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Experimental evaluation of peak and temporal changes in debris-flow initiation processes

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Abstract

Saturated sediment water mixture flow can move as landslide if the vertical sediment concentration is constant and the value takes a maximum sediment concentration, c_*, which is sediment concentration in the non-flowing layer in sediment deposition. The flow is debris flow over the rigid bed and the flow can change as debris flow with vertical sediment concentration distribution if the saturated flow reaches downstream reach, where bed inclination is around 17 to 18 degrees. The thinking proposes that it is important to know transition process in between saturated landslide and debris flows in evaluating peak and temporal changes of debris flows in initiation processes for debris-flow mitigation in planning and design of sabo dam, because the transition process can be explained by a relation between bed slope and depth-averaged sediment concentration (e.g., Takahashi 1991). In present study, important knowledge for estimating peak discharge is discussed using experimental data obtained by present flume tests. Flume tests are carried out using prismatic open channel which is set 22 degrees and around 18 degrees at downstream end. Sediment is deposited parallelly to the flume bed and water is supplied steady at upstream end, and the transition of between saturated landslide to debris flow is produced. Two kinds of sediment deposition depth and length are specified in the present tests, and temporal changes of debris flow are measured using side view of digital video camera and debris-flow runoff at downstream end of the flume. The data shows that peak discharge rate of debris flow depends on sediment volume during debris-flow running from the up to the downstream reach, and that entrained sediment volume by a debris flow will be determined by erosion capacity during a debris-flow surge.

Keywords: Debris flow; Peak discharge; Initiation process; Flume tests

1. Introduction

Estimation and prediction peak discharge of debris flow are important matters, and there are a lot of researches from experimental, numerical and field investigation approaches related to the debris-flow initiation (e.g., Takahashi, 2007; Rickenmann, 2016). Saturated sediment deposited parallelly on the bed can be stable in the region that bed slope is less than 17 to 18 degrees (= θ_*), because volumetric sediment concentration of sediment layer takes vertically uniform value of maximum sediment concentration, c_*, which is sediment concentration in the non-flowing layer in sediment deposition, over the θ_* of bed slope.

The sediment mass with constant thickness moves totally due to the driving force reduced by yield stress, if bed slope takes over the θ_*. This means that the peak discharge and temporal shape of debris flow can be estimated in the region that bed slope is less than θ_*, if the hydrograph of debris flow at the section of θ_* of bed slope, because the trigger of the debris flow can be evaluated. Previous study (Ou et al., 1993) introduced the spreading of debris-flow surge over the movable bed slope of θ_*, and the longitudinal shape and spreading characteristics of the debris flow. However, the peak discharge of the debris flow was not discussed in the literature, though the debris mass shape takes longitudinally triangle with similarity shape.

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In present studies, following experimental approaches try to be conducted, based on the meaning of the bed slope of θ_*, to discuss estimation of peak discharge of debris flow triggered in the steep region over the θ_* of bed slope: (1) Flume tests over the bed slope of θ_*, (2) Dimensional analyses of peak discharge and total volume of the debris-flow surge. Additionally, several data and related discussions are shown in present studies.

2. Flume tests

2.1. Experimental flume, hydraulic and sediment condition

Figure 1 shows experimental flume: around 8 m in length, 10 cm in width and 40cm in depth. Bed slope of the flume is set as 22 degrees and the bed slope is saturated sediment on the bed can be transported with c_* of sediment concentration. Sediment is deposited on the bed with longitudinally constant depth, D_p, and clear water is supplied from upstream end on the saturated sediment. A weir is set at the downstream reach and the bed slope there is set as 18 degrees after debris flow passing.

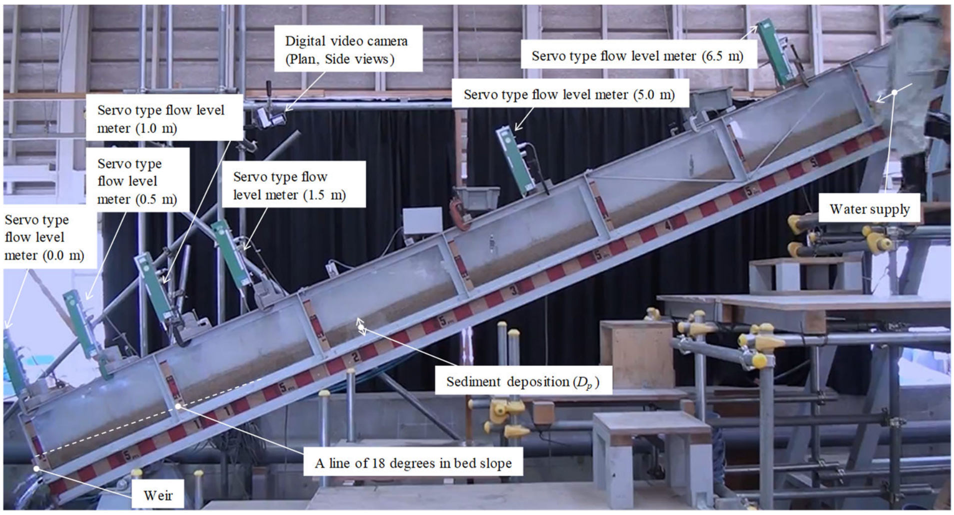

Fig. 1. Experimental flume

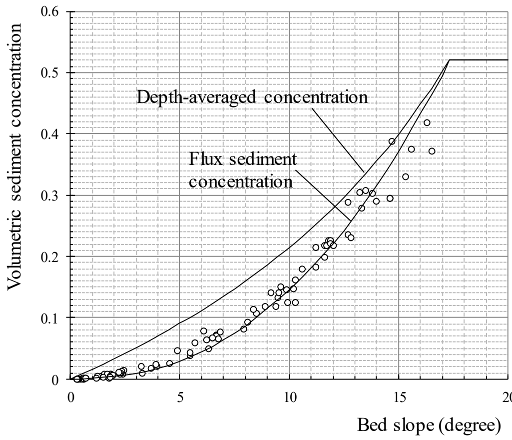

Fig. 2. Relation between equilibrium bed slope and sediment concentration (e.g., Egashira et al. 1997)

Figure 2 shows relation between equilibrium bed slope and sediment concentration in the steady and uniform debris flow (e.g., Egashira et al., 1997). In the figure, two lines are draw and those are depth-averaged sediment concentration and flux sediment concentration, respectively. The value of sediment concentration can be supposed as c_* along the flume in the present flume tests, and the value of sediment concentration less than c_* can be measured at the downstream end of the flume. Sand particles are used in the flume test with almost uniform sand in diameter, and those have physical values as follows: d_{60} is 1.4 mm, d_{max}=2.0 mm, σ/ρ= 2.66, ϕ_s= 35.9 degrees, k=0.657 cm/s and c_*=0.514. where d is the diameter of sand particles, σ is the mass density of sand, ρ is the mass density of water, ϕ_s is the interparticle friction angle and k is the permeability of sand measured by the constant head permeability test. Herein, the value of c_* is measured with uniform sand particles for present tests, and the value is usually less than that of spherical particles.

Table 1 shows experimental conditions and results that are described below. In the table, Q_u is the supplied water discharge rate, Q_d is the seepage flow water discharge in the sediment deposition layer to be saturated condition, D_p is the thickness of sediment deposition on the flume, L is the length of sediment deposition, Q_p is the peak discharge rate measured at the downstream end, T_d is the flowing duration of debris-flow surge and ΣQ is the total volume of debris-flow surge. In present flume tests, following results are shown for discussions.

1) Two kinds of the deposition length
2) Two kinds of the depth of sediment deposition on the flume
3) Three patterns of combinations of the length and the deposition thickness: (L, D_p)= (6.5m, 0.1 m), (6.5m, 0.05m) and (3.25m, 0.05m).

Table 1. Experimental runs and results

Run No.	D_p (cm)	L (m)	$D_p L$ (m^2)	Q_u (l/s)	Q_d (l/s)	Q_p (l/s)	T_d (s)	ΣQ (l)
027	10	6.5	0.650	0.5	0.15	5.62	23	42.6
034	10	6.5	0.650	0.5	0.15	8.54	17	48.6
035	10	6.5	0.650	0.5	0.15	9.52	18	62.2
042	5	6.5	0.325	0.25	0.075	6.21	12	16.4
043	5	6.5	0.325	0.25	0.075	5.15	12	31.7
045	5	3.25	0.163	0.25	0.075	4.86	14	21.7
048	5	3.25	0.163	0.25	0.075	3.42	9	18.1

2.2. Measurements

In the present flume tests, several values of hydraulic parameters are measured as follows. At the downstream end, water and sediment discharge are sampled by buckets, and the sediment concentration is calculated. Duration of measurement using a bucket is set around 2 seconds because accuracy of sampling at least is kept for data collections.

From side wall, free surface and bed of debris flows are taken by digital camera, and digital images are taken from overhead view. Longitudinal profiles of bed and free surface are obtained by image analyses using image data for bed and free surface variations from the plan and longitudinal views.

Longitudinally, servo-type level meters are set at the sections 0, 0.5, 1.0, 1.5, 5.0, 6.5 m from downstream end of flume, and temporal changes of free surface of debris-flow body are measured. Measured data of free surface level at 0 m (H) are correlative relation with sampled discharge (Q) at downstream end (H-Q relation), and temporal changes of discharge there are calculated using the relations, because sampling by buckets can obtain temporally discrete data during several seconds and cannot obtain continuously temporal changes of outlet discharge of debris flow. The method using the H-Q relation with a servo-type level meter at downstream end of the flume can obtain temporal and continuous outlet discharge through the flume end.

3. Estimation of peak discharge

Experimental data are shown for the combinations of the length. L, and the depth, D_p, of sediment deposition on the flume: (L, D_p)= (6.5m, 0.1 m), (6.5m, 0.05m) and (3.25m, 0.05m). Table 2 is the ratio of peak to inlet discharge measured at downstream end, and shows differences of measured value for peak discharge, Q_p. In the table, $Q_{p\text{-}b}$ is the measurement by buckets and the Q_p is the calculation by the correlation (H-Q relation) between free surface level, H, by servo-type level meter (at 0 m) and discharge by buckets. The calculations can estimate well the peak value of discharge, though calculations are interpolation of direct measurement by buckets. Figure 3 shows temporal changes of discharge, sediment runoff and flux sediment concentration, for Run 035, 042, 045.

In present data, the value of Q_p is applied for calculations using the correlation of *H-Q* relation. The sediment concentration, *c,* takes almost the value of c_* in the beginning stage of sediment runoff at downstream end. The duration

Table 2. Ratio of peak to inlet discharge measured at downstream end

Run No.	D_p (cm)	L (m)	$D_p L$ (m^2)	Q_d (l/s)	Q_u (l/s)	$Q_{p\text{-}b}$ (l/s)	Q_p (l/s)	Q_p/Q_u (bucket, Servo)
027	10	6.5	0.650	0.15	0.5	5.3	5.62	10.6, 11.8
034	10	6.5	0.650	0.15	0.5	6.12	8.54	12.2, 17.1
035	10	6.5	0.650	0.15	0.5	5.81	9.52	11.6, 19.0
042	5	6.5	0.325	0.075	0.25	6.21	4.54	18.2, 19.4
045	5	3.25	0.163	0.075	0.25	4.86	3.71	14.8, 19.4

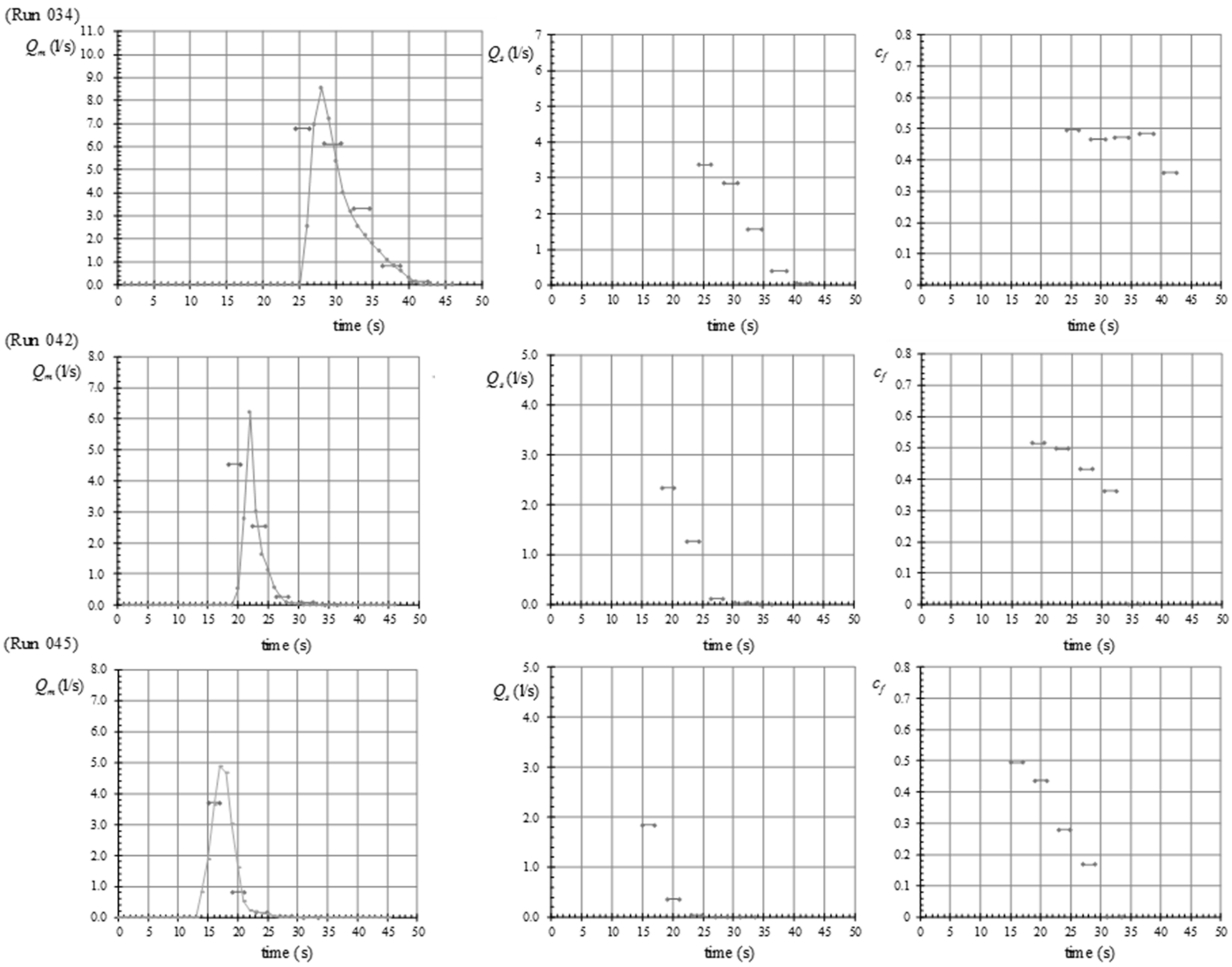

Fig. 3. Temporal changes of discharge, sediment runoff and flux sediment concentration, for Run 035, 042, 045

of $c=c_*$ becomes short due to decrease of sediment volume ($D_p L$). Temporal changes and peak value of debris flow have interesting characteristics.

Herein, Takahashi (1991, 2007) shows the ratio of peak to inlet water discharge from upstream reach using bore spreading and mass conservation relation for debris mass entrainment.

$$\frac{Q_p}{Q_{in}} = \frac{c_*}{c_* - c_\infty},\ c_\infty = \frac{\tan\theta}{(\sigma/\rho - 1)(\tan\varphi_s - \tan\theta)} \tag{1}$$

where Q_{in} is the inlet clear water discharge from upstream reach over the bed and c_∞ is the equilibrium sediment concentration, that is determined by mass density of sediment, σ, and mass density of water, ρ, interparticle friction angle of sediment particles, ϕ_s, and bed slope, θ, and the formula is described in the literature (e.g., Takahashi, 1991). Herein, substituting several values into the equation of c_∞ yields 18.4 degrees for the value of θ_*: σ/ρ = 2.66, c_*= 0.514 and φ_s= 35.9 degrees for physical parameters of experimental sand particles. The peak discharge, Q_p, in present tests cannot be calculated using Eq. (1), because the sediment concentration is supposed as c_* and the value in Eq. (1) takes infinity. Present data needs to be evaluated experimentally.

Except data of Run 027, the ratio of peak to inlet water discharge is 17.1 to 24.8, and those averaged value (peak ratio) is almost 20. Those mean that peak discharge of debris flow is determined by bed sediment volume, and that peak ratio has almost similarity to the ratio of debris-flow volume to bed sediment volume, if bed sediment is almost entrained to debris-flow body.

Figure 4 shows temporal changes of longitudinal profiles of free surface and bed elevation for Run 034, 042, 045. Herein, the experimental condition of Run 035 is same as that of Run 034. Longitudinal shape of debris flow is almost triangle and those temporal shape are almost similar each other as pointed by Ou et al. (1993), though bed elevation of the frontal part is affected by frontal parts of debris flow. Figure 5 shows spreading of frontal part from up to downstream along the flume. In the figure, the points "A", "B" and the pass line from "A" to "B" are shown for

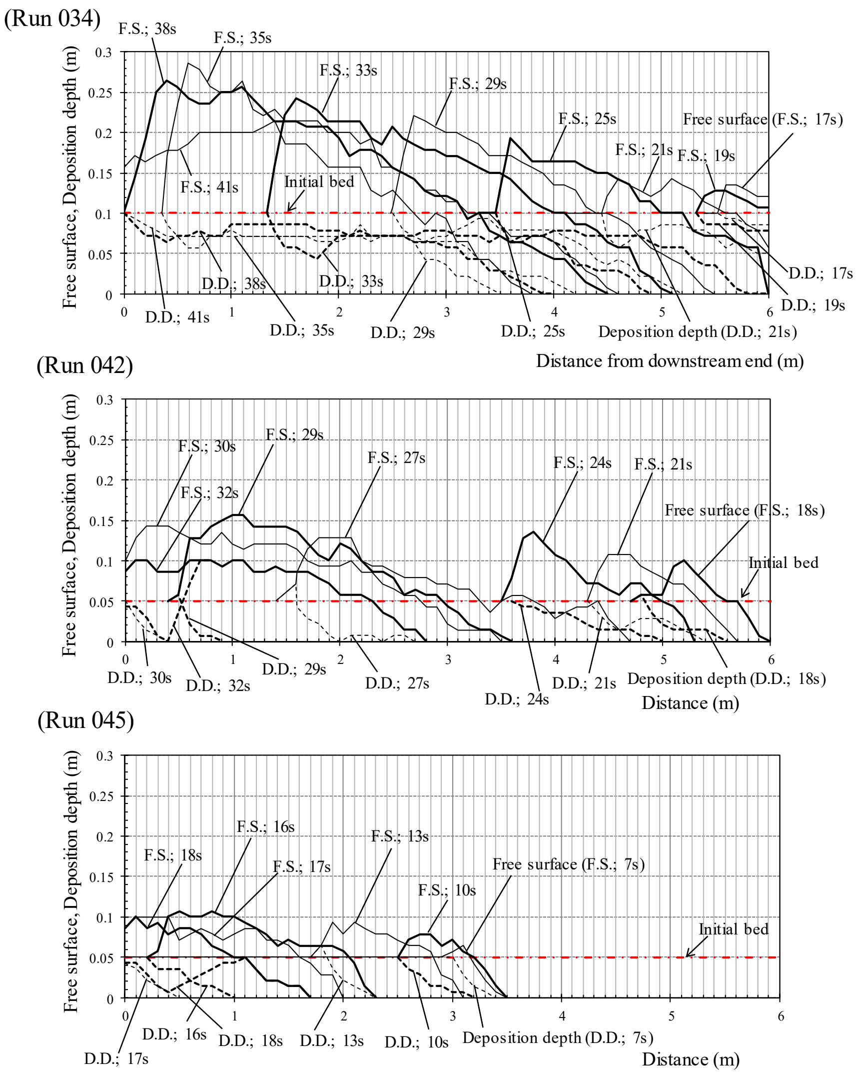

Fig. 4. Temporal changes of longitudinal profiles of free surface and bed elevation obtained by Run 034, 042 and 045

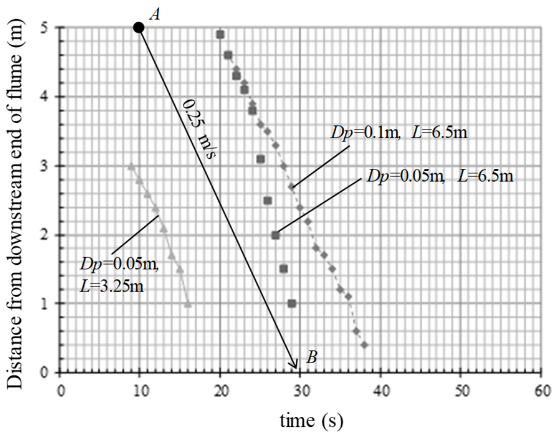

Fig. 5. Spreading of frontal part from up to downstream along the flume

understanding the spreading velocity. The spreading velocity is almost 0.25 m/s, except Run 042, because occurrences of some velocity acceleration. In Run 042 (D_p= 0.05 m, L= 6.5 m), the spreading velocity takes almost 0.5 m/s and the speed seems to be changed by increase debris entrainment due to imbalance saturation in deposition layer, D_p, as shown in data during 24s to 27s in Fig. 4.

Let us discuss estimations of peak discharge debris flow with steeper inclination than that of θ_* for c=c_*. The value of θ_* in Fig. 2 is around 17 degrees, as described in Introduction. The peak discharge of debris flow, Q_p, can be expressed dimensionally using the total volume of debris-flow surge, V, in case of mass movement for saturated bed sediment. The discharge of debris flow is calculated by the production of the cross section, A, and depth-averaged flow velocity, v. Peak discharge, Q_p, can be also expressed as;

$$Q_p = Av \tag{2}$$

The cross section, A, can be expressed using the co-efficient of cross-sectional shape and the thickness of debris deposition, D.

$$A = k_B D^2 \tag{3}$$

where, k_B is the co-efficient of cross-sectional shape of the area.

The flow depth, h, can be expressed using the thickness of debris deposition.

$$h = k_D D \tag{4}$$

where, k_D is the co-efficient of the ratio of flow depth to sediment deposition thickness.

In debris flows, velocity co-efficient, v/u_*, is proportional to relative flow depth, h/d (e.g., Takahashi 2007; Egashira et al. 1997);

$$\frac{v}{u_*} \propto \frac{h}{d} \Rightarrow \frac{v}{u_*} = k_v \frac{h}{d} \tag{5}$$

where, k_v is co-efficient of velocity factor, d is the diameter of bed sediment and debris flow and u_* is the shear velocity defined as;

$$u_* = \sqrt{ghsin\theta} \tag{6}$$

where, g is the gravity acceleration.

Substitution of Eqs. (3) to (6) into Eq. (2) yields the following relation for peak estimation.

$$Q_p = f(\theta, \frac{h}{d}, k \dots) D^{5/2} \tag{7}$$

In addition, the total volume of debris-flow surge, V, can be proportional to D^3, because the length of debris flow is almost 5 to 10 times to debris mass height according to empirical knowledges (e.g., Ashida et al. 1986) supposing the flow width can be proportional to the thickness of debris deposition, D, and Eq. (7) is re-written as follows,

$$Q_p = f(\theta, \frac{h}{d}, k \dots) V^{5/6}. \tag{8}$$

The relation between the peak discharge of debris flow, Q_p, and debris-flow volume can be the power law and the value of Q_p is proportional to the power of 5/6 for debris-flow volume, V. The peak discharge in the reach of $\theta > \theta_*$ can be estimated dimensionally, in case of saturated bed sediment.

Figure 6 shows relation between peak discharge and debris-flow volume obtained by present flume tests. The power lines of 5/6 (=0.833) are drawn in the figure, with some range from maximum to minimum of discharge. The data shows that peak discharge has similarity to debris-flow volume of flow body, and the peak value can be estimated by debris-flow volume and bed sediment volume in case of debris flow with entrained all bed sediment in saturate condition.

Figure 7 shows the relation between relative longitudinal volume and relative peak discharge of debris flow. The relative sediment volume is obtained by calculation of the longitudinal area at downstream end of the flume, as shown in Fig. 4. The value of $D_p L$ means the total volume of bed deposition on the bed in the initial stage. The relative peak discharge is defined as the ratio of the peak to inlet discharge from upstream end.

Experimental data shows that the relative peak discharge increases due to the longitudinal area of debris flow at the downstream end and the relation between relative longitudinal volume and relative peak discharge of debris flow can be determined uniquely, though data collections needs to be continued. The results emphasize that the peak

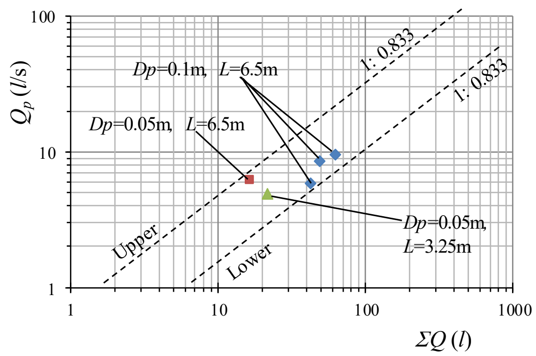

Fig. 6. Relation between peak discharge and debris-flow volume obtained by present flume tests

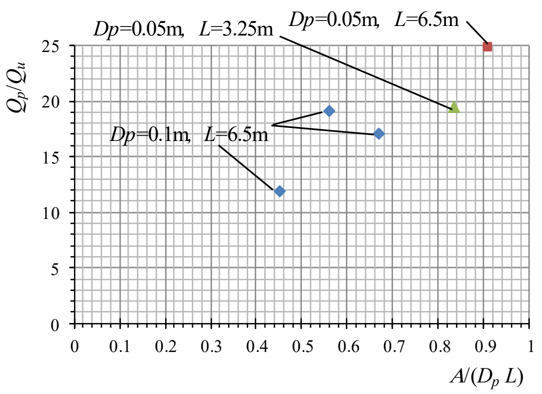

Fig. 7. Relation between relative longitudinal volume and relative peak discharge of debris flow

discharge can be estimated experimentally, in case that saturated bed sediment is transported perfectly to downstream, when bed slope is over θ_* of bed slope for $c= c_*$ (17 to 18 degrees in bed slope). Present results emphasize that peak and temporal shape of debris flows can be determined using some methods such as numerical simulation from the section that $c= c_*$ (17 to 18 degrees in bed slope), if the specific shape of debris flow is uniquely determined in the region between $c= c_*$ and $c< c_*$ through present data and future experimental data collections.

4. Conclusions

In present flume tests, peak discharge rate of debris flow over steep slope channel that is over θ_* of bed slope is experimentally discussed and those are summarized as follows.

(1) Peak discharge of debris flow, Q_p, can be estimated using total volume of a debris-flow surge, V, in dimensional analysis, under the condition that bed slope is around over 17 to 18 degrees and bed sediment is fully saturated. The peak discharge is proportional to the power of 5/6 for total volume of a debris flow, V. The relation is confirmed using present experimental data.

(2) Longitudinal shape of debris flow over the bed in case of $c= c_*$ is triangle and the debris mass increases with longitudinal similarity shape. The results support the previous report (Ou et al., 1993).

(3) Peak value and temporal changes of debris flow are discussed experimentally in the region between $c= c_*$ and $c < c_*$ in sediment concentration, c, because the peak value cannot be evaluated by theoretical consideration (e.g., Takahashi, 1991) in case of $c= c_*$. Those quantities can be evaluated using longitudinal shape of debris mass and potential volume of bed sediment.

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