the initial failure zone but also the soil added along the path of the travel [*Sassa and Wang*, 2005]. Therefore the volume of the material will increase and might form larger deposition at the junction area with the receiving stream.

Fallen trees as well as large boulders also have influence on the formation of larger deposition at the junction area. After colliding with the opposite slope, collapsed material mixed with fallen trees or large boulders drifted by the material motion will stop and formed large deposition at the junction area. Due to resistance to erosion of large boulders and reduction of water pressure due to seepage through the void created by the boulders and logs [*Yin et al.*, 2009], deposition of material mixed with fallen trees and large boulders will be harder to be eroded by the stream flow and thus easier to form landslide dam. Meanwhile, stream flow on the receiving channel/stream has two roles on the collapsed material movement; (1) on the event of the DSL disaster, its high flood runoff discharge helped collapsed material movement to flow downstream as debris flow [*Takahashi*, 2014] and the formed landslide dam will be at the risk of breaching due to raid rise in water level [*Chigira*, 2011]; and (2) after the formation of landslide dam, the impounded stream flow behind the dam will affect the dam stability (e.g. *Dong et al.*, 2011; *Li et al.*, 2011).

Those natural conditions are influencing the mobility of landslide material and the possibility of landslide dam formation. However, they are not being considered in this experiment as it is a simplified landslide material movement so that the experiment become more feasible and focused more on the topographic factors. In future researches, it is suggested to consider those natural factors in the experiment in association with the topographic characteristics. Deposition formed at the junction area possibly larger than the result obtained in this experiment and the formation of landslide dam will be more apparent if the natural factors are being considered, yet the experiment process will be much more complex.

## 5. CONCLUSION

Previous researches agree that topographic characteristics (i.e. stream gradient and inflow angle) are major factors that distinguish the formation of landslide dam and debris flow from DSL collapsed material. Small flume experiment was conducted to examine these major factors for understanding the general description of the collapsed material movement under given experimental conditions. DSL material on inflow angle of 30° and 0° was mainly transported to the lowest section of the flume as debris flow. Particularly when the material contained a lot of water (over its saturated condition), it mainly transported to lower sections and less likely to form landslide dam at the junction area.

In contrast, material with low water content (lower or equal to its saturated condition) is more likely to form landslide dam. Particularly on inflow angle of 60° and 90°. On its saturated condition, material deposition at junction area was estimated to be 32% and 49% on inflow angle of 60° and 90° respectively, which has high possibility of forming landslide dam. This experiment clarified that collapsed material movement on inflow angle of 60° and 90° has high possibility to form landslide dam at the junction area, while on inflow angle of 0° and 30° the material was likely to travel in long distance as debris flow. In addition to topographic characteristics, water content also has an important role in determining the mobilization of DSL collapsed material.

Other than topographic characteristics, natural conditions such as fallen trees, stream and slope soil layer, and stream flow also affecting the formation of landslide dam. Stream and slope soil layer and fallen trees increase the possibility of landslide dam formation while stream flow helps the collapsed material to transport downstream. In future researches, it is suggested to consider these natural factors in the experiment in association with the topographic characteristics. Clarifying the threshold between landslide dam and debris flow will be very useful for estimation of future disaster and determination of hazard area. Thus land use management, spatial planning, and appropriate countermeasures can be performed effectively.

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