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EXPERIMENTAL STUDY OF DEBRIS PARTICLES MOVEMENT CHARACTERISTICS AT LOW AND HIGH SLOPE

Yosuke YAMASHIKI[1], Mohd Remy Rozainy MAZ[1*], Taku MATSUMOTO[2], Tamotsu TAKAHASHI[3], and Kaoru TAKARA[1]

[1]Department of Urban and Environmental Engineering., Kyoto University
(Katsura, Nisihkyo-ku, Kyoto 615-8540, Japan)
[2]Sumitomo Corporation.
(1-8-11 Harumi, Tokyo 104-8610, Japan)
[3]Association for Disaster Prevention Research.
(138-1 Tanaka Asukai-cho, Sakyo-ku, Kyoto 606-8226, Japan)
* E-mail: *remyrozainy@yahoo.com*

Estimation of the potential particle impact forces from a debris flow is important for the design and structural mitigation elements. Due to this matter, particle size and particle velocity are two main parameters that have to be studied in detail. This paper discusses the particle routing segregation of a debris flow generated by bed erotion with constant discharge at 15°(low) and 25°(high) slopes. The particle diameters used for this study are 2.5 mm and 10 mm. The objective of this study is to obtain experimental proof of the debris routing particle segregation of two distinct particle diameters at two different slopes. High speed video camera (HSVC) was used in this study as a tool to visualize the particle tracing movement. The results clearly show the development mechanism of debris flow for two distinct diameters. The larger particle movements (high average velocity) were concentrated at the upper part of the fluid, while small particles (low average velocity) were concentrated near the bottom. The mechanism of "inverse grading" is closely related to the mechanisms of the accumulation of particles at the front of a debris flow. Moreover, the largest stones accumulated at the front part and the forefront contained little water; this part can be called stone flow.

Keywords : *debris flow, high speed video camera (hsvc), particle routing segregation, experimental debris flow study*

1. INTRODUCTION

Many definitions for debris flow has been given by numerous researchers. The definitions may not be the same from one researcher to another as it completely depends on various characteristics such as the content of debris flow. Debris flows are flows which contain mixtures of soil, rocks and water. These flows are commonly initiated by landslides, bank failure or hill slope failures related to high rainfall and/or large runoffs[1)].

Debris flows include many events such as debris slides, debris torrents, debris floods, mudflows, mudslides, mudspates, hyperconcentrated flow and lahar[2)]. Interaction of solid and fluid forces not only distinguishes debris flow physically but also gives them unique destructive power. Because of their high velocities in the order of several meters per second, they are the most critical type of mass movements and cause significant economic loses as well as casualties[3)]. Debris flow mainly deals with laboratory simulations[4,5)], modeling trigger and movement mechanisms[6,7)], deposits[8,9,10)], fluidity[11)], topographic conditions[12,13)] and case studies of extreme events that causes damage or casualties[14,15)]. Previous studies have also used video analysis to investigate debris flows[13,16,17,18,19,20,21,22)]. However these studies did not investigate the velocity distribution among different sized particles within debris flows.

Several debris flow models have been developed individually for boulders debris flows that consists mainly rock, gravel and water mixture[23,24,25)] in which two layers are formed with upper water and lower debris flow layers. Takahashi[26] developed a theory based on Bagnold's concept of dispersive pressure due to inter-particle collision while Hashimoto and Tsubaki[27] proposed a similar theory but for multi-particles collision. Quite a few mechanisms for inverse grading have been proposed; buoyancy in the grain mixture[28] and attributing the reasons of lift force[29]

To understand the general behavior of particle segregation in debris flow, a physical model experiment for debris flow with two distinct diameters was conducted. Furthermore, HSVC was introduced to trace individual particle behavior in debris flow. This paper focuses on particle routing segregation of two different slope angles. Slope angles of 15° and 25° have been choosen based on studies made by VanDine[30] and Takahashi[31]. Only the slope angles are similar with previous studies but the materials and discharges are different for this study. In this study, non-cohesive grain materials with specific mass of 2.7gcm^{-3} are used in order for us to clarify the physics of stony debris flow. We repeated the experiments at least three times for each slope case.

The aim of this study is to obtain experimental proof of the debris routing particle segregation of two distinct particle diameters. By assistance of HSVC, we evaluated and traced the movements of particle routing segregation. Moreover, the velocity distribution and behavior of particles in each grain size can be clearly identified using HSVC, therefore, the characteristics of particle movement in debris flow can be analyzed in detail.

2. DESCRIPTION OF THE MODEL

In order to understand the characteristics of debris flow routing mechanism and the deposition behavior, it is necessary to set up a debris flow experimental physical model. Experimental setup of the debris flow physical model was carried out at the Ujigawa Open Laboratory, Kyoto University. This laboratory provides complete facilities to operate our study.

The model consists of three main parts which are the rectangular flume (5m x 0.2m x 0.2m), deposition board (2m x 2m x 0.2m) and water intake tank (1m x 0.8m x 0.7m). The water was supplied into the water intake tank by a high pressure water pipe. Details of the experimental procedure, materials, flow, data collection, HSVC and camera setting will be discussed in the next section. **Fig.1** shows the debris flow experimental model.

3. EXPERIMENTAL PROCEDURE

Two cases of laboratory experiments were conducted in these studies which are 15° and 25° slope angles. Experiments were conducted separately but the water discharge was set to be the same for each case. To make sure the results were consistent, the materials that are the small (10kg) and large (10kg) particles were well mixed up manually for at least 10 times by the observer using a scope and bucket. For each case, the experiments were repeated at least three times to understand the mixed particle distributions and movements.

After a flume and board were set to the prescribed slopes, a constant discharge was supplied from the upstream end of the channel through an electromagnetic valve (gate). A constant discharge (3.0L/s) was supplied within 7s. A constant discharge of 3.0L/s was choosen because it is ideal for this research. It is not too high and not too low. During water supply, HSVC was employed to record the image of particle routing. The HSVC was placed under the rectangular flume to capture the movement characteristics of the individual particle grain. The HSVC can capture a video footage during short interval times (0-9s). The experimental conditions are given in **Table 1**.

Moreover, two video cameras were set at different locations to record the continuous and simultaneous debris flow particle movement characteristic processes. The position of these cameras can be refered to in **Fig.2**. The HSVC was set beside the rectangular flume channel. The distance from the deposition board is 0.5m. Camera 1 and 2 were sets at frontal part and beside the deposition board respectively. Videos were recorded during experiments at certain time.

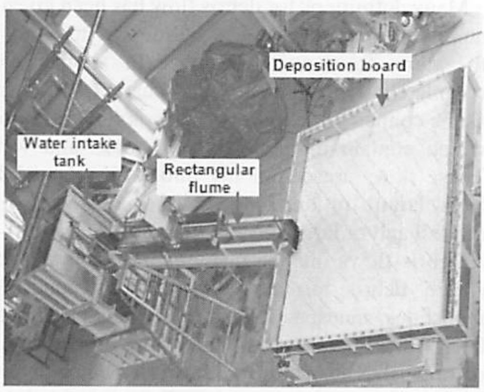


Fig.1 The debris flow experimental model

Table 1 Experimental condition

Case	Debris load length (cm)	Bed Thickness (cm)	Water supply		
			Position	Discharge (l/s)	Duration (s)
15°	81	10	Upstream end	3	7
25°	81	10	Upstream end	3	7

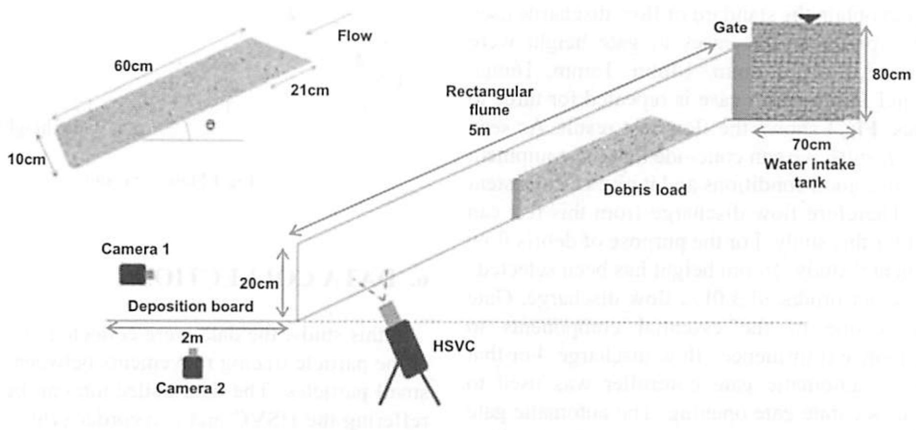


Fig.2 Illustration of experimental procedure

This important procedure should be made for further understanding of particle movement characteristicss. The videos were referred during post analysis. The characteristics of particle movement process can be more understandable by repeatingly looking through the video.

4. MATERIALS

Two different sizes of materials were used. Each material can be easily differentiated by looking at the size. The materials mean sizes were 2.5mm and 10mm respectively. The materials used have the same unit weight which is 2.7gcm^{-3}. For a single run the total weight of each material is 10kg.

Distance of free surface flow appeared 3.5m from the downstream end (deposition board); the part of the bed upstream from this point was unsaturated.

Table 2 Materials properties

Details	Large material	Small material
Quantity	10kg	10kg
Average diameter	10mm	2.5mm
Unit weight	2.7gcm^{-3}	2.7gcm^{-3}

The materials (debris load) lay on the rectangular flume with a thickness of 10cm, 81cm length and the roughness layer on the bottom of the rectangular flume was 0.3mm. The details of the material properties can be seen in **Table 2**.

5. FLOW

To make sure this experiment was conducted with a constant and accurate flow, the author carried out a flow test by using flow discharge measurement tools. This equipment included two parts which are the electrostatic level gauge (model: CWT-100) and its data logger (model: GL200A). The electrostatic level gauge contains an actuator rod which has a highly stable water level meter and it is located in the water storage tank.

The discharge data collected by data logger was analyzed using a personal computer. The data logger obtained the water level changes inside the water intake tank into voltage. Then this volt value has to be calculated to get the distance between two points. The concept behind this equipment is to calculate the water level between two points. Water heights were obtain before and after water was supplied during experiment. **Fig.3** shows the schematic diagram of the discharge measurement tools.

The gate is located in the conjunction between water tank and rectangle flume in order to control water discharge. We set up the water tank larger enough compare to the total volume of water in single experiment (around 21L) in order for the water level decrease (and thus hydrostatic pressure change) small enough (26mm) during the single experiment, henceforth the change in discharge can be neglected. In order to obtain the standard of flow discharge used for the experiment, six cases of gate height were choosen which are 13mm, 14mm, 15mm, 16mm, 17mm and 18mm. Each case is repeated for three to six times. **Fig.4** shows the flow test result. As seen from the results, we can conclude that the equipment was run in a good conditions and it gives a consistent results. Therefore flow discharge from this test can be used for this study. For the purpose of debris flow experimental study, 16mm height has been selected.

This height produced 3.0L/s flow discharge. Gate control is one of the essential components to consider since it influences flow discharge. For that reason, an automatic gate controller was used to obtain an accurate gate opening. The automatic gate controller is a combination of two equipments which are the electric actuator rod (model: RCP2W-RA6C) and controller (model: PCON-C-56PI-NP-2-O).

Power supply (model: PS-241) had connected to the controller. The controller is connected to a personal computer. To obtain the required height of the gate as what authors want, the value is inserted via controller.

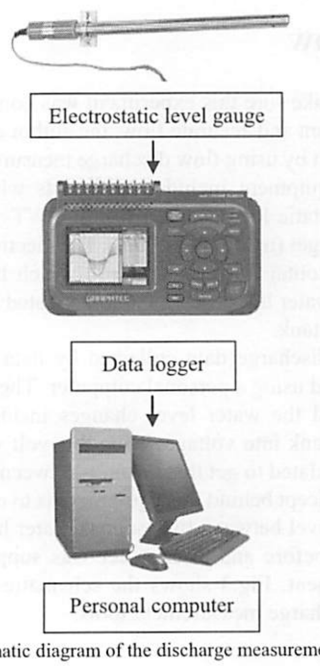


Fig.3 Schematic diagram of the discharge measurement tools

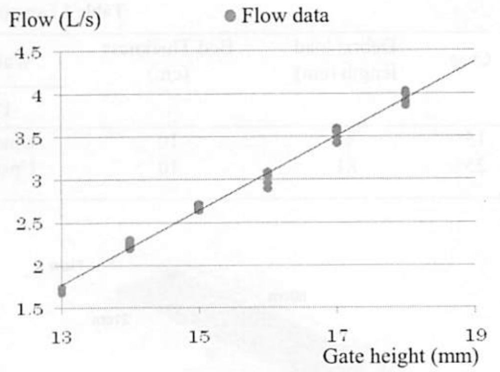


Fig.4 Flow test result

6. DATA COLLECTION

In this study, the data were collected by observing at the particle tracing movements between large and small particles. The data collection can be done by reffering the HSVC and camcorder (video camera). **Fig.5** shows the summarized steps taken during data collection.

6.1 Particle routing movements

In order to investigate the debris flow characteristics routing mechanism, HSVC was used to capture the image. By looking throughout the image movements between large and small particles, the development mechanism of debris flow can be more easy to understand. The images of particle tracing were captured between 0.015s. The distance of particle movements were identified. By knowing the distance of each particle distribution, the velocity of each particle can be calculated. The choosen particles for analysis purposes have been done by selected the most consistent and accurate image through the video. We checked the movements of 100 particles. 40 traceable particles out of the 100 are chosen as representative particles for final analysis. The 40 particles are consisted with 20 of large and 20 of small particles. This process was applied to all groups of particle-tracing captured image in each experimental case.

7. HSVC AND CAMERA SETTING

To obtain movement of individual particle flowing as debris flow, a HSVC is used. The model of HSVC is Kato Koken High Speed KIII. The dimension of this camera is 160mm x 104mm x 82mm. The HSVC was placed 0.5m from the rectangular flume, from this distance, the captured image size is 15.5cm x 12cm. The system design for this camera is scaleable and network-compatible with standard and/or laptop PCs. Recording time is up to 9s at full resolution. Longer record times with variable resolution and frame rates. The HSVC possesses maximum photographing capacity up to 2,900,000 pixels with maximum velocity up to 100,000 frames per second for the duration of only 15 millisecond. In this study, to capture longer period (up to 14 seconds from the initiation of the debris-flow motion) with acceptable quality and resolution, we selected 640 x 480 (307,200) pixels with velocity of 1,000 frames per second. The shortest exposure time (shutter speed) is 1 millimicrons/sec. This HSVC was compact designed which is superior in cost performance and can be used for long haul high-speed photographing for 6 hours consecutively with in-built hard disk. Capture device for this camera is 13.57mmx13.68mm CMOS (complementary metal-oxide semiconductor).

Four groups of time frame were carried out to understand the particle characteristics mechanism. The groups are (a) initial, no liquid-phase flow (b) starting with liquid-phase flow (c) intermediate, 2s and (d) last, 4s. For initial case, we classified this case without liquid flow. When the water flow is observed to pass by the particles, we classified this case as starting with liquid flow. For intermediate (2s) and last (4s) cases we started to obtain the particle routing movements just after 2s and 4s at the start of the experiment. The behavior and flow-depth of the debris flow on the timeline immediately after opening water supply gate is illustrated in **Fig. 9**. As is described, just after opening the gate (a)initial no liquid-phase flow starts which last only few hundreds millisecond and then (b) starting with liquid-phase flow, in 25° case, whereas only (b) liquid-phase flow after 1s since gate opening was observed in 15° case. To achieve superior performance for Full HD video and stills, JVC Everio Model GZ-HM570 is used. Two sets of camcorder with ability of 24Mbps high bit rate recording. The advantages of this model are advanced image stabilizer and it can be zooming until 40 times. It is useful especially during post deposition analysis. We can get clear view and accurate path and very clear particle movements. This camera is very important to observe the changes of particles routing happen during experimental study. These two cameras are located near the flume channel.

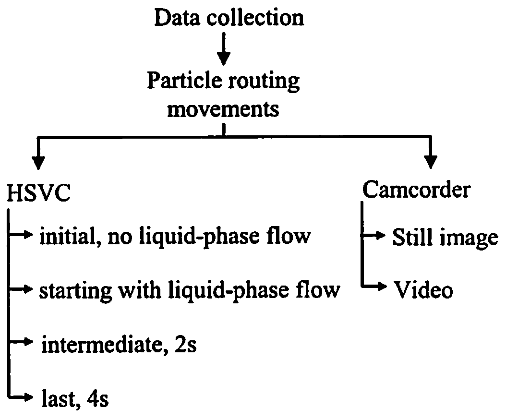
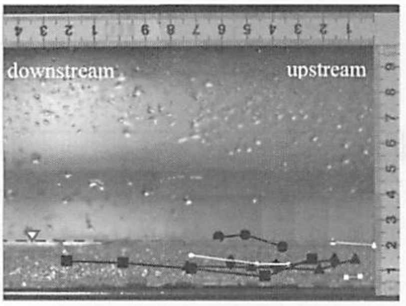


Fig.5 Steps taken during data collections

8. RESULTS AND DISCUSSIONS

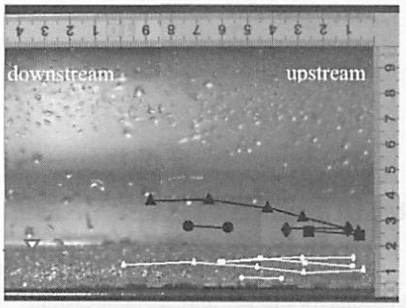
In this section the authors present results and discussions for the 15° and 25° slopes study. Tracing path lines of large particles (10mm) and small particles (2.5mm) are represented by black and white colors respectively. For the 15° case, the particle routing movements can be visualized by three cases. In each frame they are shown by using circular, square, rectangular, star, diamond and opposite rectangular shapes. The images of particle tracing were captured at intervals of 0.015s (15ms). This value was chosen to calculate the distance between two images. By knowing the distance of each particle distribution, the velocity of each particle can be calculated. Particle tracing images captured by the HSVC are traced and presented in Figure **6(a)**, **6(b)** and **6(c)**. As observed in the tracing photo results, the lengths of particle movements are different from each other. This is due to the fact that the particle movements can be traced clearly so the tracing lines are long. In contrast if the particle cannot be traced clearly the lengths are short. These figures show the results for 15° case. Particle routing movement for 15° case is presented by three cases which are starting with liquid-phase flow case, intermediate (2s) case and finally last (4s) case. For initial (no flow) case there is no such image/video footage has been obtained. In contrast, image/video can be seen for 25° cases which the large particles moving downward before mixed up with water. This phenomenon may cause by shallow slope. For starting with liquid-phase flow case, the particles were mixed up with water and moving downward to the deposition board. In average, the velocities of large particles move faster than small particles.

(a)



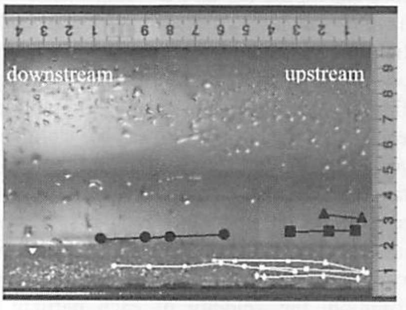
Shape	Starting with flow			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	2.91	4.47	0.10	0.15
□	11.33	0.64	0.19	0.04
△	7.71	1.92	0.17	0.13
◇	4.73	-	0.16	-
Average velocity (cm/ms)			0.15	0.11

(b)



Shape	Intermediate (2s)			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	1.8	1.82	0.12	0.12
□	2.28	6.1	0.15	0.14
△	9.7	11.08	0.16	0.18
◇	2.82	6.21	0.19	0.21
Average velocity (cm/ms)			0.16	0.16

(c)

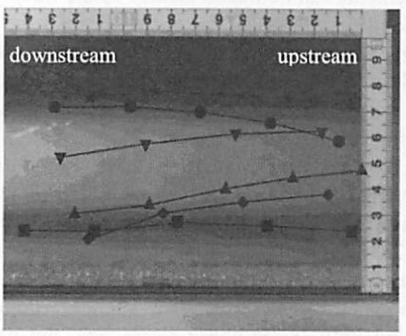


Shape	Last (4s)			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	5.65	8.39	0.13	0.11
□	2.99	4.86	0.10	0.16
△	1.74	6.89	0.12	0.11
◇	-	4.68	-	0.10
Average velocity (cm/ms)			0.11	0.12

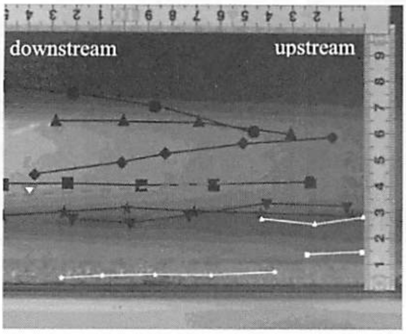
Legend: Large particle Small particle Water level

Fig. 6 Particle tracing captured by HSVC for 15° (a) starting with liquid-phase flow (b) intermediate, 2s (c) last, 4s

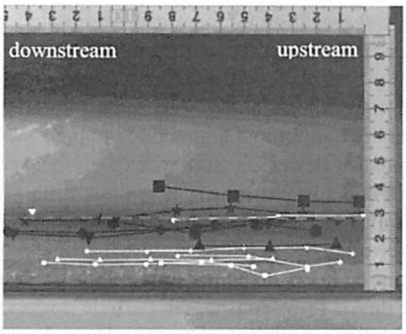
(a)



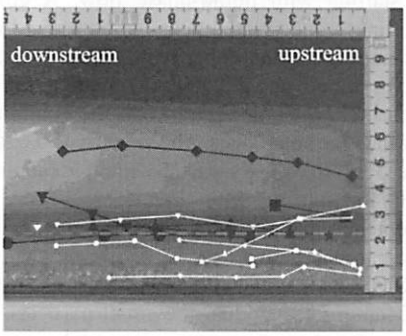
Shape	Initial (no flow)	
	Distance (cm)	Velocity (cm/ms)
	Large	Large
○	12.07	0.20
□	13.69	0.23
△	12.14	0.20
◇	10.23	0.23
☆	11.00	0.18
▽	11.03	0.25
Average velocity (cm/ms)		0.21

(b)


Shape	Starting with flow			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	10.49	4.29	0.23	0.14
□	12.73	2.29	0.21	0.15
△	9.7	8.9	0.22	0.15
◇	12.45	-	0.21	-
☆	14.48	-	0.19	-
▽	11.45	-	0.19	-
Average velocity (cm/ms)			0.21	0.15

(c)


Shape	Intermediate (2s)			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	8.45	8.75	0.19	0.15
□	8.4	6.16	0.19	0.14
△	5.65	8.96	0.19	0.15
◇	13.73	7.90	0.18	0.26
☆	13.94	6.79	0.19	0.23
▽	14.21	11.07	0.24	0.15
Average velocity (cm/ms)			0.19	0.18

(d)


Shape	Last (4s)			
	Distance (cm)		Velocity (cm/ms)	
	Large	Small	Large	Small
○	10.12	8.30	0.22	0.14
□	2.95	4.23	0.20	0.14
△	8.18	7.11	0.18	0.16
◇	12.21	12.31	0.16	0.16
☆	4.47	10.44	0.15	0.14
▽	8.06	7.11	0.18	0.16
Average velocity (cm/ms)			0.18	0.15

Legend: Large particle Small particle Water level

Fig. 7 Particle tracing captured by HSVC for 25° (a) initial, no liquid-phase flow (b) starting with liquid-phase flow (c) intermediate, 2s (d) last, 4s

Table 3 Relative velocity and depth between large to small particles at different slope angle

Item	Case	Initial, no liquid-phase flow (%)	Starting with liquid-phase flow (%)	Intermediate, 2s (%)	Last, 4s (%)	Average (%)
Velocity	15°	-	136	100	92	109
	25°	-	140	106	120	122
Depth	15°	-	123	285	278	229
	25°	-	350	207	206	254

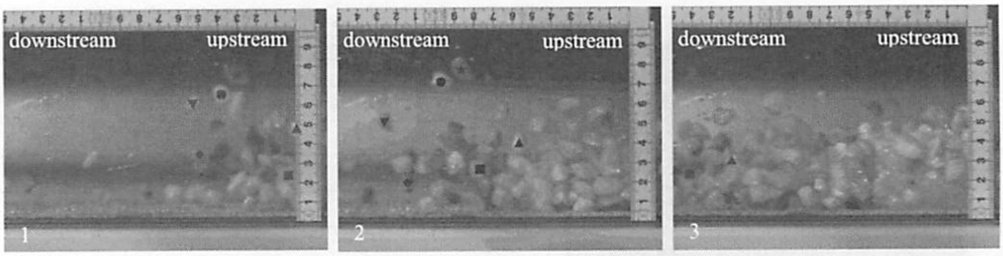


Fig. 8 Larger particles movements starting from left to right in initial (no flow) 25° case

Average velocity of large particles move 0.04cm/ms faster than small particles.

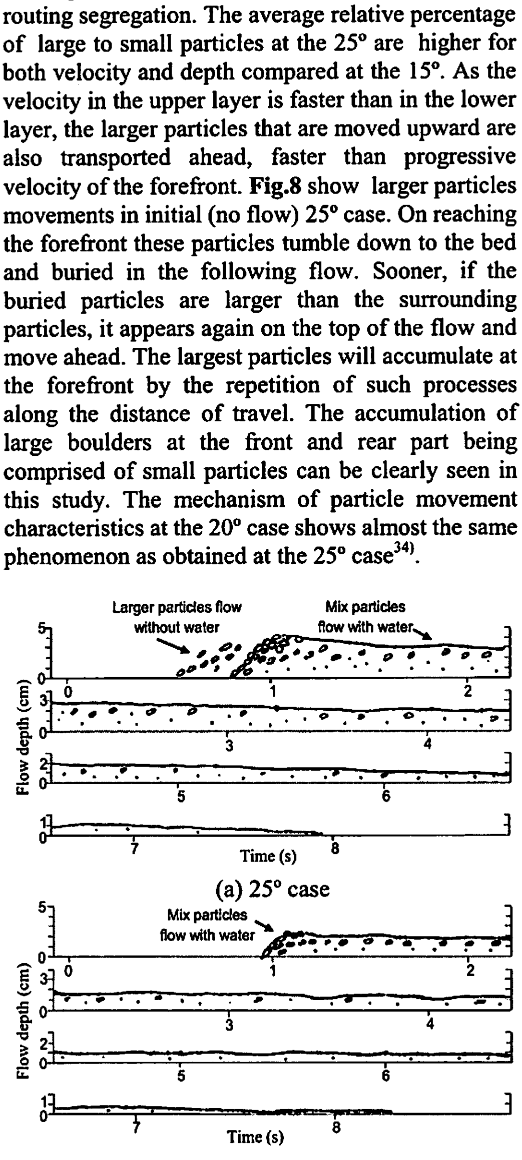
In intermediate (2s) case, the results fully demonstrated debris flow development mechanism. The larger particle movements were concentrated at the upper part of the flume, while small particles were concentrated near the bottom. Overall as we can see, small particles routing not more than 2cm height while large particles above 2cm height. Each particles (small and large) were in same average velocity of 0.16 cm/ms. This trend was not happened in 25° case. It may cause by a constant discharge with a shallow slope. The energy from the water washes out the mix particles. In the last (4s) case, average velocities of small particles are moved with 0.01cm/ms faster than large particles. Particles routing shown that the small particles were concentrated near the bottom (below 2cm height) of the flume while the large particles were concentrated at upper (above 2cm height) part. The characteristics of particles routing is such that the large particles are accumulated at the front and the rear part being comprised of small particles. This is the result of particle segregation along the distance of travel.

Particle routing movements for the 25° slope angle case can be visualized by four cases. The first case is initial, no liquid-phase flow case. **Fig.7(a)** shows the captured image for this case. Different shapes were employed to represent the particle path line. In this case no small particle images were captured. This means, large particles move faster rather than small particles. The large particles accumulated at the front part, this phenomena can be called as stone flow[32]. The longest distance of movement for large particles (circle shape) is 14.09cm and the shortest (diamond shape) is 5.74cm. The average velocity for this case is 0.19cm/ms. Suwa[33] claimed that the cause of the convergence of large particles at the front of a debris flow is caused by their faster longitudinal velocities than the surrounding small particles. A vertical particle-segregation concept can be adopted here to explain the convergence of large particles at the front.Takahashi[26] verified this theory in previous flume experiments study. The velocity varies from zero at the bottom to a high value in upper layer, and the mean velocity is somewhere in between the bottom and surface values, if grain sorting arises in the following layer and coarser particles are transferred to the upper part, those particle would be transported faster than the mean propagating velocity of the debris flow front. Small particle images can be seen starting with liquid-phase flow. A group of white lines concentrated near the bottom while the black lines are at the upper part. It shows that large particles move upward and in contrast for small particles. The average velocities of large particles are faster than the small ones. The velocity is 0.02cm/ms faster. **Fig.7(b)** shows particle tracing captured by HSVC for starting with liquid-phase flow. Same phenomenon happens for intermediate (2s) case. Large particles move upward and faster than small particles. The average velocity of the large particles is 0.04cm/ms faster than the small particles. From this captured image, we can understand the characteristics of particle movements between particles of different sizes.

For the last (4s) case, the average velocities of large and small particle are 0.18cm/ms and 0.15cm/ms respectively. The difference in average velocity is 0.03cm/ms between the two particle sizes. In **Fig.7d** we can see that the longest travel distance for small particles are 12cm and the shortest travel distance is 1.82cm. Particles routing shown that the small particles were concentrated at the bottom (below 3.5cm height) of the flume while the large particles were concentrated at upper (above 3.5cm height) part. As a result we can declare that similar phenomenons occur for large and small particle routing movements for each case of the 25° slope angle case. Further investigations could be done to understand debris flow particle routing mechanism.

By understanding the particle movements and analyzed the velocity distribution, these data can be used as an input data for further understanding particle routing of debris flow mechanism.

Table 3 shows the relative velocity and depth between large to small particles at different slope angles. From this table the authors can conclude that the slope angle really give a big impact on particles routing segregation. The average relative percentage of large to small particles at the 25° are higher for both velocity and depth compared at the 15°. As the velocity in the upper layer is faster than in the lower layer, the larger particles that are moved upward are also transported ahead, faster than progressive velocity of the forefront. **Fig.8** show larger particles movements in initial (no flow) 25° case. On reaching the forefront these particles tumble down to the bed and buried in the following flow. Sooner, if the buried particles are larger than the surrounding particles, it appears again on the top of the flow and move ahead. The largest particles will accumulate at the forefront by the repetition of such processes along the distance of travel. The accumulation of large boulders at the front and rear part being comprised of small particles can be clearly seen in this study. The mechanism of particle movement characteristics at the 20° case shows almost the same phenomenon as obtained at the 25° case[34].



(a) 25° case

(b) 15° case

Fig. 9 Temporal variation of longitudinal cross-section of the debris flow surge for (a) 25° case and (b) 15° case.

Temporal variation of longitudinal cross-section of the debris flow surge, focusing on its mainly-observed particle-size (illustrative) and flow depth, are shown in **Fig.9** for (a) 25° case and (b) 15° case, respectively. As illustrated, larger particle can be observed only initial part of the debris flow mainly, then smaller particle are mainly observed in the latter part both in (a) and (b) cases.

9. CONCLUSIONS

The results fully demonstrates the debris flow development mechanism for two distinct diameters. As a comparison between these two cases, the authors can declared that the average velocity for the 15° case was slower compared to the 25° case. In addition, the particles routing movements for both cases shows the similarity between small and large particles movements. The difference is about the average depth of particle path line between two cases, which for 25° case the average depth is higher compared to the 15° case. As a proof, the relative average depth of large to small particles are higher at 25° case compared to 15° case. The larger particle movements (high average velocity) were concentrated at the upper part of the fluid, while small particles (low average velocity) were concentrated near the bottom. Moreover, the largest particles accumulated at the front part and the forefront contained little water. This part can be called stone flow[32]. The surface of debris flow velocity is faster than the average velocity, it means that the debris flow is characterized by its fast velocity near the surface but slow in the bottom.

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