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Study on Non-Dimensional Parameter Governing Debris Flow

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Abstrak

Aliran debris merupakan suatu tipe gerakan sedimen dengan jumlah banyak, yang terjadi pada waktu gunung api meletus atau dalam bahasa Indonesia disebut aliran lahar. Tujuan penelitian ini adalah mengembangkan suatu percobaan untuk menentukan karakteristik aliran di atas dasar saluran tetap dan bergerak yang mendekati sifat aliran debris. Beberapa parameter aliran diperiksa dengan maksud untuk mengetahui situasi aliran dan juga gaya geser aliran terhadap partikel dapat ditinjau. Jadi hubungan antara besarnya konsentrasi sedimen dengan kedalaman aliran dan diameter partikel serta gaya gesek diatas dasar saluran dapat diketahui. Khususnya gaya seret butiran yang bekerja pada suatu tiang telah diukur untuk menentukan koefisien kekasaran aliran debris yang menyerupai tipe aliran di lapangan. Akhirnya parameter-parameter karakteristik aliran yang telah diukur, itu dapat dibandingkan dengan satu sama lainnya.

***Kata Kunci** : Aliran Debris, Konsentrasi, Angkutan Sedimen*

Abstract

Debris flow as a type of massive sub-aerial sediment motion, which occurs at the time of volcanic eruptions is sometimes called lahar, in Indonesian term. The purpose of this study is to develop an experiment for determining the flow characteristics on fixed and movable beds, which close to real debris flow. The parameters governing the flow situation are examined, and the frictional drag of the flow on the particles was considered. In particular there is an understanding of the relationships between concentration, flow depth and particles diameter, and friction force on a bed. Special drag force on a pile was measured to investigate friction coefficient of debris flow as typical problem. The flow characteristics parameters were measured for comparison.

***Key words** : Debris Flow, Concentration, Sediment Transport*

1. Introduction

In this study, the debris flow is defined as the sediment-water mixture with high concentration [5]. Most literatures concerned with the hyperconcentration phenomena emphasize the effect of large concentration of fine sediments on bed material transport. For extremely large sediment concentrations including mud and debris flows, the mechanics of movement and flow properties differ greatly from clear-water flow. Since the flow contains solid and liquid phases, there exists the effect of each phase on the flow behavior. However it is difficult to distinguish the role of each phase. Therefore, to a first approximation the effect of solid phase only was discussed under the condition of high concentration. Many researchers pointed out that turbulence of mixture flow plays a major role in larger values of the ratio of flow depth to sand diameter [1,7]. To aid in the understanding of these flows, non-dimensional parameters is needed to explain sediment properties, velocities, resistance and transport.

The flow behavior changes corresponding to the various conditions. It is necessary to examine parameters governing the flow situation and test their effect by making experiments. In the present work, the non-dimensional parameters for determining the flow situation is obtained, and also to discuss friction forces acting on a bed and drag forces on a tube as typical problems.

2. Literature Review

2.1. Parameters Governing Flow Situation

In their previous work, Hashimoto, H. and Hirano, M. [6] consider that debris flow as two-phase flow, namely, grain and water phases, as shown in Figure 1.

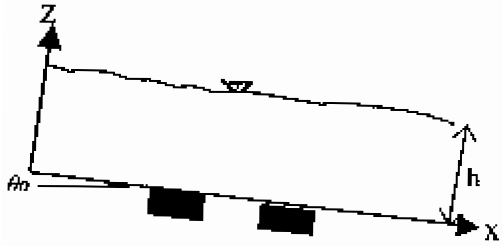

Figure 1.
Schematic diagram of gravity flow of a sand-mixture

Therefore, the mean velocity of steady two-dimensional rapid flows of sand-water mixture in open channel is governed by the x-momentum equation,

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial z}=-\frac{1}{\rho t}\frac{\partial p}{\partial x}+\frac{1}{\rho t}\left(\frac{\partial \tau_{zx}}{\partial z}+\frac{\partial \tau_{xx}}{\partial x}\right) \quad ......(1)$$

where $\rho_t = \rho(1-C)+\sigma C$ is density of mixture flows, u and v are velocity components in the x and z directions, respectively, σ is density of grain, p is pressure including gravity components of the flows, τ_{zx} and τ_{xx} are intergranular-stresses. Here, the Reynold's stress due to the turbulence of the interstitial water is assumed negligibly minor compared to the intergranular-stresses.

Further, for the two-dimensional shear flow, the equations of intergranular-stresses can be written in the form,

$$\left.\begin{aligned}\tau_{zx} &= K_{zx}\,\sigma d^2 F(C)\,(du/dz)^2\\ \tau_{xx} &= K_{xx}\,\sigma d^2 F(C)\,(du/dz)^2\end{aligned}\right\} \quad ......(2)$$

where d is grain diameter and F (C) is a function of grain concentrations C and C_* in the flow and in the bed, respectively, such that

$$F(C)=\frac{(C/C_*)^2}{1-C/C_*} \qquad (3)$$

If U is a characteristic velocity and L is a characteristic length, the inertia terms in Equation (1) are estimated as U^2/L and the intergranular-stress terms as $d^2F(C)U^2/L^3$. Therefore, from of these terms can be defined as the ratio of inertia to the intergranular-stress, which is indicated by

$$\frac{U^2/L}{d^2F(C)U^2/L^3}=\frac{1}{F(C)}\left(\frac{L}{d}\right)^2 \qquad (4)$$

Thus L/d and C are two unknown parameters and should be determined experimental. At larger values of C and smaller values of L/d, intergranular stress terms play major role compared to the inertia terms. At smaller values of C and larger value of L/d, on the other hand, the inertia term become important relatively to the intergranular-stress terms.

Since the depth of shear layer is appropriate for a characteristic length, flow depth h can be chosen as L in the discussion of friction forces acting on a bed in open channel flows, and the diameter of a pile d_L can be chosen in that of forces D on the pile.

2.2 Drag Forces on the Pile

Drag force D due to such mixture flows on a pile of unit length is divided into two forces; one is due to water phase and the other due to sand phase [3, 4]. They assume that the drag coefficient C_D due to the both phase are expressed by

$$D=\frac{\rho}{2}u^2 d_L C_D \qquad (5)$$

where u is the flow velocity.

The mixture flows on the fixed beds have approximately uniform distribution of velocity and concentration. Therefore u and C is approximately equal to average velocity ū and flux-averaged concentration C_T, respectively. Substituting measurements of drag force D, mean velocity ū and flux-averaged concentration C_T into Equation (5), so that drag coefficient C_D can be found.

3. Research Methodology

3.1 Equipment

The experiment was conducted in a laboratory flume having a width 12.5 cm and length 12 m. Two kinds fixed bed were used; one is made of acrylic board and the other of plywood. The flow could be adjusted from 0 to 250 cm^3/s, and the slope from horizontal to 18°. Slope variation was achieved by raising or lowering the upstream end of the flume with tackle. A schematic diagram of this flume is shown in Figure 2.

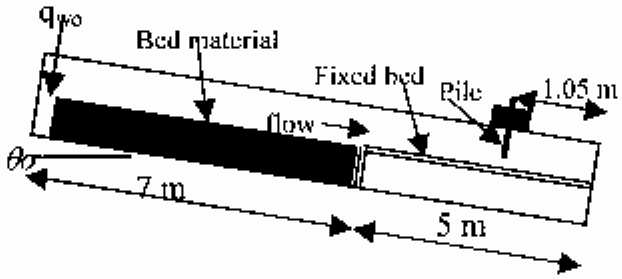

Figure 2.
Schematic diagram of flume

3.2 Bed Material

Various sands were used as bed materials, which have various sizes of d_{50}. According to grain size, the materials divided into two categories, namely, finer and coarser materials. The materials having size of d=0.07 mm, 0.09 mm, 0.17 mm, 029 mm, 0.55 mm, and 0.80 mm are termed as finer sand, while d=0.80 mm, 1.24 mm, 1.90 mm, 4.40 mm, and 7.00 mm are termed as coarser sand. All of the experiment materials and conditions are shown in Table 1, in which σ / ρ is specific gravity.

Table 1.
Experimental materials and conditions

d (mm)	σ / ρ	θ_0	d_L (mm)	q_{wo} (cm^3/s)
0.07	2.63	14°	8	100
0.09	2.60	14°	8	100
0.17	2.61	4°-18°	6, 8	100,200
0.29	2.62	14°	8	100
0.55	2.65	14°	8	100
0.80	2.64	8°-18°	6, 8	100,200
1.24	2.65	14°	8	100
1.90	2.61	14°	8	100
4.40	2.59	4°-18°	6,8	100,200
7.00	2.63	8°-18°	6,8	100,200

3.3 General Procedure

In the case of debris flow on movable bed, for the work reported here the flume bed was covered with a sediment layer about 10 cm. Prior to an experiment, the sediment bed was saturated with water which is assumed as a ground water, q_g. Then a constant rate of clear water was supplied suddenly from upstream end of the flume to produce a debris flow. The flow depth and flow velocity were measured by taking the pictures of flows from the flume side direction, with either a video camera or a 16 mm high speed camera running at 100 frame/sec. The pictures were taken at the side of the flume 1.05 m distant from the downstream end, in a plane perpendicular to the axis of the channel. The velocity of grains, u and the average depth of flow, h were measured visually by projecting the film repeatedly at a speed of 5 or 10 frames/s.

In the case of debris flow on fixed bed, prior to the start of a test, the material was spread at the upstream part 7 m in length and 11 cm in thickness and saturated with water. The water was supplied from

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upstream end of the flume, then a flow of sand-water mixture occurred and flow on the fixed bed. Futher, procedure for measuring the other parameters were same as that case of movable bed.

For measuring the drag forces due to the clear water and debris flow, they used two kinds of pile; one is 38.5 cm long and its diameter is d_L = 8 mm, and the other is 32.5 cm long and d_L = 6 mm. Strain gages were attached to the upper end of the piles for measuring drag forces exerted on them. The video camera was used to measures catching time of debris flow at the downstream end of flume. Flow depth was measured at 1.05 m from downstream end of the flume by use of a video camera too, which is placed on the right side of the flume. Measurements were made during each run.

4. Result and Discussion

4.1 Estimation of Resistance Coefficient

Flow resistance of fixed and movable beds may be defined in terms of velocity ratio, $\bar{u}/u_*$, then to discuss about how to estimate friction factor for debris flow. In application, this estimation was based on the value of relative flow depth and flux-averaged concentration. By definition, the Darcy-Weisbach friction factor f' is given by [6]

$$f' = 2\left(\frac{u_*}{\bar{u}}\right)^2 \qquad \text{......(6)}$$

where u_* = $\sqrt{gh\sin\theta_o}$ is friction velocity and $\bar{u} = q_t/h$ is mean velocity.

Consideration of the processes of flow indicates that flow resistance is a function of the combined from drag of the sediment particles, bed channel shape, concentration of sand, bed form drag and sand movement effects. As the ratio of flow depth to sand size h/d plays an important role all these processes, the friction factor f' is plotted against h/d using the flume data of the fixed and movable beds in Figure 3.

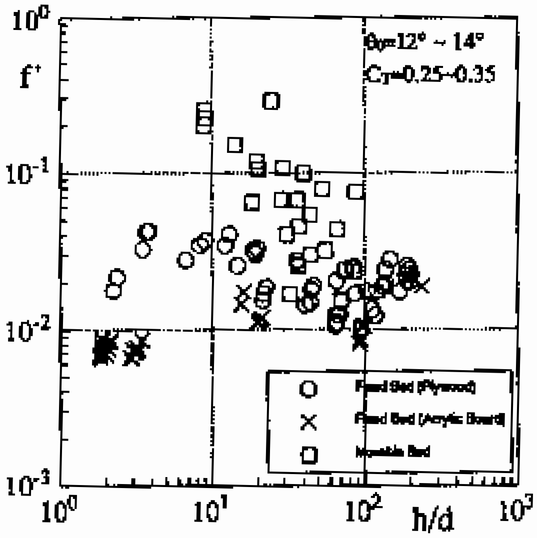
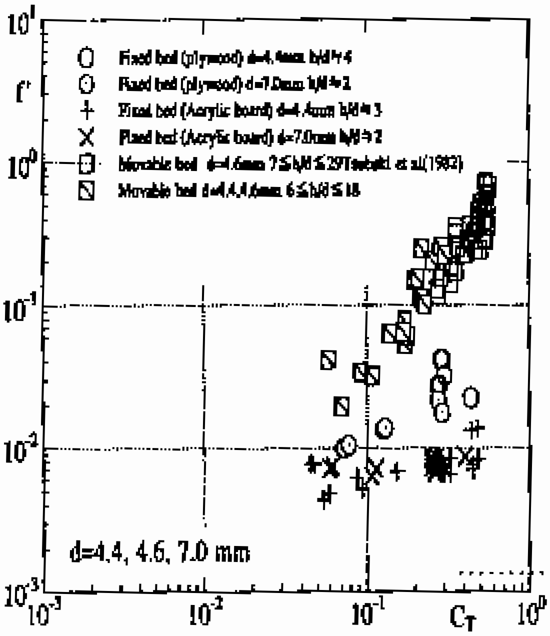


Figure 3.
Variation of friction coefficient f' with relative depth h/d



......(6)

Figure 4.
Variation of friction coefficient f' with flux-average concentration C_T for gravel material

It is found that f' sharply decreases with h/d at smaller value of h/d, and gradually decreases at the larger values for movable bed. On the other hand, the values of f' are almost constant for fixed bed. Thus, it is found that different values of f' appear at the region of h/d ≤25, but the same values at the region of h/d ≥ 100, for fixed and movable beds.

The effect of sand concentration on the friction factor is shown in Figures 4, 5 and 6, where f' is plotted against flux-averaged concentration for three beds conditions with the certain values of h/d. The values of f' become almost constant against C_T in the case of fixed bed of the acrylic board, but for other cases, the value of f' increases with C_T. Those figures also show the value of f' sharply increases with C_T at smaller values of h/d and f' gradually increase at large values of h/d. It may therefore be concluded that flow resistance varies directly with sand concentration.

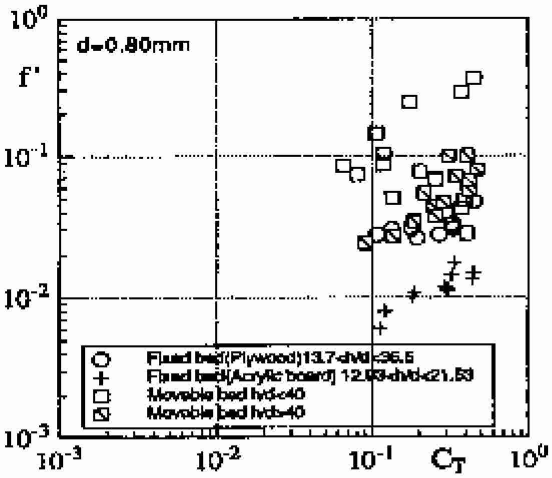


Figure 5.
Variation of friction coefficient f' with flux-averaged concentration C_T for coarser material

Since intergranular-stresses become smaller at h/d ≥100 in the three cases, the velocity distribution can be expressed as a logarithmic law [2, 4],

$$\frac{u_s - u}{u_*} = -\frac{1}{\kappa} \ln \frac{z}{h} \tag{7}$$

where u_s is surface velocity and κ is the Karman's constant. For determining κ value, namely, first to determine the value of u_s/u_* in Figure 7, then from Figure 8, it can estimate the value of $\alpha(u_s - u)/u_*$ by using straight line. Therefore, the values of κ can be calculated by using Equation (7). Finally, the κ values are plotted on Figure 9. This figure shows the scattered κ values. Therefore, the experimental results give that κ is approximately 0.25 ~ 0.46.

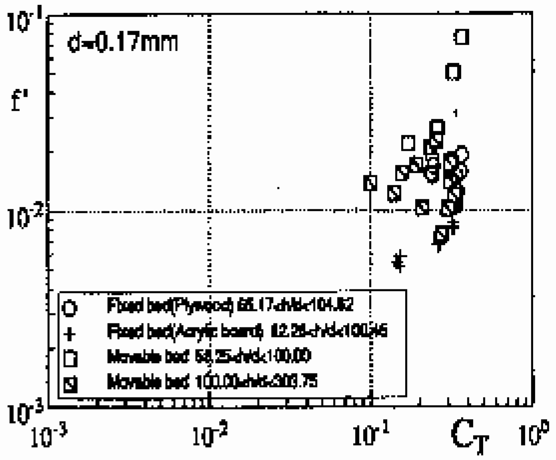


Figure 6.
Variation of friction coefficient f' with flux-averaged concentration C_T for finer material

3.2 Drag Coefficients

The average values of variables or parameters for each experimental run were obtained by results of experimental work of the Taguma *et al.* [7]. Using the measured data graphs was drawn to investigate the relationships between: (1) C_D/C_{DW} and d_L/d; (2) C_D/C_{DW} and C_T as shown in Figures 10 and 11.

Figure 10 shows the resistance curve for a pile; on a logarithmic coordinate system, the relative drag coefficients C_D/C_{DW} are plotted against the non-dimensional diameter of the pile d_L/d. As can be seen from this figure, C_D/C_{DW} value rapidly decreases with d_L/d at its smaller values, gradually decrease at the larger values and tend to approach to unity. This implies that the mixture flows behave like clear water for larger d_L/d. In the case of clear water the measurements of C_{DW} were done at Reydolds numbers of Re = 9800 ~ 21100. Here Re is the symbol used for the Reynolds numbers, defined as Re = $\bar{u}\, d_L/\nu$, where ν is the kinematics viscosity. For clear water flow under this condition, turbulent resistance is dominant.

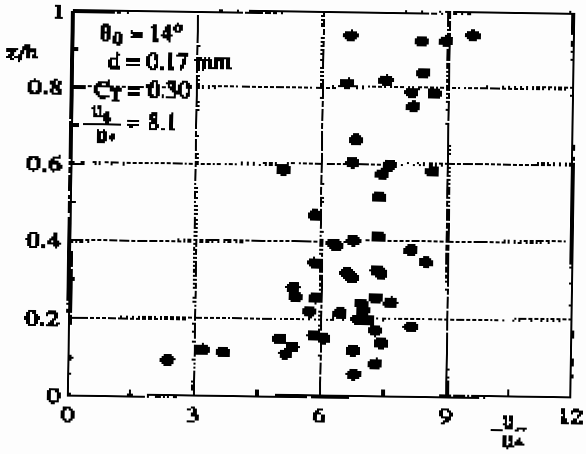


Figure 7.
Typical plot of z/h and u/u* for determining the value of u_s/u_*

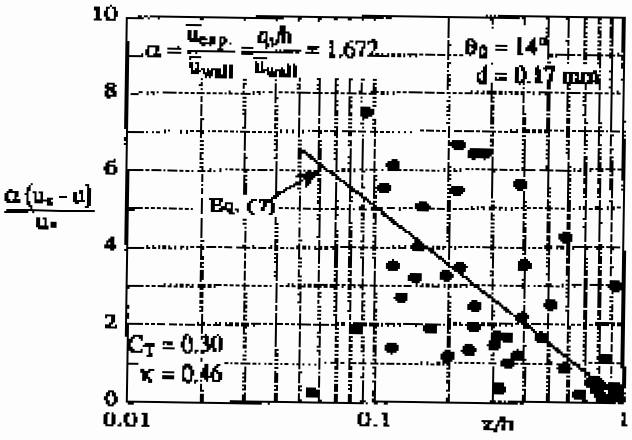


Figure 8.
Typical plot for calculating κ value; line is for mean value

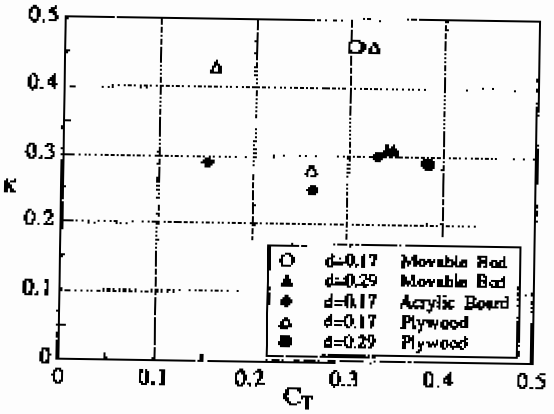


Figure 9.
Variation in Karman's constant with concentration

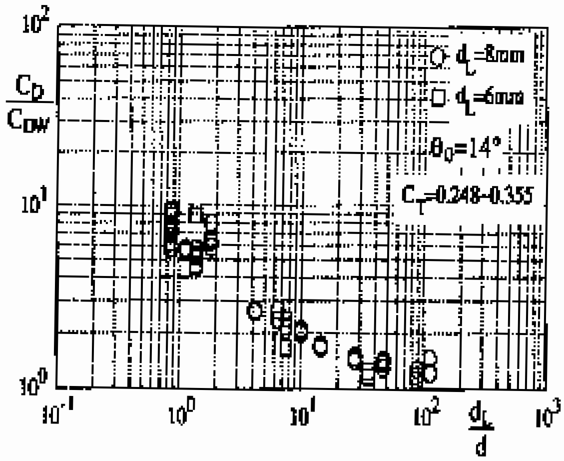


Figure 10.
Variation of relative drag coefficients with non-dimensional diameter of pile

Hence for larger d_L/d the drag force are found due to turbulent resistance of mixture flows.
This result corresponds to the discussion in previous section.

Figure 11 shows the relation of C_D/C_{DW} and flux-averaged concentration C_T. it is found that the relative drag coefficient of C_D/C_{DW} decreases with a decrease in C_T, and tends to approach to unity for smaller C_T. This shows that the role of interstitial water becomes important at the smaller values. Such dependence of relative drag coefficient C_D/C_{DW} on non-dimensional pile diameter d_L/d and concentration C_T is similar to that of friction coefficient f' on relative depth h/d and concentration C_T; this

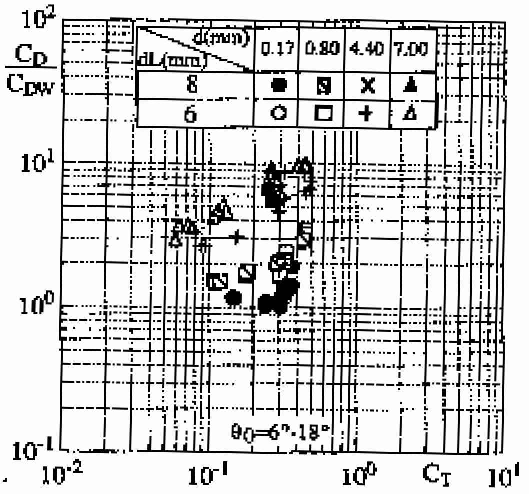


Figure 11.
Variation of relative drag coefficients with concentration

result verifies that h/d and C_T for the determination of friction forces acting on a bed, and d_L/d and C_T for that of drag forces on a pile are significant non-dimensional parameters

5. Conclusions

This study of non-dimensional parameter governing debris flows in steep channel indicates that:

1. Sand concentration, C_T and non-dimensional parameters diameter, L/d determine the flow situation of sand-water mixture flow at high concentration.
2. Friction forces, f' on a fixed bed in open channel-flow varies as a function of concentration, C_T and relative flow depth. When the relative flow depth, $h/d < 20$ and concentration, $C_T > 0.25$, the intergranular-stress terms in the momentum equation play dominant role. On the other hand, at the larger relative depth, major effect of the inertia terms has been confirmed.
3. For non-dimensional diameter such that $d_L/d < 10$ and concentration such that $C_T > 0.30$, forces due to multi-body collisions are dominant. Dependence of drag coefficients of pile on d_L/d and C_T is similar to that of friction coefficients of bed on h/d and C_T.

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