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DEFORMATION OF STREAM BED DEPOSIT AND RUNOFF PROCESS AT DEBRIS FLOW INITIATION ZONE

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ABSTRACT

Generally, debris flow occurs in response to heavy rainfall. The way in which debris flow occurs may be influenced by the conditions of the stream bed deposit, such as its shape, gradient and deformation. In past studies, a hydraulic experiment conducted to analyze debris flow occurrence used a steep flume and uniform gradient, and then some water was supplied to saturate the stream bed deposit before the debris flow was occurred. But in a natural torrent, the riverbed gradient becomes gentler downstream, the stream bed deposit is not uniform thickness, and also the deposit is sometimes unsaturated. We observed and analyzed the condition and deformation of a stream bed deposit and the runoff process of debris flow in the zone where debris flow is initiated through hydraulic experiments. The experiments were carried out on an experimental flume whose bed slope was 30° at the upstream end and 12° at the downstream end. We supplied a small amount of water, nearly as much as the infiltration flow at first, and rising as the surface water level rose. The experimental results clarified the following: 1) In the steep section with a gradient of 27°-30° and a small amount of surface water, a moving layer was formed that flowed downhill slowly. This moving layer started to move when the layer was saturated by the infiltration flow. When the moving layer flowed down in this section, no surface water or infiltration flow was observed at the downstream end. 2) As the gradient decreased to 21°-24°, the moving layer started to deposit and form a dune. The upper part of the dune had no surface water but the lower part did. The dune flowed down gradually, finally reaching the downstream end with a constant discharge. This dune started to move or deform when the surface water reached and flowed over the shoulder of the dune, forming a conspicuous peak. 3) As the amount of supplied water discharge (q_{in}) was small and the moving layer flowed down, the runoff discharge containing sediment at the downstream end (q_{out}) was constant and the ratio of q_{out} / q_{in} was around 0.8. Over time, q_{in} increased and the dune moved dynamically, forming a conspicuous peak. Values for q_{out} were variable and the ratio of q_{out} / q_{in} was around 2.0.

***Key words**: debris flow, initiation zone, deformation of stream bed deposit, moving layer, dune, runoff process*

INTRODUCTION

Hydraulic experiments to analyze the mechanism of debris flow occurrence, flow properties and deposition, experimental condition must be necessary to make sure a debris flow as a sediment gravity flow. Therefore, in many experiments the grains were layered on the bed of a steep flume with a uniform gradient and saturated it beforehand and the rapidly supplied large amount of water from upstream end (Kaki, 1955; Yano & Daido, 1959; Takahashi, 1977). In natural torrents, however, the riverbed gradient usually becomes gentler from the upstream toward the downstream, the stream bed deposit is not uniform thickness and grain sizes, and also deposit sometimes is unsaturated when there is no precipitation even while stream flow is available. Furthermore, the process of rainfall infiltration during precipitation and the process of appearance of surface flow remains unclear, the stream bed deposit sometime have high permeability, infiltration flow become so much, unsaturated condition seems to be present even in during heavy rainfall (SATOFUKA & MIZUYAMA, 2009). In past, a few studies focused on consider a natural torrent, experimental flume continually changing slope gradient have been used (TAKAHASHI, 1977; IKEYA & MIZUYAMA, 1982; MIZUYAMA & HU, 1989), and a small amount of water nearly as much as infiltration flow is supplied (Yano *et alii*, 1969), unfortunately, and general studies involved saturated deposits and large amounts of water. While the occurrence of debris flow is probably related with properties of stream bed deposit (deposit gradient, thickness, grain size, etc.) at the initiation zone of debris flow and its time and spatial variations (deformations), few studies have focused on deposits and their runoff process.

This study thus attempts to clarify deformative characteristics of torrential debris flow at initiation zone in order to adopt a suitable measure to prevent or to mitigate the disasters by discussing the moving properties, deformation of stream bed deposit through hydraulic experiments, using a flume in which the gradient gradually becomes gentler (hereinafter referred to as "the gradient changing flume"), presuming a natural torrent.

EXPERIMENTAL SETUP AND PROCEDURE

As shown in Figure 1, the experimental flume is a gradient changing flume (horizontal length is approximately 12 m and height is approximately 4.5 m) with a width of 15 cm and a length of 1.8 m, with seven connected flumes. The flume bed slope is 30°at the upstream end and 12°at the downstream end, continually changing at intervals of 3° as 30°, 27°, 24°, 21°, 18°, 15°, and 12°. The depth of the flume is 30 cm. Smooth glass was attached on the left lateral side, and a mesh for measurement was also attached. Roughened bottom surfaces were attached on the flume floor from the 21° to the 30° gradients to prevent slide, which is stuck by a wooden piece at 10 cm intervals, and a steel mesh board of the same height as the thickness of the deposit was installed at the end of the flume as a stopper. A water gauge was installed at the downstream end and a tank and weight gauge at the downstream of the flume to measure discharge and sediment volume.

Sand for the experiment is mixed with an average grain size of 4.42 mm as shown in the grain size distribution in Figure 2. The sand was laid on the bottom of the flume to a thickness of 5 cm. Table 1 shows the experimental conditions, and Figure 3 shows the model hydrograph used in the experiment. In the preliminary experiment, the discharge which did not cause surface water was found to be about 0.02 L/sec; thus 0.05 L/sec was used as the minimum discharge assuming that it resembled a normal stream flow in natural torrents. Presuming that the discharges of stream flows in natural torrents gradually increase during precipitation,

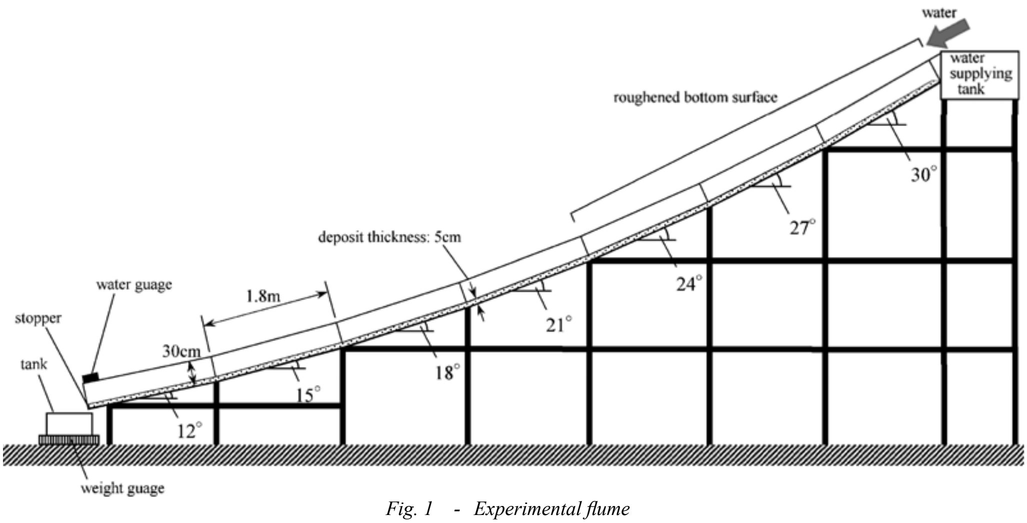


Fig. 1 - Experimental flume

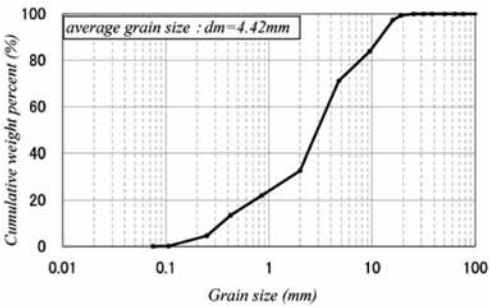


Fig. 2 - Grain size distribution of the experimental sand

CASE	Discharge (L/sec)	Supply duration time (sec)	Condition
1	0.30	720	
2	0.05	300	
3	0.10	300	Initial riverbed is after CASE-2.
4	0.20	420	Initial riverbed is after CASE-3.
5	0.30	1110	Initial riverbed is after CASE-4.

Tab. 1 - Experimental conditions

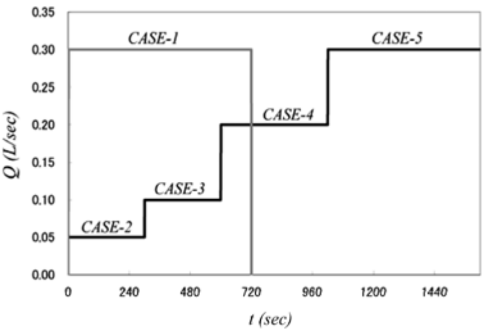


Fig. 3 - Model hydrograph

the discharge levels were set at 0.05 L/sec, 0.10 L/sec, 0.20 L/sec, and 0.30 L/sec (CASE 2 to 5). Water was supplied until the sediment stopped moving in each discharge level. In the preliminary experiment, the sediment was observed to reach the end of the flume at 0.30 L/sec; thus, the water was supplied at 0.30 L/sec assuming it resembled debris flow in natural torrents during a sudden onset of heavy rain (CASE 1).

RESULTS OF EXPERIMENTS

CHANGES IN THE DEFORMATION, SURFACE WATER AND INFILTRATION FLOW

Figures 4 to 8 show stream bed deposit deformations and their changes in each case using profile of bed surface. As a result of detailed observations on the flow ranges and changes in surface water and infiltration flow based on the movement of deposit in each case, the following phenomena are found as the deposits which moved from upstream to downstream. Meanwhile, the sediment layer which flowed down with a clear forefront was defined as a "moving layer," and the layer which formed a shoulder after the moving layer had stopped and moved in a layered form as if extending downward as a "dune."

1) In the steep section with a gradient of 27°-30°, shortly after the small amount of water was discharged, surface water appeared and eroded the surface of the deposit, forming a moving layer, and this flowed down above the deposit gradually. Infiltration flow occurred inside the deposit beneath the surface water, and the deposit became saturated.
2) Although the moving layer appeared saturated, no surface water was observed. Meanwhile, the deposit at the downstream end of the moving layer was unsaturated, and surface water was not observed.
3) The moving layer flowed down ahead of the infiltration flow. After the moving layer had stopped, the infiltration flow reached the downstream end of the moving layer, and the moving layer started to move when the deposit became saturated.
4) When the gradient decreased to 21°-24° and the dune began to form, the surface water infiltrated into the dune from its upper end, and it flowed down along with the infiltration flow in the deposit.
5) Although surface water was observed at the back surface of the dune, and the dune appeared saturated, no surface water was observed at the fore surface of the dune. Also, the deposit at the lower part of the dune was unsaturated, and no surface water was observed.
6) The dune began to move as if extending downward when the surface water at the back surface of the dune flowed over the shoulder of the dune, and the infiltration flow reached the downstream end of the dune and saturated the deposit beneath the dune.
7) Surface water appeared above the deposit at the lower part of the dune, when the forefront of the dune reached a gradient gentler than 18°.

RELATIONSHIP BETWEEN MOVING PROPERTIES AND RIVERBED GRADIENT

Two types of moving properties of debris flow were observed: the moving layer of sediment which flowed down above a stream bed deposit with a clear leading edge; and the dune which formed a shoulder after the moving layer had stopped and flowed down gradually in a layered form with the stream bed deposit. There was a tendency for the moving layer to form in steep gradient zones (about 30° to 27°) where the surface water

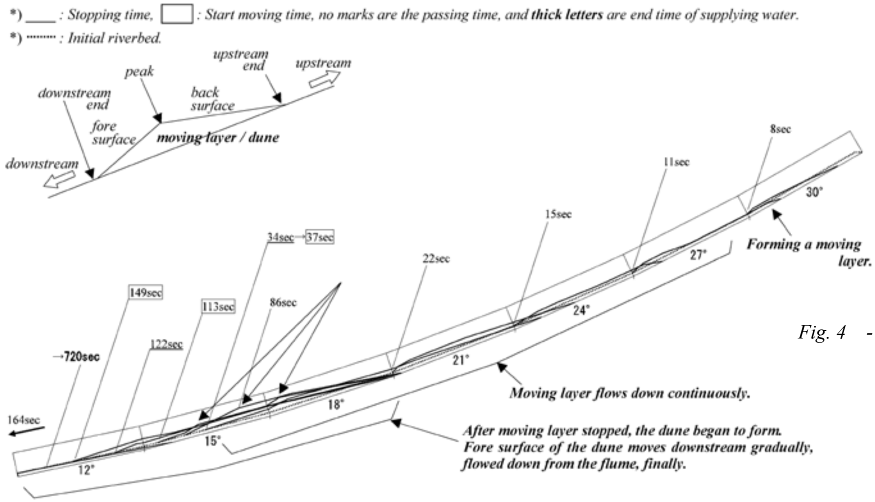


Fig. 4 - Profile of bed surface (CASE-1: 0.30L/sec)

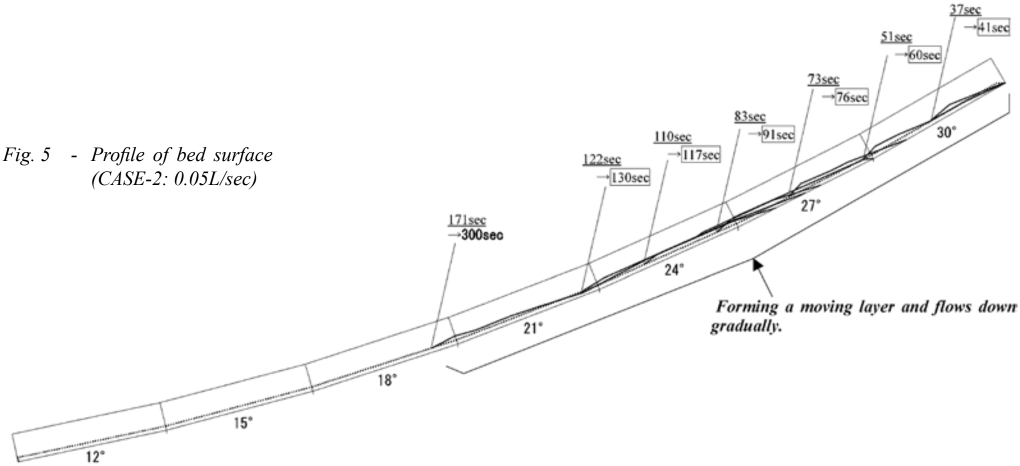


Fig. 5 - Profile of bed surface (CASE-2: 0.05L/sec)

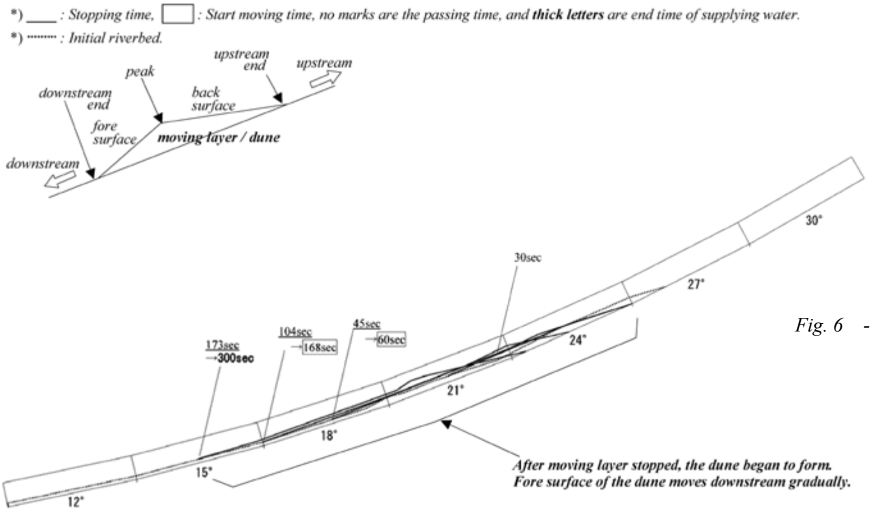


Fig. 6 - Profile of bed surface (CASE-3: 0.10L/sec)

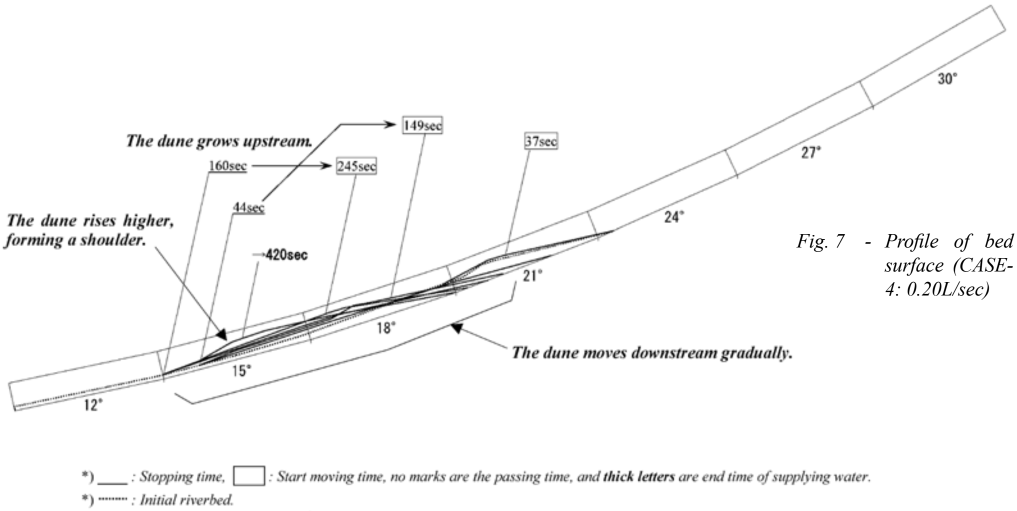
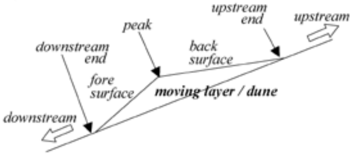


Fig. 7 - Profile of bed surface (CASE-4: 0.20L/sec)



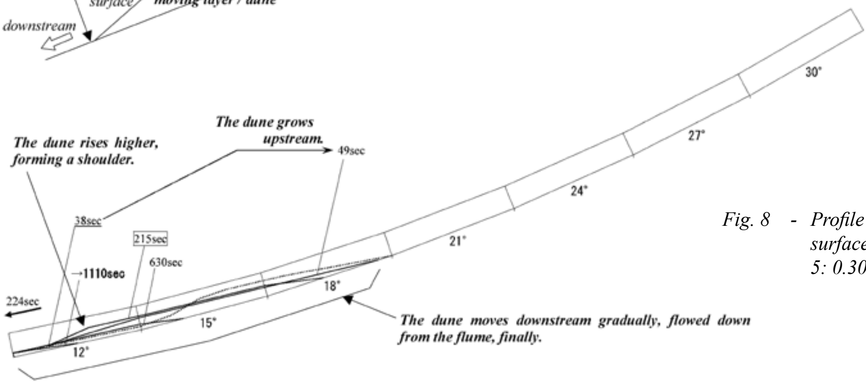


Fig. 8 - Profile of bed surface (CASE-5: 0.30L/sec)

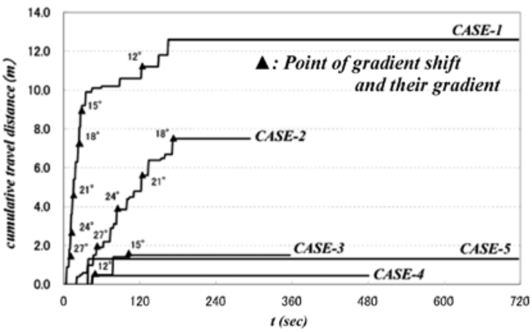


Fig. 9 - Travel-distance curve of moving layers and dunes

discharge was small and the deposit was less eroded. Meanwhile, the dune tended to form and rise higher in low-gradient zones (less than 24°) where the moving layer stopped and the sediment supplied from the upstream increased. Moving layers and dunes tended to stop at zone of gradient shift in all cases. Thus, the first dune formation often occurs at zone of gradient shift. The thickness of the moving layer increases as it erodes and flows down along sediment layers. On the contrary, the thickness of the dune shoulder increases and the fore surface of the dune become steeper as the sediment supplied from upstream accumulates at the dune peak and its back surface.

TIME CHANGES IN THE TRAVELLING DISTANCE AND MEAN VELOCITY OF MOVING LAYERS AND DUNES

The distance between the points where the leading edge of a moving layer and a dune stopped and started moving again and its time changes in each case were studied. Figure 9 shows the traveldistance curve to clarify the average velocity (the velocity which takes

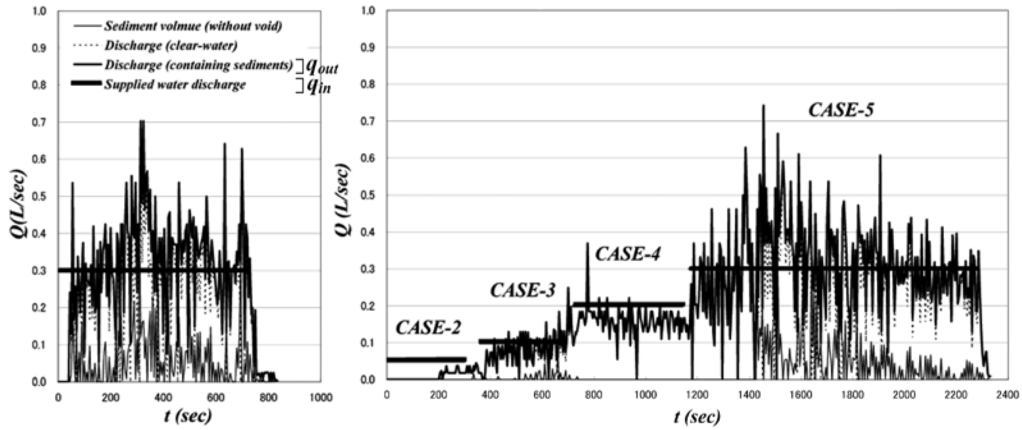


Fig. 10 - Relationship between supplied water discharge and runoff discharge, sediment volume

account of the time of moving and stopping). Flume gradient shift points and their gradients are shown on the line in the figure. Travelling distances greatly vary from several centimetres to several meters regardless of the discharge volumes and gradients in all cases. In terms of gradients, the mean velocity tends to be faster in steep gradient zones and slower in low gradient zones. The velocity increases or decreases in proportion to discharges. Moving layers and dunes tend to take longer before starting to move again when they reach areas where the gradient is gentler than 18°.

TIME CHANGES IN THE SUPPLIED WATER DISCHARGE, RUNOFF DISCHARGE AND SEDIMENT VOLUME

Figure 10 shows time changes in supplied water discharge (qin), runoff discharge at the downstream end (clear-water discharge and discharge containing sediments (q_{out}), and sediment volume (sediment volume without void). In CASE-1, the deposit movement, deformation of the deposit and discharges dynamically changed from the start to the end of the flow. The peaks of both discharges and sediment volume appeared around 300 seconds and then gradually decreased. The ratio of q_{out} / q_{in} was around 1.3. The peak, which ratio of q_{out} / q_{in} was around 2.0, appeared when the dune collapsed and caused a sudden movement of the sediment. Meanwhile, CASE- 2 to 4 and until the first 200 seconds in CASE-5, the discharge change is small, and the ratio of q_{out} / q_{in} was around 0.8 and the sediment discharge at the downstream end was small, too. Immediately after the collapse of the dune (after 200seconds) in CASE-5, however, the discharge dynamically changed, forming a conspicuous peak as in CASE-1. The peaks of both discharges and sediment volume suddenly increased and then gradually decreased. The ratio of q_{out} / q_{in} was around 1.3, and the peak, which ratio of q_{out} / q_{in} was around 2.0, appeared when the dune collapsed and caused a sudden movement of the sediment as CASE-1. Actual sediment volumes without air void exhibited good adaptations to changes in discharges in all cases, and the sediment concentration was approximately 25%.

DISCUSSION

The following deformation processes of stream bed deposit and their factors are estimated based on the observations and analyses described in the above chapters: 1) stream bed gradient (gradient of a flume); 2) shape of stream bed (fore surface slopes and back surface slopes of moving layers and dunes); 3) flow ranges of surface water (discharge) and infiltration flow, etc. In terms of flow ranges of surface water and infiltration flow, the surface gradient of the infiltration flow inside moving layers and dunes were studied and the relationships of each factor was discussed based on the fact that moving layers and dunes start moving when the infiltration flow reaches the lower end of the moving layer or the dune or the surface water flow over the dune shoulder.

Figure 11 shows the relationship between shape of stream bed deposit and stopping gradient (the fore surface and back surface gradients of a moving layer and dune). The back surface gradients are about the same as or smaller than the stream bed gradients, and the fore surface gradients are about 1.5 times steeper than stream bed gradients in all cases. Both the fore sur-

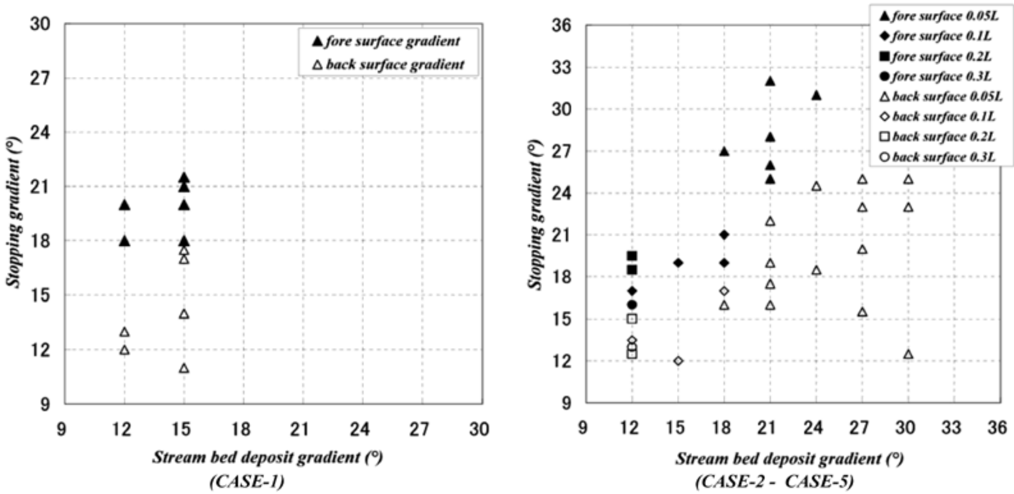


Fig. 11 - Relationship between shape of stream bed deposit and stopping gradient

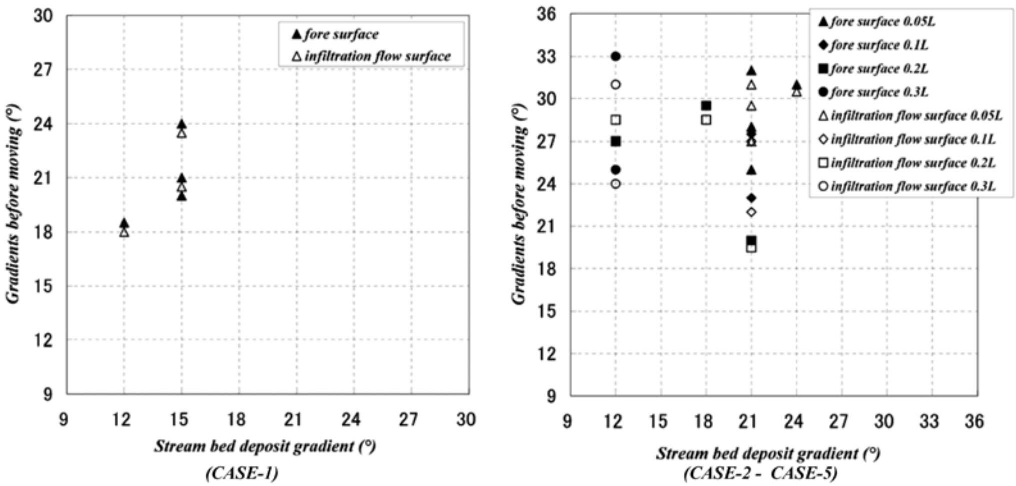


Fig. 12 - Relationship between gradient of stream bed deposit and imlfiltration flow surface

face slopes and back surface slopes are proportional to the gradients. While there is no major difference in tendencies among discharges, they tend to show large variations because dunes are formed in low-gradient zones, and the fore surface gradients of dunes change due to the sediments supplied from the upstream.

Figure 12 shows the relationship between the gradient of stream bed deposit (the fore surface gradients of moving layers and dunes) and infiltration flow surface. In comparison to the gradient while stopping in Figure 11, the fore surface gradients are steep in all cases, and the forefront of moving layers tend to bulge or dune shoulder tend to rise higher in them. Also, the fore surface gradients are about 1.5 times steeper than stream bed gradients, as in the slopes while stopping. Meanwhile, the fore surface gradients of moving layers and dunes and the gradient of infiltration flow surface show that while there are variations depending on discharges, the fore surface gradients before moving are about the same as the infiltration flow surface gradients. It probably indicates the condition in which the infiltration flow surface gradient increases and matches the fore surface gradient of moving layers and dunes, which is the condition that arises when the surface of infiltration flow goes over the shoulders.

In terms of the supplied water discharge (q_{in}), runoff discharge containing sediments at the downstream end (q_{out}) and sediment volume, while a small discharge (0.20 L/sec or less) does not have a large influence on the downstream end, a discharge goes through large fluctuations when it gets larger (0.30 L/sec), and the ratio of q_{out} / q_{in} was around 1.3. It is probably because the movement is based on state of traction when the discharge is 0.20 L/sec or smaller, and the movement is based on debris flow when the discharge becomes larger than 0.20 L/sec. The discharge and sediment volume largely depend on dune shapes and moving process at the 15° to 18° zones; when a dune is formed and the surface water is retained at the back surface of the dune, the discharge slightly decreases, and the discharge also increases when it goes over the dune shoulder and the dune start to move.

CONCLUSION

In this study, the following aspects were found in experiments conducted based on gradient-changing flumes and discharge conditions which mimicked natural torrents.

- The stream bed deposit at the initiation zone of debris flow is also moving (deforming) during a small-scale discharge which is only slightly larger than an infiltration flow. The deformation processes based on gradients are roughly categorized as follows:
  1) 30° to 27°: The moving layer with a clear leading edge is formed. The moving layer flows down over the stream bed deposit. The velocity is relatively fast.
  2) 24° to 21°: The moving layer stops and forms a dune. The moving sediment shifts from a moving layer to dune. The entire dune moves gradually with the development of a dune shoulder. The velocity is slower than 1).
  3) 18° to 12°: The dune is still the main morphology type. The velocity is slow. The stream bed gets deformed instead of experiencing sediment movement.
- When a moving layer or a dune is formed, the surface water infiltrates into the layer at its upper end or the back surface. Thus, no surface water is observed at the fore surface of the moving layer or the dune.
- Deposits tend to stop and accumulate at zone of gradient shifts, and dunes are likely to form and rise higher at the 24° gradient zone (deposits tend to accumulate).
- Moving layers formed in relatively steep gradient zones (equivalent of 1) in the previous descriptions) start moving when the deposit gets saturated with the surface water or infiltration flow. Also, dunes formed in relatively low gradient zones (equivalent of 2) and 3) in the previous descriptions) tend to start moving when the deposit gets saturated with the surface water or infiltration flow, or when the surface water goes over the dune shoulder.
- Changes in discharge and sediment volume at the downstream end become active when the supplied water discharge is larger than 0.30 L/sec, and the ratio of q_{out} / q_{in} was around 1.3. Meanwhile, changes in discharge and sediment volume become small when the supplied water discharge is smaller than 0.30 L/sec, and the ratio of q_{out} / q_{in} was around 0.8. In actual settings, the former is estimated to be the debris flow and the latter the state of traction.
- Changes in discharge and sediment volume at the downstream end (the shape of hydrograph) is related to the dune forming, deformation and moving process at the 15° to 18° gradient zones.

CONCLUDING REMARKS

Based on this study, the stream bed deposit at the initiation zone of debris flow is estimated to be moving (deforming) even during slight discharges. The study also indicated the possibility that after going through such moving (deforming) processes, deposits are not necessarily in stable forms; rather, they accumulate in unstable forms like dunes where fore surfaces become steep, or they accumulate in a large amount at zone of gradient shifts. The study also indicated the possibility that surface water occurs if a discharge that is larger than the infiltration flow is supplied from the upstream (including from sides and branch streams) regardless of the saturation level of the deposit. In addition, the discharge and shape of stream bed deposit at the initiation zone of debris flow are estimated to have great influences on the hydrograph which flows toward downstream. In general, slope collapses and mobilization of stream bed deposit have been estimated as cause of debris flow occurrence. According to the forms of stream bed deposit and its deformation at the initiation zone of debris flow conjectured in this study, however, occurrence conditions of debris flows might change. As a future study, it is necessary to investigate and observe the phenomena clarified in this study in actual torrents, examine how temporal and spatial moving (deformation) processes of deposits at the initiation zone of debris flow affect conditions which cause debris flow, and explore the conditions which cause debris flow while taking account actual torrent conditions. And also we intend to observe and analyze the sediment movement using different sediments in the experiment, and to measure cohesion and internal friction of the sediment which may have a role in affecting the formation and movement of the dunes.

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