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Research Article

Development of Debris Flow Impact Force Models Based on Flume Experiments for Design Criteria of Soil Erosion Control Dam

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Soil erosion control dams are widely used as part of measures to reduce damage caused by debris flow all over the world. Engineering considerations are needed for proper design of erosion control dams, but in the Republic of Korea, the impact force of debris flow is not fully reflected in the current design criteria of the dam. Against this backdrop, this study was conducted to estimate the impact force of debris flow for the practical purpose of designing erosion control dam. Simulated flume experiments were performed to develop the relationship to estimate the flow velocity as well as the impact force of debris flow. Experimental results showed that increases both in sediment mixture volume and flume slope gradient led to an increase in flow velocity. Especially, it was found that as clay content increased gradually, the flume slope gradient had greater impact on the increase of flow velocity. Also, it was proved that the impact force of debris flow was well fitted to the hydrodynamic model as it showed linear correlation with the flow velocity. Then, the debris-flow velocity model was established based on the factor related to the debris-flow velocity. Finally, the dynamic model to estimate the impact force of debris flow was introduced utilizing correlations between the established debris-flow velocity model and Froude number. Both models which were developed with using statistically significant watershed characteristics succeeded in explaining the experiment results in a more accurate way compared to existing models. Therefore, it is highly expected that these models can be fully utilized to estimate impact force of debris flow which will be required to design erosion control dams in practical use through overcoming their identified limitations.

1. Introduction

Debris flow refers to a geological phenomenon in which mixture of sediment and water consisting of various soil particles ranging from fine clay to large boulder rushes down a mountainside at high velocity [1]. While debris flow occurs from various causes generally, particularly, in South Korea, localized heavy rain in summer is the main reason for debris flow [2]. In most cases, landslide-induced sediment at hillside becomes debris flow as it flows into a mountain stream. Such debris flow was rarely found in South Korea until the 1980s when the government almost completed reforestation. However, since 2000, its occurrence has been on the gradual increase to become the type of sediment-related disaster inflicting the biggest damage. The average landslide-damaged area was 715 ha per year in 2000s while it was 313 ha per year during 1981–1999 [3]. Recently, debris flow that killed tens of people and caused hundreds of property damage occurred at Mt. Umyeon in Seoul, the capital city of South Korea, in July 2011. It is the first sediment-related disaster in South Korea which occurred and brought massive damage to the center of the urbanized area. Since the devastating landslide occurred in the city, the paradigm shift was introduced in the formulation of land disaster policy focused on from "mountain area" to "sphere of daily life."

The most common countermeasures against debris flow include structure measure, nonstructure measure, and watershed management. The method of employing soil erosion control dam (ECD) is to block debris flow directly with structure. It is the most applicable as well as effective in urban areas with high population density and intensive land use. To perform the function of ECDs as debris-flow barriers or breaker structures in urban area, dynamic features of debris flow shall be considered in the design of structures. In nations such as Japan and Austria, a number of debris barriers have been constructed to block debris flow directly under the design criteria considering the impact force of debris flow.

Generally, it is difficult to quantitatively measure the impact force of debris flow at the field. Therefore, modeling approach has been employed to calculate the force which utilizes the dynamics of flow characteristics of debris flow and impact force [4–7]. The hydrodynamic model is applied and used well in practical use because it can provide the clear and explicit understanding on the physical phenomenon of "impact" with physical factors such as density and flow velocity of debris flow [8–10]. In order to utilize the hydrodynamic model to estimate the impact force of debris flow, it is most important to estimate the debris-flow velocity. Various methods have been applied so far from simple empirical model to precise numerical analysis. Despite high accuracy of numerical analysis models, it is not used widely for both challenges in practice: (i) it is difficult to attain the parameter at the field and (ii) observed data to verify the results are insufficient. For these reasons, a simple empirical model has been commonly used to estimate the flow velocity of debris flow.

In the past, the focus had been placed on the "soil conservation" to restore degraded mountainous areas rather than "disaster prevention" to protect against debris flow directly when ECDs were constructed. Thus, except for static characteristics of sediment pressure and water pressure, dynamic characteristics such as impact force of debris flow were not fully considered in the design of ECDs. Therefore, it is urgent and necessary to establish the estimation of impact force of debris flow applicable to the situation of South Korea and design standard for construction of ECD. The size of debris flow in South Korea is relatively small when compared to that of Australia and Japan with a high frequency of debris flow. Moreover, the construction budget including design per each unit—250 million Korean Won (≈200 thousand USD) per unit—is cheaper. For these reasons, the impact force of debris flow shall be calculated with the cost-effective way.

From this point of view, the current study was conducted to suggest that impact force of debris flow be incorporated in designing ECDs. As part of this effort, it was intended not only to estimate the flow velocity of debris flow by using design factors of debris barrier or watershed characteristics but also to develop a model to calculate the impact force based on the flow velocity. We tried to clearly identify the relations between two factors, flow velocity and impact force, by conducting debris-flow flume experiments, and to derive the models to estimate flow velocity and impact force of debris flow, respectively.

2. Materials and Methods

2.1. Experimental Flume. Small-sized flume (Figure 1) employed for the debris-flow experiment was made of transparent polycarbonate (PC), and it has $0.2\,\mathrm{m} \times 0.3\,\mathrm{m}$ rectangular section whose total length is 2.0 m. The upper part of the flow path is linked with sediment mixture storage tank whose capacity is $0.48\,\mathrm{m}^3$ equipped with manually operated movable gate. Force plate with load cell is attached to the bottom of the flow path to measure the impact force of a sediment mixture. The gradient of the flume is adjustable manually by 5° interval within ranges from 20° to 40°.

2.2. Sediment Mixture of Experiment. To simulate the key feature of debris flow in flume experiment, various mixed sets of clay, sand, and gravel combined with water were employed. The result of field investigation around watersheds of Mt. Umyeon where debris flow event occurred in 2011 was reflected to decide the composition of sediment mixture. SMG [11] indicates that the largest diameter size of boulders found in the debris flow was 1.5–2.0 m. The diameter of gravel, representative of large particle, was set as 5 mm in average based on the length ratio of experiment flume and the real debris flow, 1 : 300. It was reported that both silt and clay accounted for about 50% of the total particle composition of colluvium layers in the site [11]. However, the ratio of sand and clay was set as 1 to 1, the same ratio of the field, while it was hard to satisfy dynamic similarity if considering the length ratio of 1 : 300.

After considering particle composition of sediment mixture, we chose two factors of "total volume" and "viscosity" among various characteristics of sediment mixtures that could affect to flow velocity and flow depth. A total of nine types of sediment mixture were provided by classifying each factor (total volume and viscosity) into three levels, respectively (Table 1). Specifically, the volume of sediment mixture was classified into three sizes—small (indexing "S," $5.03 \times 10^{-3}\,\mathrm{m}^3$), medium (indexing "M," $6.65 \times 10^{-3}\,\mathrm{m}^3$), and large (indexing "L," $8.35 \times 10^{-3}\,\mathrm{m}^3$). As for viscosity, clay content was divided into 21% (A), 25% (B), and 29% (C) of the total weight of sediment mixture. Except for both factors, the density of $1{,}676\,\mathrm{kg{\cdot}m^{-3}}$ and gravitational water contents of 0.36 of sediment mixture were fixed to the same value in each set of sediment mixture.

2.3. Experimental Condition and Result Analysis. For measurement of flow velocity and impact force of sediment mixtures, flume experiments were repeated three times for every nine types of sediment mixtures with different volumes and clay contents under three conditions of flume gradients, 25°, 30°, and 35°. Whenever we implemented experiments, water and soil of the sediment mixture were fully mixed before it was put into the storage of the flume. Afterwards, they were continuously stirred even just before the storage gate opened to minimize separation. And then, the storage gate was opened to discharge the sediment mixture. The video camera was installed to capture how sediment mixtures were flowing, and the impact force was measured when the sediment mixture reached the plate attached with the load cell at the bottom of the flow path.

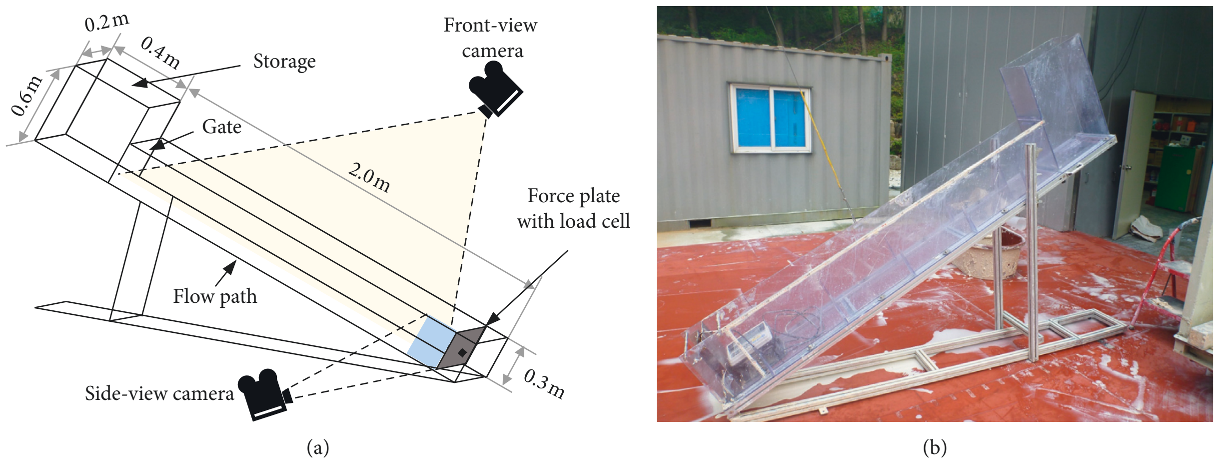

FIGURE 1: Schematic design (a) and photograph (b) of experimental flume and measuring instrument.

TABLE 1: Overview of mean (±the standard error of the mean) sediment mixture properties.

Volume index	Viscosity index	Total volume (10^{-3} m^3)	Weight (kg)	Density (kg m^{-3})	Clay (kg)	Sand (kg)	Gravel (kg)	Water (10^{-3} m^3)
	A	5.02 ± 0.03	8.40 ± 0.03	1672.38 ± 0.03	1.80 ± 0.03	1.80 ± 0.03	1.80 ± 0.03	3.00
S	B	5.04 ± 0.02	8.40 ± 0.02	1667.67 ± 0.02	2.10 ± 0.02	2.10 ± 0.02	1.20 ± 0.02	3.00
	C	5.04 ± 0.03	8.40 ± 0.03	1668.35 ± 0.03	2.40 ± 0.03	2.40 ± 0.03	0.60 ± 0.03	3.00
	A	6.74 ± 0.03	11.20 ± 0.03	1661.37 ± 0.03	2.40 ± 0.03	2.40 ± 0.03	2.40 ± 0.03	4.00
M	B	6.59 ± 0.07	11.20 ± 0.07	1701.43 ± 0.07	2.80 ± 0.07	2.80 ± 0.07	1.60 ± 0.07	4.00
	C	6.61 ± 0.04	11.20 ± 0.04	1694.24 ± 0.04	3.20 ± 0.04	3.20 ± 0.04	0.80 ± 0.04	4.00
	A	8.34 ± 0.02	14.00 ± 0.02	1679.52 ± 0.02	3.00 ± 0.02	3.00 ± 0.02	3.00 ± 0.02	5.00
L	B	8.37 ± 0.02	14.00 ± 0.02	1672.15 ± 0.02	3.50 ± 0.02	3.50 ± 0.02	2.00 ± 0.02	5.00
	C	8.36 ± 0.04	14.00 ± 0.04	1675.18 ± 0.04	4.00 ± 0.04	4.00 ± 0.04	1.00 ± 0.04	5.00

"S, M, and L" mean different volume conditions (about 5.03×10^{-3} m^3, 6.64×10^{-3} m^3, and 8.35×10^{-3} m^3, respectively) and "A, B, and C" mean different clay contents (about 21%, 25%, and 29% of total weight, respectively).

Flow characteristics of the sediment mixtures were obtained by using an image analysis method with two cameras (30 fps). The flow velocity was analyzed from the front-view camera image while the flow depth was estimated from the side-view camera image. As the flow velocity, we used velocity of the snout of the sediment mixture just before its impact to the force plate of the flume. Also, maximum depth of the snout of the sediment mixture at 0.1 m away from the force plate was used as flow depth. Load cell (Model MN-100L by CAS) and data logger of 80 Hz sampling frequency (Model CI-201A by CAS) were used to measure the impact force of the flow.

The experiment results, such as relationships among flow velocity, flow depth, and impact force of sediment mixture, were statistically analyzed to propose relevant models. Statistical analysis on the correlation of flow velocity, impact force, and experimental parameters such as volume and clay contents of sediment mixture and flume slope gradient was conducted by utilizing three-way ANOVA. Furthermore, model parameters for debris-flow impact force model were induced based on the experiment results, and regression analysis was employed to identify the relationship between the coefficient of the model and Froude number (Fr) that represented the flow characteristics. R software ver. 3.3.2 was utilized for such statistical analysis and introducing the model.

3. Results and Discussion

3.1. Results of Flume Experiments

3.1.1. Consideration of Similarity. We compared Froude numbers between flume experiment and real debris flow events in the previous studies to review reproducibility of the debris flow. The results of flume experiments in the current study showed the Fr of 2.3–9.1. It is hard to compare Fr of the Mt. Umyeon debris flow event in 2011 as we have no measured flow velocity. Fr of debris flow generally ranges from 0 to 3 in the gentle gradient of less than 25° [6, 12]. Exceptionally, it was also reported that it ranged from 5 to 7 in some case [5, 12]. In small-scaled flume experiments [12, 13] which were assessed to reproduce the phenomenon of debris flow, Fr ranged from 1.2 to 12. In conclusion, it displays a tendency that the Fr range in the flume experiment is in accordance with previous studies. Therefore, it can be concluded that the current study reproduced the debris flow.

3.1.2. Variations of Flow Characteristics and Impact Force under Experimental Conditions. As shown in Figure 2, the results indicated that the flow velocity of sediment mixture tended to increase when the flume gradient and volume of

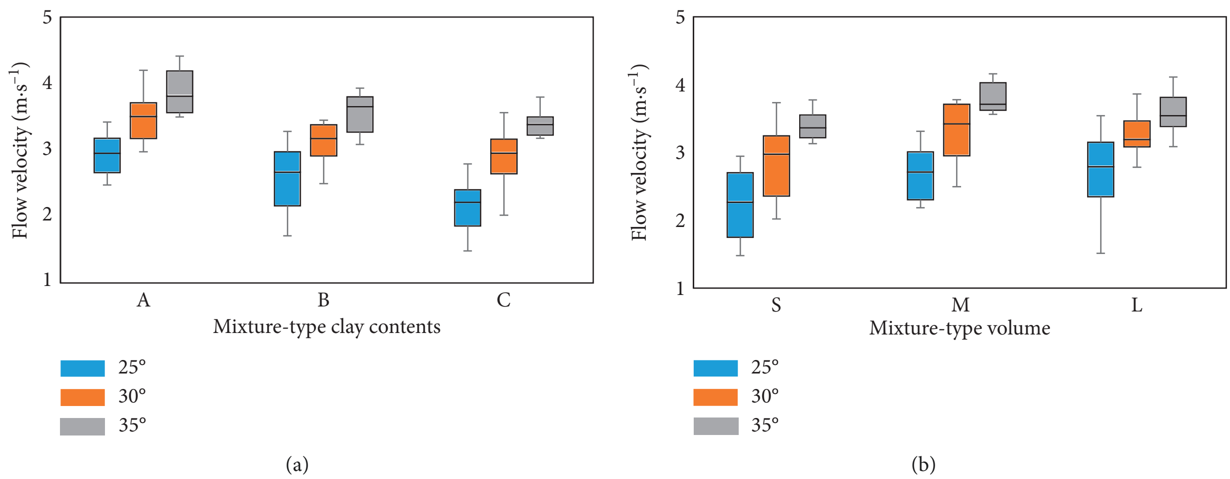

Figure 2: The change of flow velocity according to clay contents (a) and mixture volume (b) as slope condition changes.

the mixture increased while clay content decreased (Table 2). Especially, it showed that the higher the clay content was, the greater impact the flume gradient had on the increase of velocity of sediment mixture. While an increase of flume gradient or volume enhanced gravity force to make flow velocity faster, it was proved that energy loss caused by internal shear friction originated from increased clay content led to flow velocity reduction [14, 15].

It was found that the flow depth of sediment mixture was statistically related to the volume ($r = 0.53$, p value < 0.01) despite a statistically weak correlation between the flume slope and the clay content (Figure 3). Generally, a correlation between total volume and flow depth of debris flow is well known [16], but it is assumed that such a weak correlation among flow depth of sediment mixture, clay content, and flume slope might be affected by several factors such as measurement errors due to video camera performance and status of mixture which was not fully mixed.

The experiment results showed that flume gradient, volume, and clay content of sediment mixture were statistically significant with the impact force of sediment mixture with the significance level of 99% (ANOVA). Meanwhile, it appeared to be an interaction between the flume gradient and clay content (p value < 0.01). Considering the relation between flow velocity and impact force expressed as a hydrodynamic model, it seems to reflect that the increase rate of flow velocity with increasing slope tended to vary depending on the clay content.

3.1.3. Relationship between Flow Characteristics and Impact Force of Sediment Mixture. Figure 4 shows flow velocity and flow depth of sediment mixture with impact force, respectively. According to Figure 4, while flow velocity was in the linear correlations with impact force, linear correlations between the flow depth and impact force was weak.

In previous studies [6, 12], a hydrodynamic model indicates that there is a linear correlation between the square of flow velocity and impact force of debris flow, but the results showed that impact force had a close linear correlation with flow velocity as the exponent of flow velocity in the experiment is close to one. It is because the coefficient of a hydrodynamic model exhibits the linear correlations with Fr^{-1} [12]. Because Fr^{-1} is dimensionless coefficient that is proportional to flow velocity, impact force shows the linear correlations with flow velocity by multiplying Fr^{-1} and square of flow velocity in the case where it is expressed only as flow velocity as shown in Figure 4(a).

Table 2: The result of ANOVA of the flow velocity and experimental variables.

	Degree of freedom	F value	p value ($>F$)
MR	2	25.49	<0.01
V	2	17.63	<0.01
S	2	80.42	<0.01
MR ∗ V	4	1.04	0.39
MR ∗ S	4	1.06	0.38
V ∗ S	4	1.71	0.16
MR ∗ V ∗ S	8	0.62	0.75
Residual	75		

"MR" is mixing ratio, "V" is volume, and "S" is channel slope.

3.2. Estimation of the Debris-Flow Velocity Model. Most existing debris-flow velocity models were expressed as the function of channel slope and flow quantity that is represented as flow depth [5, 14] or instant discharge [16]. Meanwhile, flow depth or instant discharge are closely correlated with total sediment discharge [10, 16], and the results of flume experiments also showed the similar relationship between flow depth and total volume of mixture. Considering this correlation, the current study built the function of flume gradient and volume of water-sediment mixture to estimate the velocity of debris flow based on the results of the flume experiments. The experiment results indicated that changes in the debris-flow velocity at certain flume gradient were affected by clay content, "viscosity." Based on the results, a power function of the viscosity of sediment mixture was set as an exponent of flume gradient. The following equation to estimate the velocity of debris flow was established:

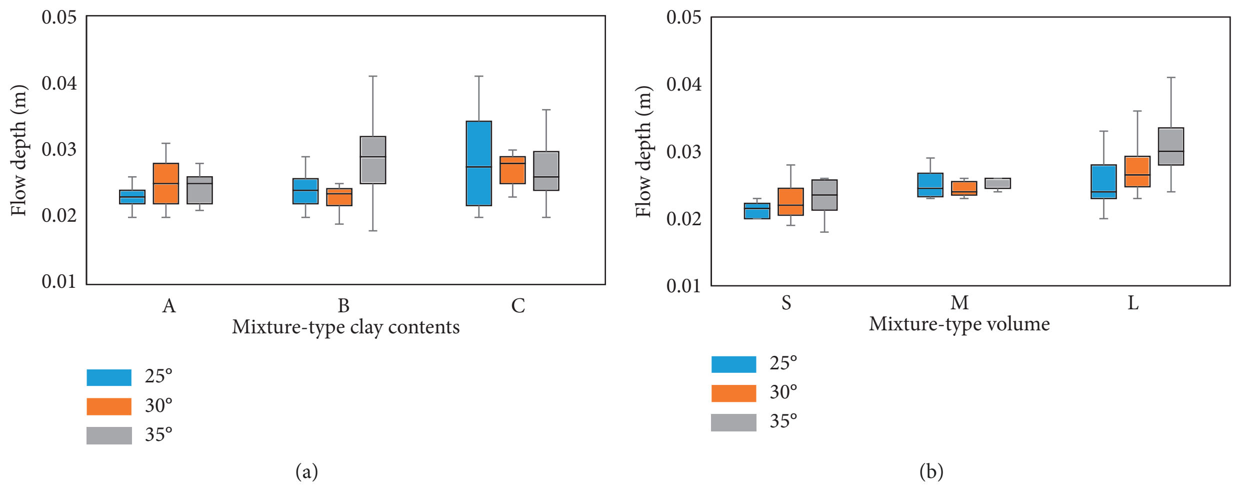

FIGURE 3: The change of flow depth according to clay contents (a) and mixture volume (b) as slope condition changes.

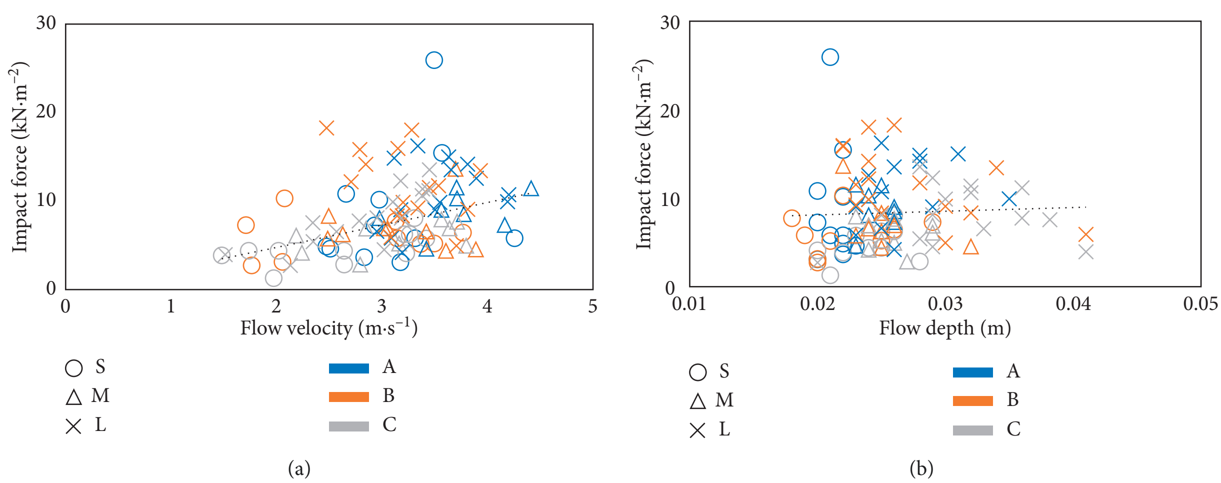

FIGURE 4: The relationship between impact force and flow behavior. The horizontal axis is flow velocity (a) and flow depth (b). Circle, triangle, and cross symbols mean "S, M, and L" of volume condition. Blue, orange, and gray colors mean "A, B, and C" of viscosity condition.

$$v = C_e S^{\alpha Cr^{\beta}} V^{\gamma}, \tag{1}$$

where v represented the velocity of debris flow (m·s^{-1}), S is the gradient of the flume (m·m^{-1}), Cr is the viscosity factor, V is the volume of sediment mixture (m^3), and C_e, α, β, and γ are all constants. It follows how the values of constants α, β, γ, and C_e were calculated step by step.

(i) Volume constant γ: volume constant γ at clay content of A, B, and C by each flume gradient was calculated to 0.1966 (p value < 0.01), 0.3936 (p value < 0.01), and 0.3484 (p value < 0.05), respectively. If the dimensions of both sides of equation (1) are different due to flow depth or exponent constant of the volume, the constant C_e is to have dimension L to offset this. As indicated in Rickenmann [16] and Eu and Im [14], if we use the constant whose dimension is L, it is hard to explain debris flow in reality because of the scale problem. Therefore, in the current study, we assumed γ as a dimensionless value, that is, 0.33 (≈1/3), for better applicability at the site.

(ii) Empirical constant C_e: Because γ was determined, both side of equation (1) were divided by $V^{1/3}$, and it is expressed as equation (2). Then, to determine C_e, we conducted the regression analysis of power model. Meanwhile, it was hard to calculate C_e using simple power model regression since the exponent of S also expressed as a power function form which has α and β as unknown. Thus, to minimize unknown, the power model regression was derived in clay content A, B, and C, separately; it was expressed as equation (3)–(5), respectively. As the result C_e in equation (3)–(5) showed very small variation, we estimated the value of C_e as the average value of 25.91 from equation (3)–(5).

$$\text{Base: } \frac{v}{V^{1/3}} = C_e S^b, \quad (2)$$

$$\text{Case (A): } \frac{v}{V^{1/3}} = 25.60\, S^{0.63}, \quad R^2 = 0.5759,\ p\,\text{value} < 0.01, \quad (3)$$

$$\text{Case (B): } \frac{v}{V^{1/3}} = 25.52\, S^{0.86}, \quad R^2 = 0.5394,\ p\,\text{value} < 0.01, \quad (4)$$

$$\text{Case (C): } \frac{v}{V^{1/3}} = 26.62\, S^{1.12}, \quad R^2 = 0.5555,\ p\,\text{value} < 0.01. \quad (5)$$

(iii) α and β: equation (6) was produced when applying the logarithm (ln) to both sides of the equation and leaving b in the right hand. Here, b was according to equation (1):

$$\frac{\ln\left(v/V^{1/3}\right) - \ln C_e}{\ln S} = b = \alpha Cr^{\beta}. \quad (6)$$

To obtain values of α and β, we substituted values of flume experiment results to equation (6). As for viscosity index, we applied the universal value of water-to-clay ratio that had been utilized in Jeong [17] instead of clay content in soil which exhibited greater variability. In the study of Jeong [17], the liquidity index (LI) was utilized to assess the viscosity of debris flow. Atterberg limits were evaluated as the amount of fine particles less than 425 microns, which corresponded to clay in the sediment mixture employed in the current study. Therefore, it was reasonable to apply water-to-clay ratio as in equation (6) when considering the correlation with Atterberg limits. We assumed equation (6) as regression equation of power function, and the results on the value of constant α and β were produced as $\alpha = 1.54$ (p value < 0.01) and $\beta = -1.76$ (p value < 0.01). Finally, equation (7) was produced after substituting the constant value of γ, C_e, α, and β, which had been derived from (i) to (iii):

$$v = 25.91\, S^{1.54 Cr^{-1.76}} V^{0.33}. \quad (7)$$

Equation (7) was the debris-flow velocity model derived by using the experimental result in the current study. Comparing the derived model and existing models [14, 16] with using the experimental result, Table 3 showed that coefficient of variance (CV) and root mean square error (RMSE) of the derived model were the smallest. The reason was assumed that CV of C_e value in equation (7) was small enough to be less affected by scale than other models. C_e has T^{-1} dimension, the same dimension with shear rate closely related to shearing stress of fluid. The shear stress is affected by the viscosity of fluid and surface roughness of stream bed. Especially, C_e cannot fully reflect roughness conditions of stream bed of debris flow in reality because smooth flume bed without certain treatment to adjust roughness was utilized in the experiments. Therefore, more precise C_e value can be introduced if the shear stress model considering the roughness of stream bed is utilized to estimate it.

3.3. Estimation of Debris-Flow Impact Force Model. The model to calculate the flow velocity of debris flow was assumed as equation (7), and we also tried to introduce the hydrodynamic model, equation (8), to calculate the impact force of debris flow based on equation (7):

$$p_{\text{peak}} = a\rho v^2, \quad (8)$$

where p_{peak} represents the impact force of debris flow, a is a coefficient, ρ is the density (unit weight) of debris flow, and v is the velocity of debris flow. Various studies [12, 20, 21] indicated that a in equation (8) and Fr have power function relationships. By utilizing results of the debris-flow flume experiment and the observed debris flow event [12], correlations between coefficient a and Fr can be estimated as Figure 5 and equation (9). Especially, equation (9) is similar to relation of a and Fr ($a = 4.5\text{Fr}^{-1.2}$), which were estimated by the wide range of Fr of 1.2 to 12 suggested by the previous study [13] with small-sized flume experiment. After considering related precedent studies, we can reach the conclusion that the relation between a and Fr in the current study produced a general result which can be applied to wide range of Fr.

$$a = 4.77\text{Fr}^{-1.27}, \quad R^2 = 0.6648,\ p\,\text{value} < 0.01. \quad (9)$$

Finally, estimation of the debris-flow impact force model after combining equations (7)–(9) is concluded as

$$p_{\text{peak}} = 3.20\text{Fr}^{-1.27} \rho S^{3.09 Cr^{-1.76}} V^{0.67} \ (\text{unit: kPa}). \quad (10)$$

Components of equation (10), sediment discharge, content of fine particles in soil, and flume gradient, are closely related with necessary components for designing an ECD. Conducting field survey for designing ECD in South Korea includes topography investigation, soil investigation, and estimation of sediment discharge. Therefore, it was assumed that no additional expense would be required except the field survey cost if equation (10) was employed. Moreover, equation (10) also considers fine soil particle into the calculation of the impact force of debris flow. Recently, several studies indicated the possibility that fine soil particles can be fluidized caused by phase shift, which can lead to an increase in density and flow regime changes of debris flow accordingly [22, 23]. These recent findings were well reflected into equation (10).

However, there are limitations which shall be resolved to estimate impact force of debris flow by utilizing equation (10) to reflect it in designing ECDs in practice. First, the estimation method for moisture content in sediment or debris flow shall be considered. Although the moisture content is an important factor to decide density and volume of debris flow and flow characteristics, it is hard to accurately estimate the moisture content when real debris flow occurs in the field. Furthermore, there is also uncertainty as "sediment discharge volume," representative of "volume V" in the current study, is utilized as an input variable. Because debris flow undergoes

Table 3: Summary of the result of the comparison of velocity estimation models.

	Formula	Coefficient Notation (unit)	Coefficient Value (mean ± standard error)	RMSE	CV	Reference
Newtonian laminar flow	$v = (1/3)(\rho g/\mu)H^2 S$	μ ($kg \cdot m^{-1} \cdot s^{-2}$)	0.73 ± 0.03	1.32	0.50	[5]
Dilatant flow	$v = (2/3)\xi H^{3/2} S^{1/2}$	ξ ($m^{-1/2} \cdot s^{-1}$)	2044.80 ± 58.08	1.14	0.29	[5, 18]
Newtonian turbulent flow	$v = (1/n)H^{2/3} S^{1/2}$	n ($m^{-1/3} \cdot s$)	0.0221 ± 0.0006	0.62	0.26	[5, 19]
Voellmy flow	$v = C_1 H^{1/2} S^{1/2}$	C_1 ($m^{-1/2} \cdot s^{-1}$)	25.57 ± 0.46	0.56	0.18	[16]
This study	$v = C_e S^{1.54 Cr^{-1.76}} V^{1/3}$	C_e (s^{-1})	25.60 ± 0.31	0.37	0.12	

The value of each coefficient is expressed as “mean ± standard error.” RMSE is the root mean square error and CV means the coefficient of variance.

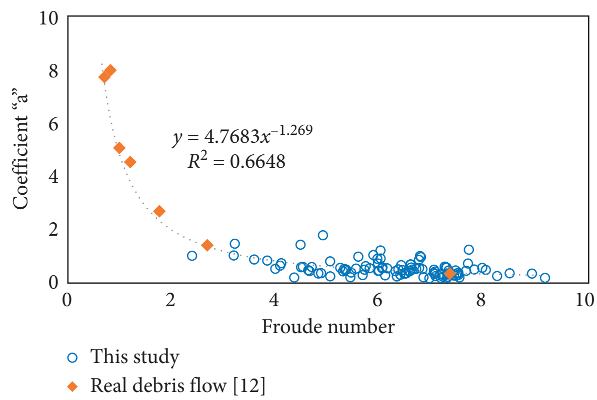

Figure 5: The relationship between the coefficient of hydrodynamic model for impact force and Froude number. Blue circles show the results of this experiment, and orange diamonds represent data of real debris flow [12].

phases of soil erosion and deposition repeatedly in the process of its flowing, it is difficult to identify the precise amount of sediment discharge at a certain point. To overcome these challenges, several studies tried to calculate velocity as well as the impact force of debris flow by utilizing instant flux. However, it was not reflected into the current study due to limitations on experimental equipment. Lastly, the applicability of the developed models to “real” debris flow event was not fully examined in the current study. The debris flow cases of the previous studies [5, 12] did not fully support information of variables required in equation (10), and their flow velocity as well as impact force was also estimated by employing empirical models. The applicability of equation (10) was not fully examined due to these difficulties of field data use. Therefore, field application shall be reviewed after utilizing observed values in large-scale flume experiment or real debris flow cases in the future.

Comprehensively, the model, equation (10), shall be improved and verified by conducting further experiments to be utilized in practice. However, even after such model is improved and verified through additional experiment, it has its own limitations because it is inevitable to assume under which conditions in the field (such as soil moisture content) debris flow will occur. As the suggested models in the current study are expressed in simple empirical formula, they cannot estimate dynamic characteristics of debris flow and its temporal changes of the impact force in detail like numerical models [23, 24]. Despite such challenges, equation (10) is meaningful for following reasons: (i) under few practical assumptions, impact force of debris flow can be easily estimated cost effectively in South Korea in a situation in which related design criteria are insufficient and (ii) the model was developed through flume experiments considering soil and topographic characteristics in South Korea while we had inadequate observation equipment for debris flow in field. In this sense, the current study results can lay the foundation for further related experiments in the future.

4. Conclusions

This study was preliminary work to suggest that impact force of debris flow shall be considered in designing ECDs in South Korea. As part of this effort, the flume experiments were conducted to develop the model to estimate the impact force of debris flow. Correlations among sediment mixture conditions, flow characteristics, and impact force of the experiments were statistically analyzed, and both models to calculate debris-flow velocity and impact force were introduced successively. Especially, we applied characteristics of soil and topography in South Korea into the models as part of efforts to consider regional conditions of the site where debris flow can occur. Besides, we utilized the design factor of ECDs as input variables of the model to estimate the impact force of debris flow for cost efficiency.

In conclusion, in given conditions of South Korea, the developed model can be applicable enough at a practical level even though there are some clear limitations that shall be resolved by conducting further experiments. It is highly expected that this model can be utilized better at the site with some improvements through additional experiments. If we can obtain sufficient filed observation data on debris flow in the future, the model can be much advanced in practice.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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