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Examining the impact force of debris flow in a check dam from small-flume experiments

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Abstract

Debris flow is one of the most hazardous disasters in mountain regions of Korea. Rainfall-induced debris flows have occurred more frequently during past decades due to climate changes. Especially, its threat on many lives and properties in urban or suburban areas have increased. To control debris-flow disaster, check dams have been constructed in forest watersheds since 1985. Although check dams that recently constructed in Korea are expected to function as debris-flow barriers, impact force has not been considered during design procedure. For effective structure design regarding debris-flow disaster, estimation of debris-flow impact force is necessary. Meanwhile, it is well known that impact force is closely related to the flow characteristics of debris flow. In this study, small flume experiments were conducted to analyze the influence of flow characteristics to impact force of debris flow. Flume slope, total volume, and viscosity of mixture were selected as experiment variables. As a result, faster flow velocity was observed on steeper channel slope and larger mixture volume condition. In terms of viscosity, sediment-water mixture flowed faster as the viscosity becomes lower. The effect of flume slope on flow velocity was different as the viscosity of mixtures. However, flowing depth was correlated only to total mixture volume. Impact force was positively correlated to flow velocity and flow depth. By comparing various impact force estimation model, the hydrodynamic model has been selected for the best method to appropriately calculate the design impact force for check dams in small forested watersheds.

Keywords: Debris flow; Impact force; Flume experiment; Structure Design

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1. Introduction

Debris flow is one of the most hazardous disaster in a forested mountain area in the Republic of Korea. Most debris-flow disasters that occurred in Korea were induced by severe rainfall (Woo et al., 2014). Due to climate change, debris-flow events have been increased last decades. Especially, the debris-flow hazard in urban areas nearby mountainous regions has become increased (Yoon et al., 2017). To prevent huge damage to lives and properties in an urban area due to these disasters, many debris-flow control structures, such as check dam or erosion control dam, have been implemented.

Structural mitigation is one of the most typical approaches to prevent damages from debris-flow disaster (Hübl et al., 2009). In Korea, more than 11,000 of check dams have been installed since 1985 (KFS, 2017). Recently, these structures are expected to function as debris-flow barriers or breakers that need to endure debris-flow impact force directly. Thus, it is necessary to consider the effect of debris-flow impact force on check dam during designing.

To apply debris-flow impact force to check dam design, appropriate impact force estimation is important. Through several pioneer studies (Hungr et al., 1984; Armanini, 1997; Proske et al., 2011), it is well known that debris-flow impact force is closely related to debris-flow behavior. Based on this relationship, many researchers have conducted flume experiments to develop a model for impact force estimation (Moriguchi et al., 2009; Scheidl et al., 2013), and suggested several models for impact force estimation, such as hydraulic static or dynamic models (Hungr et al., 1984; Armanini, 1997).

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In this study, we conducted small-scale flume experiment to analyze the relationship between flow behavior and corresponding impact force. Flume experiments were conducted with various sets of the sediment composition, slope, and water-sediment mixture volume. With measured flow characteristics and impact force, we derived impact force estimation model that is most appropriate to explain our data.

2. Materials and Methods

2.1. Sediment mixtures

As shown in Table 1, we used various combination of sediment mixture that consisted of gravel, sand, clay, and water. During the preparation of mixtures, we applied four different mixing ratios to analyze the effect of viscosity on flow behavior. Also, we tried to use three different total mixture volume because the volume condition is one of the most effective factors controlling flow depth. The average density of mixtures was 1669.39 kg m^{-3}, and it was not significantly different between experimental conditions.

Table 1. Overview of mean (± standard deviation) sediment mixture properties. “A, B, and C” mean different volume conditions (about 8,400, 11,200, and 14,000 cm^3, respectively), and “A′, B′, C′, and D′” mean different clay contents (about 21%, 25%, 29%, and 32% of total weight, respectively).

Category	Total volume (cm^3)	Total weight (g)	Density (kg m^{-3})	Composition of each material			
				Water (cm^3)	Clay (g)	Sand (g)	Gravel (g)
A-A′	5026.27 ± 91.97	8399.66 ± 1.15	1671.71 ± 30.24	3000	1799.61 ± 0.90	1799.88 ± 0.56	1800.17 ± 0.57
A-B′	5042.95 ± 56.89	8400.15 ± 2.97	1665.93 ± 18.55	3000	2099.82 ± 2.85	2100.23 ± 0.18	1200.09 ± 0.22
A-C′	5016.54 ± 119.68	8400.37 ± 0.78	1675.50 ± 40.46	3000	2400.22 ± 0.74	2400.07 ± 0.15	600.07 ± 0.11
A-D′	5075.64 ± 78.87	8400.55 ± 0.67	1655.47 ± 25.39	3000	2700.45 ± 0.68	2700.10 ± 0.34	0
B-A′	6734.43 ± 63.74	11200.45 ± 0.39	1663.31 ± 15.68	4000	2400.27 ± 0.30	2400.11 ± 0.15	2400.08 ± 0.11
B-B′	6601.20 ± 170.48	11200.37 ± 0.54	1697.87 ± 44.57	4000	2800.22 ± 0.51	2800.09 ± 0.13	1600.07 ± 0.16
B-C′	6598.00 ± 114.05	11199.95 ± 1.74	1697.98 ± 29.12	4000	3200.16 ± 0.79	3200.05 ± 0.89	799.74 ± 0.34
B-D′	6625.76 ± 122.30	11200.69 ± 0.87	1691.05 ± 31.27	4000	3600.37 ± 0.43	3600.32 ± 0.70	0
C-A′	8334.82 ± 116.74	14002.96 ± 3.26	1680.39 ± 23.61	5000	3000.06 ± 1.31	3001.60 ± 1.94	3001.30 ± 1.55
C-B′	8373.84 ± 61.93	14000.39 ± 3.63	1672.01 ± 12.34	5000	3499.75 ± 3.16	3500.59 ± 0.69	2000.05 ± 1.16
C-C′	8384.82 ± 148.30	13999.29 ± 3.58	1670.12 ± 29.59	5000	3997.64 ± 3.40	4001.12 ± 1.72	1000.52 ± 1.12
C-D′	8557.15 ± 246.76	13996.97 ± 21.82	1637.04 ± 49.59	5000	4499.57 ± 9.77	4497.40 ± 19.69	0

2.2. Small-scale flume experiment

The flume apparatus used in this study (Fig.1) was 2.4 m in length including 0.4 m of sediment storage. The cross section was 0.2 m in width and 0.3 m in height. Although the slope of this flume can be changed from 20˚ to 40˚ manually, we applied four slope conditions: 25˚, 30˚, 35˚, and 40˚. Between slope conditions, 35˚ and 40˚ of channel slope seem to be steep than general slope observed at channelized debris flow. However, initial part of debris flow in Korea is generally steeper than 30˚ and reach 40˚ in some case. Thus, we included those gradients of channel in experiments. In terms of measuring devices, we used two video cameras; one was installed in front of the flume to measure flow velocity, and the other was implemented beside the flume to measure flow depth. To measure the impact force of simulated debris flow, the load cell (MNC-100L, CAS), which is connected to data logger (CI-201A, CAS), was installed 0.1 m backside from the outlet.

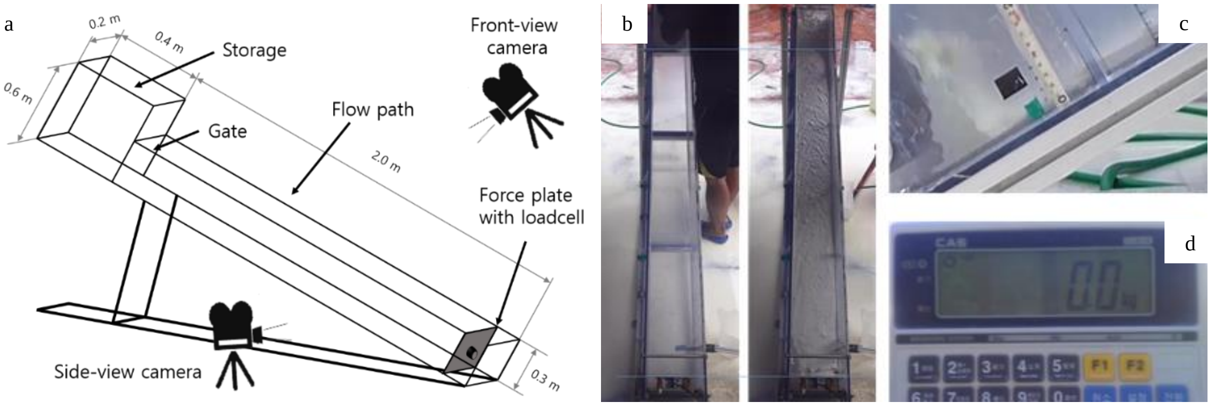

Fig. 1. (a) Experimental flume and setting up of measuring instrument, and examples of actual experiments: (b) an image from the frontal camera for flow velocity, (c) an image from the side camera for flow depth, and (d) an image of the data logger.

2.3. Experimental procedure

In each experiment, the sediment-water mixture is preliminary mixed using a mixer drill, total volume and weight of which are measured in that time. Then, the mixture was pulled in the storage, and kept being mixed just before opening the gate to minimize deposition of sediments. After the mixture prepared, the gate is opened immediately, and flow behavior (average velocity and flow depth) and impact force are measured. While conducting total sets of experiments, we carried out five replications in every combination of sediment mixture and the slope condition. After finishing experiments, flow velocity and depth were accurately calculated by analyzing the video images. By comparing each experimental condition with corresponding flow behavior, the effect of mixing ratio, total volume, and slope on flow characteristics were examined. To analyze the relationship between impact force and flow behavior, we synchronized the change of impact force and flow behavior. Then, we statistically analyzed maximum impact force, which is the maximum logged value in the data logger, and flow behavior at the time.

3. Results and Discussion

3.1. Flow behavior

As a result, flow velocity increased when the inclination of the flume increased, or the clay contents decreased (Fig. 2a). Especially, flow velocity of sediment mixture that has lower clay contents increased more drastically. Also, the effect of volume on velocity was significant; the larger mixture volume showed faster flow velocity (Fig.2b).

Higher clay contents induced stronger shear stress in the flow body, so the flow velocity tends to decrease in same slope condition. On the other hands, in steep slope condition, the difference of velocity between sediments mixture is much smaller. Assuming that simulated debris flow in this study as Bingham fluid or Herschel-Bulkley fluid (Takahashi, 2014), it seems that the acceleration of flow body is large enough to ignore yield strength of viscous debris flow. In terms of volume, the larger volume means greater acceleration, so debris flow can move to downward much faster.

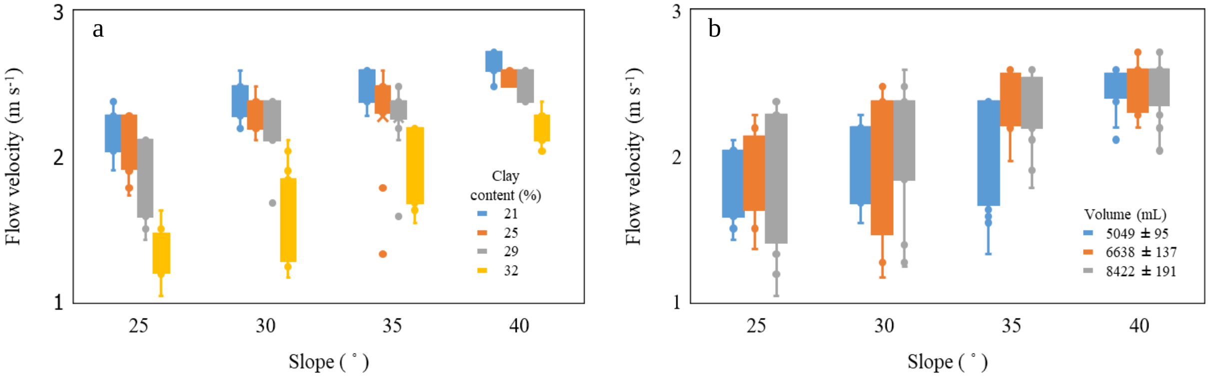

Fig. 2. The change of flow velocity according to (a) clay contents, and (b) mixture volume, as slope condition change

Flow depth was significantly correlated with mixture volume while there was no change of flow depth along slope condition (Fig. 3a). It can be interpreted that the initial volume of mixture affects flow depth dominantly than other factors. Although clay contents seemed to affect flow depth, it was not significantly different between mixture volumes (Fig. 3b).

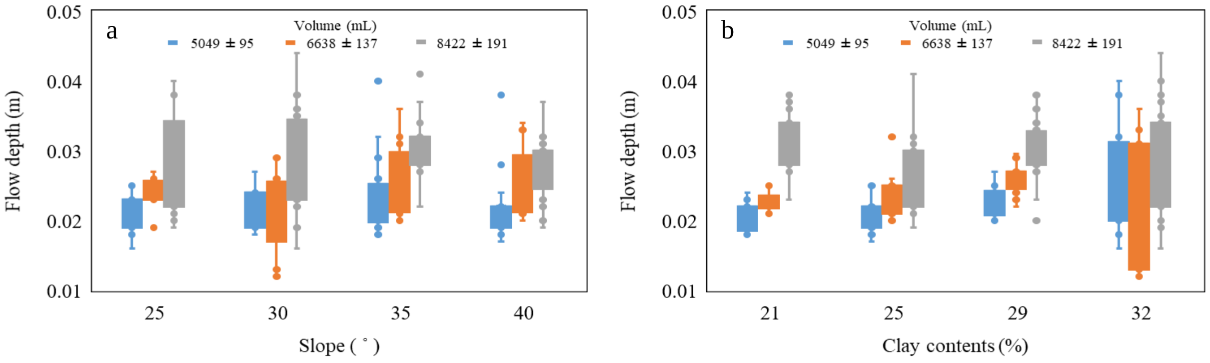

Fig. 3. The change of flow depth according to (a) flume slope, and (b) clay content, as total mixture volume change

3.2. Impact force estimation

Fig. 4 shows the analysis result of the relationship between impact force and flow velocity. Flow velocity is positively correlated to impact force, and the relationship between flow depth and impact force was also significant. With flow velocity and flow depth from flume experiments, the impact force of debris flow is well explained by hydrodynamic model (Scheidl et al., 2013). The general form of hydrodynamic model is as the following equation,

$$p_{peak} = a\rho v^2 hw \tag{1}$$

where p_{peak} is the maximum impact force (kN); ρ is the density of sediment-water mixture (kg m^{-3}); v is the flow velocity (m s^{-1}); h is the flow depth (m); w is the width of the channel (m); a is dynamic coefficient (dimensionless). Although several properties, such as the density of mixtures, are change in time and space, we used those values measured during the mixture preparation due to difficulty of installation of measuring instruments that can simultaneously measure the change of mixture property, such as density.

In terms of coefficient "a", several researchers have suggested the value of a. According to Proske et al. (2011), previous studies generally have reported this value between 1.0 and 2.5. When calculating coefficient "a" using the results of flume experiment and equation (1), coefficient of this research was 2.07 ± 1.38. Especially, About 68% of calculated “a” were 1-3 in Froude number that ranged from 2 to 6, which is similar to Proske et al. (2011).

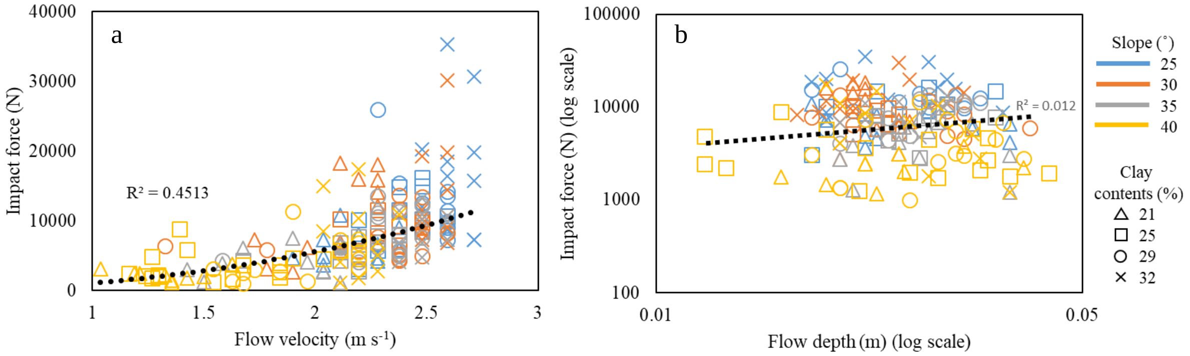

Fig. 4. The relationship between the impact force and the flow behavior; (a) flow velocity; (b) flow depth.

4. Conclusion

In this study, we conducted small-scale flume experiments to understand flow characteristics and impact force of debris flow. The flow characteristics was closely related to slope condition, sediment mixture composition, and total mixture volume. The flow velocity increased as flume slope increased, and sediment viscosity decreased caused by low clay contents. The flow depth becomes deeper in larger volume of mixtures. The impact force of debris flow was positively correlated to both the flow velocity and the flow depth, and it can be well explained by the hydrodynamic model. Using the hydrodynamic model, coefficient “a” was calculated about 2 with Froude number ranging from 2 to 6.

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