EFFECTS OF PARTICLE-SIZE DISTRIBUTION AND STREAM GRADIENT ON SEDIMENT SORTING OF A DEBRIS FLOW

IAHR-APD 2020, Sapporo, Japan

TAKASHI WADA, JUMPEI MAEDA and HIROSHI MIWA
Department of Social Systems and Civil Engineering, Tottori University, Japan

1. INTRODUCTION

◇ A debris flow is characterized by **coarser particles being concentrated toward the flow front** during down flow in mountainous streams. (**Figure 1**)

⇒ This characteristic implies that **sediment sorting occurs in the flow's interior**.

◇ The devastation and loss of life caused by a debris flow on flooding areas can be extensive as the destructive force at the flow front become enlarged by this characteristic.

⇒ **A practical method is required to predict sediment sorting in the debris flow's interior**, including the concentration of coarser particles at the flow front during down flow in mountainous streams.

1) We conducted **flume experiments** with a tilted straight flume using sediment mixtures composed of particles of two different sizes, in order to gain insight into the mechanism of the sediment sorting and the effects of particle-size distribution and stream gradient on the sediment sorting.

2) We developed **a numerical model to describe the changing particle-size distribution in the flow's interior** and the concentration of coarser particles at the flow front based on the model proposed by *Satofuka et al*. (2007).

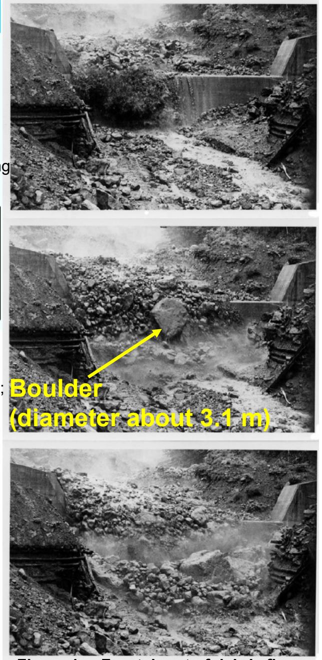


Figure 1. Frontal part of debris flow occurred at valley Kamikamihorizawa of Mt.Yakedake in 1976 (*Okuda et al*., 1977)

2. FLUME EXPERIMENTS

◇ The flume experiments consisted of a tilted straight flume and a movable sampler with 4 boxes (**Figure 2**). The sediment materials were composed of 2 particles chosen from 4 particles in the range of 1.4–10.7 mm; the mass density of the materials (σ) was 2.635 g/cm³, and the concentration in the static sediment bed (C_*) was 0.558.

◇ The experiments combined various conditions based on two key factors; the particle-size distribution of the materials and the flume gradient (stream gradient) (**Table 1**). In these cases, the rate of supplied water was set to a unit width of 67cm²/s.

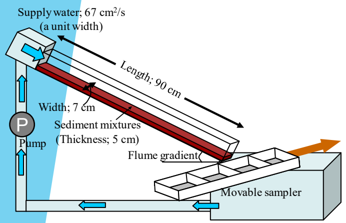
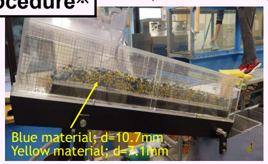


Figure 2. Experimental setup

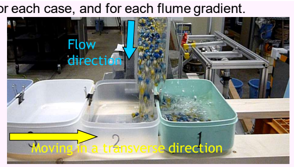
Table 1. Experimental cases and conditions

Case	Particle-size distribution of material (Diameter; ratio)	Mean volume diameter (mm)	Flume gradient (°)
Case 1.1	10.7 mm; 50%, 7.1 mm; 50%	9.25	15, 20, 25
Case 1.2	10.7 mm; 20%, 7.1 mm; 80%	8.10	
Case 2.1	10.7 mm; 50%, 3.0 mm; 50%	8.55	15, 20, 25
Case 2.2	10.7 mm; 20%, 3.0 mm; 80%	6.44	
Case 3.1	10.7 mm; 50%, 1.4 mm; 50%	8.50	15, 20, 25
Case 3.2	10.7 mm; 20%, 1.4 mm; 80%	6.28	
Case 4.1	7.1 mm; 50%, 3.0 mm; 50%	5.77	15, 20, 25
Case 4.2	7.1 mm; 20%, 3.0 mm; 80%	4.53	
Case 5.1	7.1 mm; 50%, 1.4 mm; 50%	5.65	15, 20, 25
Case 5.2	7.1 mm; 20%, 1.4 mm; 80%	4.19	
Case 6.1	3.0 mm; 50%, 1.4 mm; 50%	2.46	15, 20, 25
Case 6.2	3.0 mm; 20%, 1.4 mm; 80%	1.97	

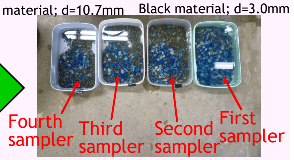
Procedure※ ※These procedures were repeated three times for each case, and for each flume gradient.



1) The materials were set on the flume. Water was supplied at the upstream end of the flume.



2) When the debris flow arrived at the downstream end of the flume, the flow encountered the sampler moving at a constant speed in a transverse direction. The debris flow front was separated by the sampler into the four boxes over a constant time interval in the range of 1–2 s.



3) Measurements were performed to determine the temporal changes in the total flow discharge, sediment discharge, sediment flux concentration, and proportion of each size in each sample.

◇ The proportions of coarser particles increased more as being closer to the flow front, whereas the proportions of finer particles decreased (**Figure 3**).

◇ As the sizes of the debris-flows materials became **coarser** or the flume gradient became **lower**, the sediment sorting at the flow front **progressed more remarkably** (Figure 4). Decreasing the debris-flow velocities due to lowering the flume gradient and enlarging the materials' sizes might have caused **the sediment sorting to progress more remarkably**.

◇ Decreasing the debris-flow velocities **enlarges the movement of materials in the depth direction**, *Middleton's suggested mechanism* (1970), which is **a falling mechanism of finer particles through the interstice between the materials in the flow's interior (dynamic sieving)**, may explain this phenomenon.

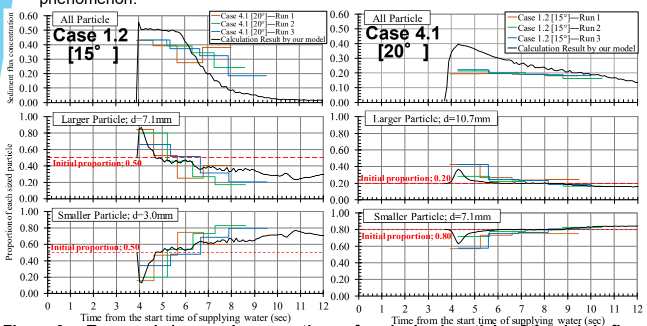


Figure 3. Temporal changes in proportions of each sized particle of the debris flows at the downstream end of the flumes. (Experimental and Calculated results)

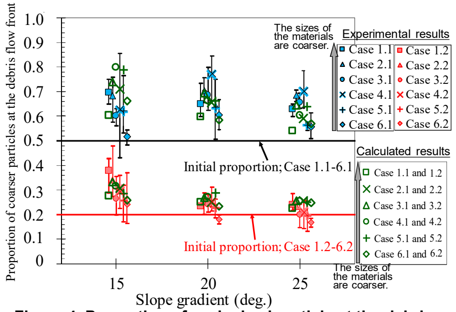


Figure 4. Proportion of each sized particle at the debris-flow fronts at downstream end of the flume in all cases. (Experimental and Calculated results)

3. APPLICATION WITH ONE-DIMENSIONAL NUMERICAL MODEL CONSIDERING SEDIMENT SORTING OF A DEBRIS FLOW

3.1 Outline of our developed model

◇ In the model, the debris flow depth (h) is divided into several layers (the number of layers = n_p) with the same thicknesses ($D_L = h/n_p$) (**Figure 5**). Based on the theoretical equations for distributions of velocity and sediment concentration of a debris flow by *Takahashi et al*. (1996), the migration velocity of materials (u_p) and the sediment concentration of k-th particles (C_{kp}) were considered in each divided layer. The falling volume of downward movement of k-th particles (r_{kp}) was also incorporated.

$$r_{kp} = \alpha\left(\frac{s_{p-1}}{d_k}\right)^3 \frac{\Delta u}{\Delta z} C_{kp} D_L = \alpha\left[\frac{dm_{p-1}}{d_k}\left\{\left(\frac{\sum_{k=1}^{k_e} C_{k\cdot p-1}}{C_*}\right)^{1/3} - 1\right\}\right]^3 \frac{\Delta u}{\Delta z} C_{kp} D_L \quad (1)$$

Notations:
where α = the coefficient related to the falling of particles, s_p = the interstice between particles in the p-th layer, which is evaluated on the equidistant particle arrangement of the flow including highly-concentrated particles proposed by *Bagnold* (1954), d_k = the diameter of k-th particles, d_{mp} = the mean volume diameter of all particles in the p-th layer, k_e = the number of particle classes, $\Delta u / \Delta z$ = the velocity gradient (shear strain) between the p-th and p-1th layers.

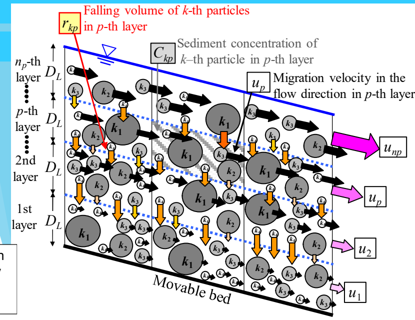


Figure 5. Outline of our developed 1-D model

◇ The governing equations of our developed model are briefly discussed as follows.

The momentum equation for the flow mixture in the total flow layer

$$\frac{\partial M}{\partial t} + \beta\frac{\partial uM}{\partial x} = -gh\frac{\partial(z_b + h)}{\partial x} - \frac{\tau_b}{\rho_m} \quad (2)$$

The continuity equation for the flow mixture in the total flow layer

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} = \sum_{k=1}^{k_e} i_{bk} \quad (3)$$

The equation of bed variation

$$\frac{\partial z_b}{\partial t} + \sum_{k=1}^{k_e} i_{bk} = 0 \quad (4)$$

The continuity equation of k-th particles in the p-th layer

$$\frac{\partial C_{k1} d_l}{\partial t} + \frac{\partial q_{bk1}}{\partial x} = \frac{\partial P_{k1}\overline{C_k}h}{\partial t} + \frac{\partial u_p P_{k1}\overline{C_k}h}{\partial x} = i_{bk}C_* - r_{k2} - r'_{k1} \quad (p = 1)$$

$$\frac{\partial C_{kp} d_l}{\partial t} + \frac{\partial q_{bkp}}{\partial x} = \frac{\partial P_{kp}\overline{C_k}h}{\partial t} + \frac{\partial u_p P_{kp}\overline{C_k}h}{\partial x} = (r_{kp} - r_{k\cdot p+1}) - (r'_{kp} - r'_{k\cdot p-1}) \quad (1 < p < n_p) \quad (5)$$

$$\frac{\partial C_{kn_p} d_l}{\partial t} + \frac{\partial q_{bkn_p}}{\partial x} = \frac{\partial P_{kn_p}\overline{C_k}h}{\partial t} + \frac{\partial u_{n_p} P_{kn_p}\overline{C_k}h}{\partial x} = r_{kn_p} + r'_{k\cdot n_p-1} \quad (p = n_p)$$

Notations:
where t = the time, x = the coordinate axis of the flow direction, β = the momentum coefficient (= 1), M = the momentum flux for the total flow layer (=uh), z_b = the height of the movable bed, τ_b = the shear resistance of the river bed, i_{bk} = the sediment erosion/deposition velocity of k-th particles, q_{bkp} = the transportation volume of k-th particles per a unit width in the flow direction in the p-th layers (=$u_p C_{kp} h/n_p$), r_{kp}' = the transportation volume of k-th particles from the p-1th layer to the p-th layer, which is the surplus volume for the maximum volume in the p-1th layer obtained by the theoretical equation for distributions of sediment concentration by *Takahashi et al*. (1996).

3.2 Calculation result

◇ Our model can explain that **coarser particles exist relatively in the upper layer** and **concentrate at the flow front** during downflow (**Figure 6**).

◇ The calculated results are quantitatively consistent with the experimental results on the proportions of each sized particle of the flow front at the downstream end of the flumes. Our model can quantitatively describe **the temporary changes in the flux concentration of coarser and finer particles at the flow front** (**Figures 3 and 4**).

Table 2. Experimental cases and conditions

Parameters/Variables	Value	Unit
Total simulation time	30	sec.
Time step Δt	0.0001	sec.
Diameters of particles d_k (two of four particle diameters)	10.70, 7.10, 3.00, 1.40	mm
Mass density of material σ	2635	kg/m³
Mass density of interstitial fluid ρ_m	1000	kg/m³
Concentration in the static sediment bed C_*	0.558	–
Internal friction angle of material ϕ	32.85	deg.
Gravity acceleration g	9.8	m/s²
Coefficient of erosion rate δ_e	0.03	–
Coefficient of accumulation rate δ_d	0.05	–
Interval of calculation points Δx	0.01	m
Coefficient to be related to the falling of particles α	500	–
Number of the divided layers n_p	4	–

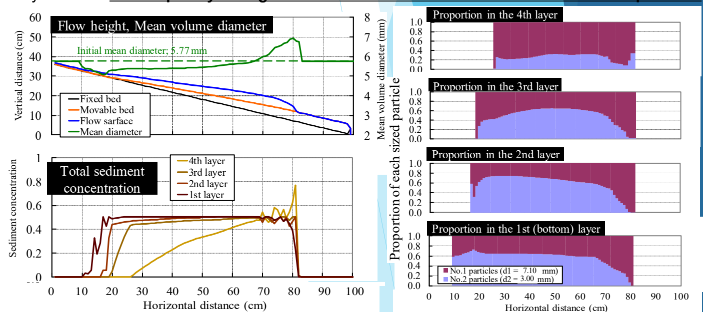


Figure 6. Calculated longitudinal results in 3.5 s after supplying water at upstream end of the flumes in Case 4.1 [20°]

4. CONCLUSIONS

◇ As the sizes of the debris-flows materials became **coarser** or the flume gradient became **lower**, the sediment sorting at the flow front **progressed more remarkably**.

⇒ Decreasing the debris-flow velocities due to lowering the flume gradient and enlarging the materials' sizes might have caused **the sediment sorting to progress more remarkably**.

⇒ Decreasing the debris-flow velocities **enlarges the movement of materials in the depth direction**, *Middleton's suggested mechanism* (1970), which is **a falling mechanism of finer particles through the interstice between the materials in the flow's interior (dynamic sieving)**, may explain this phenomenon.

◇ We developed **a numerical model to describe the above mechanism in the flow's interior** based on the 1-D model proposed by *Satofuka et al*. (2007)

⇒ Our model can explain **the inverse grading in the flow's interior**, and **the concentration of coarser particles at the flow front** during downflow.

⇒ Our model can quantitatively describe **the temporary changes in the flux concentration of coarser and finer particles at the flow front**.

◇ However, in the case that the sizes of coarser and finer particles were similar, the calculation results **underestimated** the experimental results for the proportion of coarser particles at the flow front.

⇒ In our model, incorporating the rising movements of coarser particles in the upper layer of a debris flow, which is caused by a collision or contact between particles in the flow's interior is needed to describe this more accurately.

REFERENCES

◇ Middleton, G. V. (1970); *J. ed., Flysch Sedimentology in North America, Geological Association of Canada Special Paper 7*, pp.253–272.
◇ Satofuka, Y., Iio, T. and Mizuyama, T. (2007); *Proceedings of 4th International Conference on Debris-Flow Hazards Mitigation.*
◇ Takahashi, T., Satofuka, Y., and Chishiro, K. (1996); *Annuals of Disaster Prevention Research Institute, Kyoto Univ.*, 39(B-2), pp.333–346 (in Japanese with English abstract).