ORIGINAL ARTICLE

Assessment of dynamic impact force of debris flow in mountain torrent based on characteristics of debris flow

Man-Il Kim[1] · Jae-Hwan Kwak[1] · Byung-Sik Kim[2]

Abstract

Landslides and debris flows that occur around residential areas are considered, globally, as significant disasters that cause damage to human life and property. With terrain slope defining the flow characteristics of debris flows, flow depth, flow velocity, and impact force vary by time and distance. In particular, when a structure is located in the flow path of debris flows, the flow characteristics of debris flows vary by terrain slope and direction angle. To simulate the flow characteristics of these debris flows, the simulation results obtained by FLO-2D were analyzed with six-stage conditions for the research area. In the analysis, the flow depth, flow velocity, and impact force were estimated on the basis of the outlet of the research area in the presence and absence of structure(s) at certain distances. With this, the variation of the impact force in accordance with the variation of the flow depth of the debris flows was highly similar to the simulation results obtained by FLO-2D, when the correction index (α) of the suggested dynamic impact force equation was 0.3–0.4. There were sections where the estimated value of the impact force was overestimated near the outlet, and it was judged that the fixed values of the terrain factors (width, roughness coefficient, slope, etc.) caused the impact force to be overestimated. However, the correlation analysis showed that the correlation index was above the normal ranges in the suggested dynamic impact force equation for debris flows with the application of the terrain factors.

Keywords Debris flow · Impact force · Flow depth · Correlation index (α) · Outlet

Introduction

Global warming causes extreme weather events, such as typhoons, floods, and heavy rainfall, in all parts of the world. In the case of South Korea, where about 68% of its territory is mountainous, extreme weather events, such as heavy rainfall, typhoons, and concentration rainfall in summer, are likely to damage to human life and property caused by sediment disasters such as landslides and debris flows, especially in mountainous regions. In particular, the Mt. Umyeon landslide that occurred in July 2011 formed debris flows and caused great damage to roads and housings. During the same period, a similar sediment disaster occurred in Chuncheon, Gangwon Province, South Korea, and caused some damage to human life. With this, as debris flows continue to occur broadly in residential areas, potential hazards from sediment disasters are magnified (Quan Luna et al. 2011).

A debris flow is a phenomenon in which soil and rocks that are saturated by heavy rainfall or persistent rainy weather cannot support the bottom friction and slide down, mainly occurring where much weathering has proceeded. In particular, debris flows are caused by a combination of factors particular to the area, and result in damage to human life and property in the form of deposition, entrainment, or direct impact (Hu et al. 2011). Impact force is one of the main causes of serious damage on structures in debris flow occurrences (Mizuyama 1979; Hungr et al. 1984; Zhang 1993a, b; Armanini 1997; Shieh et al. 2008; Hübl et al. 2009; Moriguchi et al. 2009); moreover, structures can be easily damaged by debris flows when the former is fundamentally weaker than the impact force of the latter (Moriguchi et al. 2009; Hu et al. 2012; Wendeler and

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Volkwein 2015). Because of this, it is important to have the most accurate estimate of the impact force of debris flows to help prevent or reduce damage to human life and property caused by such phenomena. However, because there is little research with regard to debris flows in South Korea than in overseas countries, South Korea is less prepared for such geological phenomena (Kim et al. 2013). On the other hand, for overseas countries with increasing research on the evaluation of vulnerability and risks of structures based on the prediction of the impact force of debris flows or on simulation results (Bugnion et al. 2011; Pirulli and Pastor 2012; Scheidl et al. 2013; Han et al. 2015), their studies did not give consideration to the effects of structures based on impact force models for debris flows.

There are various ways to measure and evaluate the impact force of debris flows, such as the measurement of the actual impact force of debris flows, large-scale simulation testing, and numerical analyses based on past cases (Okuda et al. 1980; Zhang 1993a, b; DeNatale et al. 1999; König 2006; Wendeler et al. 2007; Bugnion et al. 2011; Hu et al. 2011; Wei et al. 2012). However, actual measurement through a monitoring system or a large-scale test does not consider the effects of structures on debris flows because the frequency of debris flows is inconstant, and there are difficulties in financing, testing methods, and configurations. This explains why FLO-2D, with its ability to take into account the effects of structures on the behavior of debris flows and easily simulate the behavior of debris flows, is the most widely used numerical model in the world among numerical models that can predict debris flow behavior (Julien and O'Brien 1997; Bertolo and Wieczorek 2005; Lin et al. 2005; Četina et al. 2006; Li et al. 2011).

This study analyzed the flow characteristics of debris flows using FLO-2D in the presence and absence of structures at certain distances on the basis of the outlet where the diffusion and deposition of debris flows begin after the debris flows transport through a mountain torrent. For the analysis, an impact force equation for debris flows, which can take into account the impact force varying by structure, was suggested. First, the simulation of the debris flows was performed for six-stage conditions with the locations and number of the structures taken into account on the basis of the outlet. Then, the impact force of the debris flows, which varies by structure, was analyzed. The analysis results were used for the reliability verification of the suggested equation, which is a dynamic model in which the concentration, density, and flow velocity of debris flows are adjusted. It is expected that the results of this study will be used for the evaluation of the vulnerability and risks of structures through the quantitative estimation of the impact force of debris flows.

Research area

In the period of July 14–18, 2006, sediment disasters occurred because of Typhoon Ewiniar and heavy rainfall events in Pyeongchang, Gangwon Province, South Korea. The heavy rainfall events with a maximum precipitation of 540 mm (maximum hourly precipitation of 82 mm) following that period caused massive landslides mainly in the regions of weathered granite residual soil (granite soil), followed by the flow of driftwood and debris into the downstream area. In general, these sediment disasters have caused significant damage to the agricultural land of the mountainous areas as well as to human life, housing, and structures mainly in the downstream areas either by burying and flooding.

The research area in this study includes Berti rimmyeon, Pyeongchang, Gangwon Province, South Korea, where landslides and debris flows occurred in the past, and where residential areas and structures are located in contact with mountainous areas and mountain torrents. This location was classified as an area where landslides and debris flows are more likely to occur on the Landslide Information System provided by the Korea Forest Service, with most of the residential and structure areas classified as first grade. Moreover, there are some mountain torrents in the form of a tributary around the town together with the main stream that joins Bangrimcheon, and direct damage is possible in some of the areas with structures when landslides and debris flows occur. In particular, as the altitude is gradual in the central part of the areas where the mountain torrents in three directions meet, the direct damage of the structures is likely to occur because of the diffusion and deposition of earth and sand when debris flows occur.

The geological composition of the research area is classified as Precambrian rocks and Mesozoic Jurassic rocks (KIGAM 1979), and bedrocks exposed within the mountain torrents are made of Precambrian granite–gneiss. Their main types of rocks are porphyroblastic gneiss, banded gneiss, biotite gneiss, and augen gneiss, and these are known to have been formed by metamorphism (granitization) actions on the Precambrian Bangrim layer distributed in the north–northeastward direction on the right side of the research area. The Bangrim layer was formed earlier than the rocks made of granite–gneiss, and chlorite biotite schist is its main type of rock. There are rocks made of biotite granite distributed in the southern part of the research area, and coarse-grained hornblende biotite granite is their main type of rock. Their intrusion period is known to be sometime during the Mesozoic-Jurassic era.

In this study, a 5×5 m digital elevation model (DEM) was generated for the application to the FLO-2D

simulation using 1:5000 scale digital maps for Pyeongchang, Gangwon Province, South Korea. As seen in Fig. 1, the generated diffusion and deposition of the debris flows were taken into account with a focus on the main stream among the mountain torrents in the research area. Residential structures equal to or larger than 36 m², which is the minimum living space for a family of three, were selected for the structures for the debris flow simulation, and the height of the structures was fixed at 10 m to analyze the variation phases of flow–diffusion–deposition.

Research method

Impact force model for debris flows

Debris flow impact models suggested for the design of engineering structures by Hübl et al. (2009) can be classified into hydraulic and solid collision models. This twofold classification reflects the complexity of debris flow processes, where the impact can either be caused by fluid-phase slurry thrusting or a pointwise loading caused by coarse solid particle collision (Hu et al. 2011). Their research focuses on hydraulic models, which can be separated into hydrostatic and hydrodynamic models.

Lichtenhahn (1973) and Armanini (1997) presented widely used, easily calculated methods for hydrostatic models with the ability to estimate the impact force using height (flow depth) data of the debris flows in an easily calculable without any uncertain values except empirical coefficients.

The hydrostatic impact force equation for debris flows is presented in Eq. (1).

$$p_{\max} = k\rho gh, \tag{1}$$

where $p_{\max}$ is the maximum impact force, k is an empirical coefficient, ρ is the density in accordance with the flow type, g is gravitational acceleration, and h is the height. For the height of a debris flow, the maximum flow depth at the maximum peak discharge can be taken by predicting their scale. According to previous research (Li and Luo 1997; Okuda et al. 1980), the density of debris flows is between 2000 and 2200 kg/m³.

As the empirical coefficient varies by several factors, such as the characteristics of a basin, the features of debris flows, and rainfall characteristics, it can be estimated using the examples of past debris flows. For the range of the empirical coefficient k, 2.8–4.4 was proposed by Lichtenhahn (1973), and 2.5–7.5 was proposed by Scotton and Deganutti (1997).

On the other hand, the dynamic impact force equation for debris flows is presented in Eq. (2).

$$p_{\max} = k\rho V^2, \tag{2}$$

where V is the flow velocity of a debris flow. The empirical coefficient for dynamic models k can be determined in accordance with the flow type of debris flows. For example, 2.0 was proposed by Watanabe and Ikeya (1981) for debris flows mainly composed of laminar flow or fine sand, while 2.0–4.0 was proposed by Egli (2005) for debris flows mainly composed of coarse sand. Zhang (1993a, b) proposed the value of 3–5 through the field investigations of 70 debris
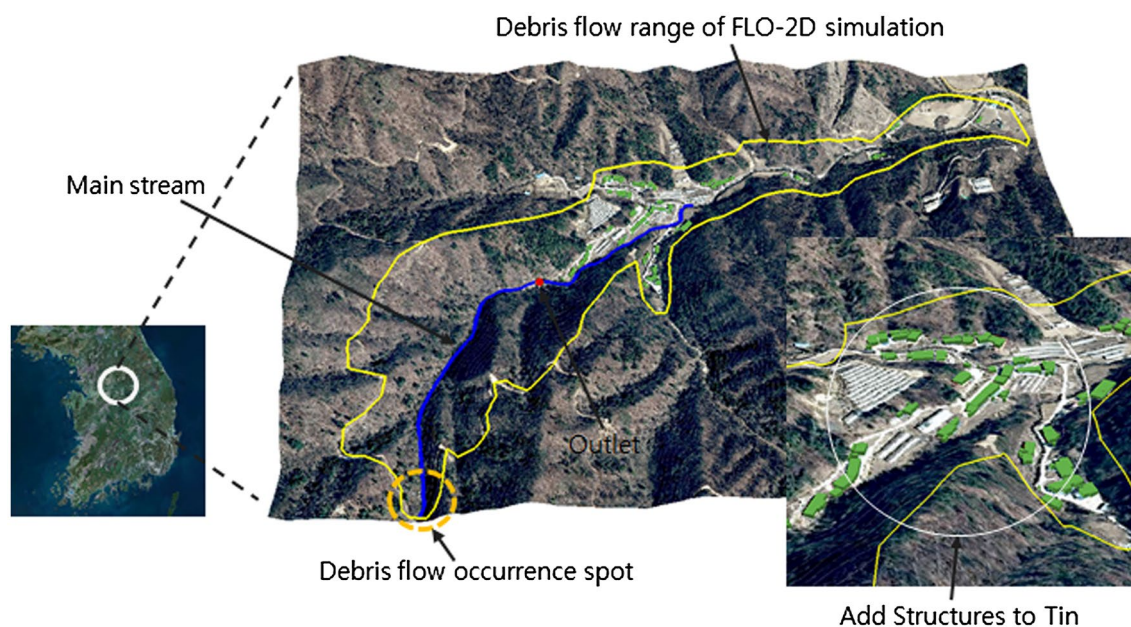

Fig. 1 Addition of structures to tin and setup debris flow range of FLO-2D simulation

flow sites in China. As seen in Eq. (3), The FLO-2D Manual proposes the value of 1.28 or an empirical equation that can estimate it using the weight index for each sediment type of debris flow (C_w means sediment concentration by weight). Table 1 presents the variation of k for each impact force model (Hübl et al. 2009).

$$k = 1.261 e^{C_w} \tag{3}$$

A modified hydrodynamic formula is given by Hübl and Holzinger (2003). They measured impact forces on debris flow barriers, based on miniaturized tests. To achieve a scale-free relationship, they further relate the Froude number (Fr) to normalized impact forces. Based on a correlation analysis, a numerical expression is given as Eq. (4):

$$p_{max} = 5\rho v^{0.8}(gh)^{0.6}. \tag{4}$$

Governing equation for FLO-2D

FLO-2D, a two-dimensional finite difference model, is widely used for its high reliability in modeling and analyzing flood and debris flow; furthermore, it has been certified by the Federal Emergency Management Agency. Its governing equation, which is defined with flows in eight directions on a two-dimensional plane, consists of continuum and momentum equations in each direction. The modeling of debris flows consists of five shear stress components as seen in Eq. (5).

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d, \tag{5}$$

where τ is the total shear stress, τ_c is the shear stress caused by cohesive forces, τ_{mc} is the Mohr–Coulomb shear resistances, τ_v is the viscous shear stress, τ_t is the turbulent flow shear stress, and τ_d is the dispersed shear stress. This can be converted to the secondary flow model and presented as Eq. (6).

$$\tau = \tau_y + \eta \left(\frac{dv}{dy}\right) + C_i \left(\frac{dv}{dy}\right)^2, \tag{6}$$

where τ_y is the yield stress, η is the viscous coefficient, and C_i is the inertial shear stress coefficient. Equation (6) can be arranged as Eq. (7) by integrating Eq. (6) with respect to the flow depth.

$$S_f = S_y + S_v + S_{td} = \frac{\tau_y}{\gamma_m h} + \frac{K\eta V}{8\gamma_m h^2} + \frac{n^2 V^2}{h^{4/3}}, \tag{7}$$

where S_y is the yield slope, S_v is the viscosity slope, S_{td} is the turbulence dispersion slope, τ_y is the yield stress, γ_m is the specific gravity of mixtures, K is the laminar flow drag coefficient, n is the Manning's roughness coefficient, h is the depth, V is the flow velocity, and η is the viscosity. Among them, the yield stress (τ_y) and viscosity (η) can be presented as follows (Eqs. 8, 9, respectively) in accordance with the sediment volume concentration (C_v). α_1, α_2, β_1, and β_2 are empirical coefficients determined by testing and proposed in some of the previous research.

$$\tau_y = \alpha_2 e^{\beta_2 C_v}, \tag{8}$$

$$\eta = \alpha_1 e^{\beta_1 C_v}. \tag{9}$$

Simulation of debris flows

Estimation of discharge

The peak discharge for the simulation of debris flows was obtained using a rational formula for the estimation of discharge, as presented in Eq. (10), which is widely used as a method for the design of water flow discharges because of its simplicity (Chow et al. 1988) and to determine the design of water flow discharges in a mountainous gully or debris flow gully (Berti et al. 1999; Chen et al. 2008; Chen and Chuang 2014). In particular, the formula is useful when the discharge data are not available for the mountain torrents for the area in question.

$$Q = C\,i\,A/360, \tag{10}$$

Table 1 Comparison of different k factors for selected impact models (modified after Hübl et al. 2009)

Hydraulic model	Previous research	k (–)	Notes
Static	Lichtenhahn (1973)	2.8–4.4	Transferred from water density
Static	Armanini (1997)	5.0	–
Static	Scotton and Deganutti (1997)	2.5–7.5	Miniaturized tests
Dynamic	VanDine (1996)	1.5 A	Introduction of area A
Dynamic	Watanabe and Ikeya (1981)	4.0	–
Dynamic	Zhang (1993a, b)	6.0–10.0	Field measurements
Dynamic	Tiberghien et al. (2007)	13.5	Miniaturized test
Dynamic	Wendeler et al. (2007)	1.4–4.0	Miniaturized test on flexible barriers
Dynamic	Bugnion et al. (2011)	0.8–1.6	Real-scale experiments on hillslope debris flows
Modified dynamic	Hübl and Holzinger (2003)	7.5	Transfer caused by exponents
Mixed, static, and dynamic	Kherkheulidze (1969)	1	Mean values

where Q is the peak discharge, C is the runoff coefficient, A is the catchment area, and i is the maximum rainfall intensity. The research area is about 65.7 ha, and 234.7 mm/h, the maximum rainfall intensity with the frequency of 100 years provided by the Korea Precipitation Frequency Data Server (http://k-idf.re.kr) run by the Ministry of Land, Infrastructure, and Transport (MOLIT) of South Korea, was selected as the maximum rainfall intensity. In particular, this study reflected the consequence of a landslide through the simulation of the maximum hourly rainfall equivalent to the rainfall frequency for 100 years or longer that was observed during the landslides at Mt. Umyeon in Seoul on July 2011 and an area in Inje in Gangwon Province, South Korea, in July 2006 (Bang 2013). The value of the runoff coefficient C was selected as 0.4 with the River Design Criteria provided by MOLIT (2009) taken into account.

The representative cases of landslides that occurred in Gangwon-do indicate that the maximum amount of rainfall reached 474 mm for 2 days, and 62 mm for 1 h (Chae et al. 2010). In this study, the simulation duration was set to 4 h, which reflected the landslide cases in Gangwon-do, and the rainfall duration was assumed to be 2 h for the simulation of debris flow. The rainfall input values for the simulation of debris flow tend to increase up to the maximum amount of rainfall and then decrease (Fig. 2).

Determination of input variables for FLO-2D simulation

As analysis results depend largely on input variables in numerical analyses, the appropriate determination of input variables plays an important role in analyzing the behavior of debris flows and their effective ranges. As mentioned above, the basic input variables in FLO-2D consist of the laminar flow drag coefficient (K), Manning's roughness coefficient (n), sediment volume concentration (C_v), inflow,
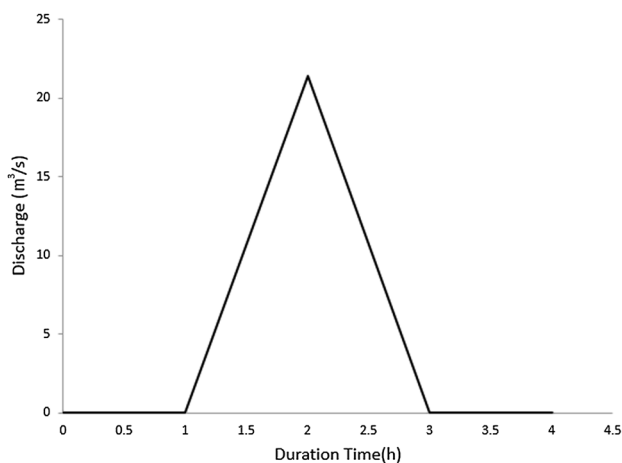
and rheological properties (τ_y: yield stress, η: viscosity), and the area/width reduction factor, which can take into account the effects of structures and barriers, can be considered as well. In this study, for the basic input variables, such as the laminar flow drag coefficient (K), Manning's roughness coefficient (n), and empirical coefficients in relation to the rheological properties (α_1, α_2, β_1, and β_2), their values were appropriately determined.

The values suggested from the FLO-2D reference manual were initially selected. Then, the appropriate values were calculated through the comparison and analysis with the field data. Finally, the input variables were chosen through trial and error. For the Manning's roughness coefficient, which is an important factor in the simulation of debris flow among the input variables, Quan Luna et al. (2011) applied 0.04 m$^{-1/3}$ s to Selvetta Watershed in Valtellina Valley of the Central Italian Alps, where a channelized debris flow occurred. To simulate the debris flow that occurred in Hsiaolin Village in Taiwan in August 2009, Li et al. (2011) applied 0.06 m$^{-1/3}$ s as the value of the roughness coefficient in the cases of hillslope debris flows and 0.045 m$^{-1/3}$ s in the cases of low-concentration flows after sediment inflows reached the river. In this study, 0.04 m$^{-1/3}$ s was selected for the roughness coefficient for the simulation of debris flow based on the literature review and field data. Table 2 presents the input variables determined as above.

Determination of input variables for impact force equation for debris flows

Important factors in estimating the impact forces of debris flows were selected with reference to previous research. According to the Ministry of Land, Infrastructure, Transport, and Tourism of Japan (MLIT 2007), 2600 kg/m^3 was proposed as the density of sediment, 1200 kg/m^3 was proposed as the density of water, while the suitable ranges of the densities of sediment and water for the planning and modeling of disaster-prevention structures are 1800–2600 and 1200 kg/m^3, respectively. Furthermore, according to Jang et al. (2011), the sediment volume concentration of debris flows was 0.38–0.42, and it is reported that mudflow, which is most similar to debris flow, has the most similar

Fig. 2 Hydrological curve of the study

Table 2 Adopted parameters of the FLO-2D simulation

Parameters	Value
Specific gravity (Gs)	2.65
Sediment volume concentration (Cv)	0.4
Laminar-flow drag coefficient (K)	1000
Manning's roughness coefficient (n) (m$^{-1/3}$ s)	0.04
Viscosity (poises)	97.29
Yield stress (dynes/cm^2)	25.26

fluid characteristics to debris flow when its sediment concentration is 0.40–0.45. Therefore, in this study, the impact forces of debris flows were estimated with the density of sediment set at 2600 kg/m^3, the density of water at 1200 kg/m^3, and the sediment volume concentration at 0.4, to apply to general debris flows. The width of the mountain torrents was determined to be 25 m, the average width, and the direction angle was fixed at 45°.

Debris flow simulation design with changes in the structure conditions

The debris flow simulation was performed with six-stage conditions for the locations and number of the structures, and the flow depth, flow velocity, and impact forces of debris flows were compared and analyzed. Grids, showing relatively large values, relevant to the main mountain torrent were extracted and selected as representative values. The debris flow simulation was performed with the constant values of FLO-2D input variables, DEMs, grid sizes, structure sizes for each stage, and the conditions for each stage are presented in Table 3. The debris flow simulation for each stage performed within the research area was analyzed in accordance with the flowchart in Fig. 3.

Research results

Reference data

To compare and analyze the variation of the flow characteristics of debris flows, the debris flow simulation without any structure (Case 1) was preferentially performed.

For the simulation results with the Case 1 conditions, the flow depth, flow velocity, and impact forces of debris flows were estimated with the value of the main mountain torrent, showing a relatively large value on the basis of the outlet, taken as the representative value. In addition, when more than one grid existed at the same distance as seen in Fig. 4, values, such as the flow depth, flow velocity, and impact forces, were averaged for use.

Debris flow simulation results

Analysis of the characteristics of the debris flow simulation with the structures

The debris flow simulations in the study conducted were classified into six based on locations and the number of

Table 3 Debris flow simulation conditions on a case-by-case basis

Case no.	DEM (m)	Grid size (m)	Number of structures	Location of structure (m)	Structure size (m)
1	5×5	5×5	0	0	20×10×10
2			1	50	
3			1	100	
4			2	100, 200	
5			2	100, 300	
6			2	100, 500	

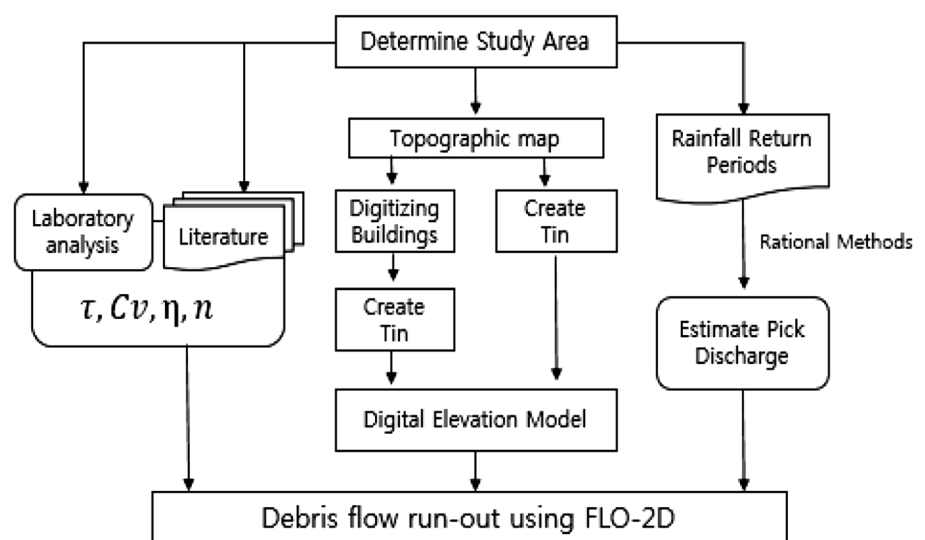**Fig. 3** Flowchart of the debris flow simulation

Fig. 4 Conversion of values to a mean value

structures at a certain distance from an outlet. For the analysis of the overall flow characteristics based on simulation results, the study selected Case 1, without any structures, and Case 6, with the largest scale where there are two structures. The characteristics of the debris flow in each case were analyzed. The scale was converted from 0 to 1.0 so that the change in flow characteristics, namely, the flow depth and the impact force (Figs. 4, 5), could be analyzed. The ratio of the flow depth means the ratio of the flow depth in question to the maximum flow depth, which ranges from 0 to 1.0. It also indicates that the bigger its value grows, the larger the flow depth of debris flow in question becomes.

The analysis result showed that the flow depth and impact force slowly decreased as the debris flow moved away from the outlet because of distribution and sedimentation (Fig. 5). As shown in Fig. 5, the ratios of the flow depth and the impact force gradually diminished as it went farther away from the outlet, and this tendency is shown in all cases regardless of the presence of structures.

However, according to the simulations, the presence of structures, including sedimentation from the structures, accordingly caused the rapid decrease in flow depth and impact force (Fig. 6). Moreover, as the debris flow passed down from narrow trails and inflection points with changes in topography, the flow depth and impact force rapidly increased (Fig. 7).

The flow depth after the presence of the structure(s) was slightly smaller at the same distance on the basis of the outlet compared to the case without any structure (Case 1). It was judged that this phenomenon resulted from the slight decrease in the sediment volume after the presence of the structure(s) because some sediments of the debris flows were stored up by the structure(s).

The impact forces varied by structure(s) as the debris flow flowed down, but they did not tend to increase constantly. In the absence of any structure (Case 1), the impact forces rather decreased by structure(s) at some of the sections where they were supposed to increase. This resulted from the

geometries of the structure(s) and their surroundings; it was judged that the variation occurred when the flow direction of the debris flows changed toward a section with a gentle slope at the location of the structure, and this resulted in this phenomenon with a broader range of dispersion.

Analysis of flow characteristics of debris flows in accordance with geographical variations

The effects of the geographical variations caused by the flowing down of the debris flows on the flow characteristics of the debris flows were analyzed. The sections in which the variation range of the flow depth, flow velocity, and impact force were large were selected based on the previous analysis results, and the topographic maps were constructed for these sections to perform the analysis. The characteristics of the sections in which geographical variations occurred were classified into three types for the analysis in accordance with the distances from the structure as shown below.

First, for the 100–250 m section, the dispersion range of the debris flows decreased with about three inflection points or more within the main mountain torrent. Furthermore, the dispersion range of the debris flows was estimated at 64 m at its upper bound at the 100 m section from the outlet, while it was estimated at 20 m at its upper bound, which decreased to about one-third, at the 100–250 m section, as seen in Fig. 7. This phenomenon resulted in the decrease of the dispersion range of the debris flows and the increase of the flow depth and flow velocity, as the terrain slope became steeper in the vicinity of the inflection points of the main mountain torrent and the width of the main mountain torrent became narrower.

Second, for the 150–200 m section, the flow depth and flow velocity of the debris flows tended to be relatively large in this section in which the dispersion range was narrow, located at the inflection point of the main stream. However, the dispersion range tended to partially increase as the flow direction of the debris flows changed in the presence of the structure near the main mountain torrent (Fig. 8). The partial change of the flow direction was caused by the structure when the debris flows flowed down as the terrain slope at the location of the structure was relatively gradual. This resulted in the decrease in the flow depth and flow velocity.

Lastly, for the 250–300 m section, it was assumed that the structure was located within 300 m from the main mountain torrent, and the dispersion range of the debris flows was about 45 m and the flow depth around 1 m without any structure (Case 1). However, the dispersion range of the debris flows decreased to about 25 m, and the flow depth increased to around 1.5 m in the presence of the structures (Case 5) as seen in Fig. 9.

The analysis results of the flow variation of the debris flows, with the geographical change caused by the

Fig. 5 Results of the debris flow simulations using FLO-2D: (s) mean is structures; the ratios of the flow depth and the impact force mean those of the debris flow in question to the maximum flow depth and that of the impact force in question to the maximum impact force; the farther the rates get away from the outlet, the smaller the ratios become
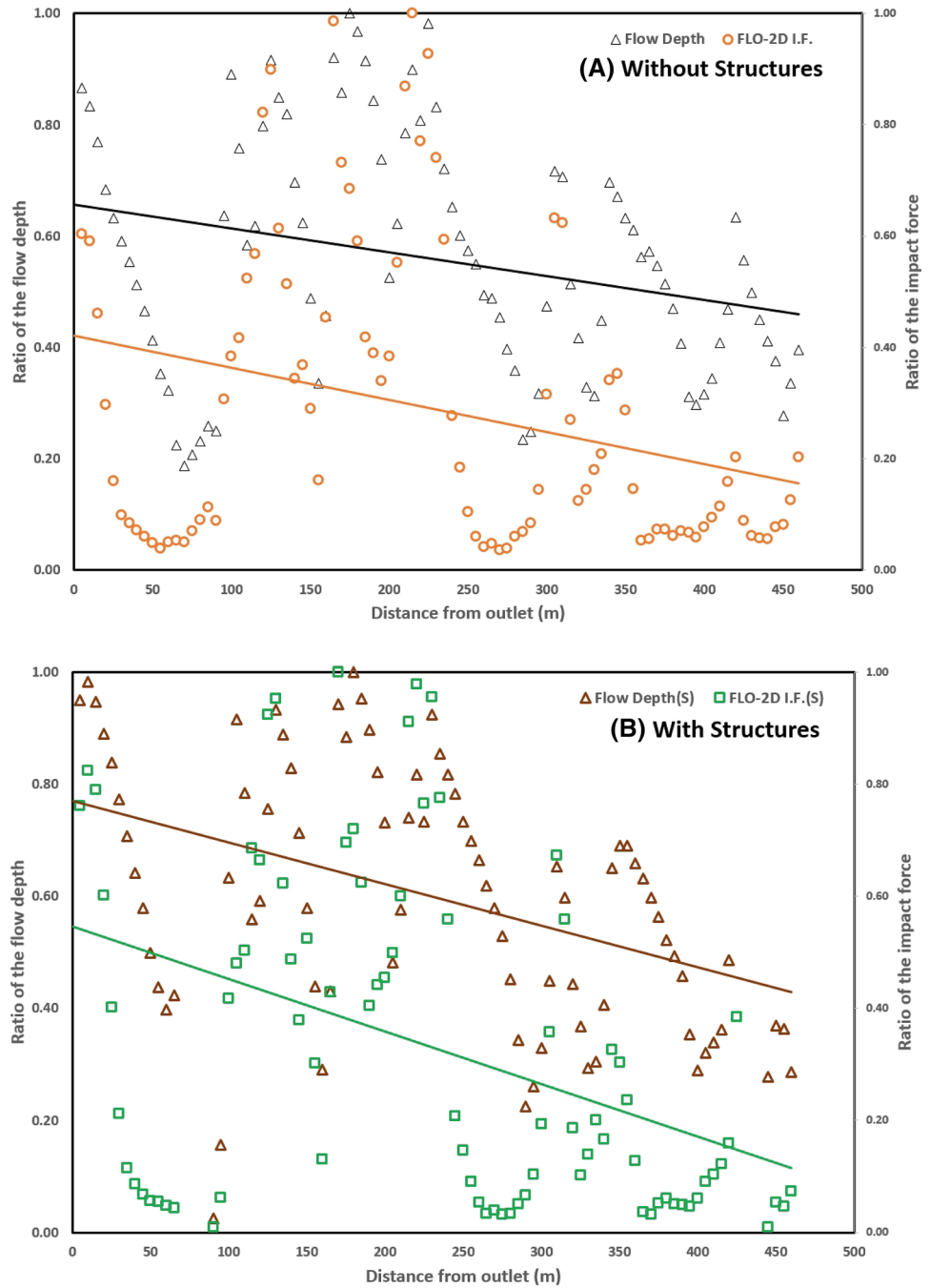

structure taken into account, indicated that the flow characteristics of the debris flows varied in the presence of the structure within the main mountain torrent. In particular, the flow characteristics tended to increase when the dispersion range was narrow or the inflection point was located along in the flow direction of the debris flows. This phenomenon indicated that geographical change was likely to occur in the presence of the structure, and it affected the flow characteristics of the debris flows as a result.

Discussion

Suggestion of impact force equation for debris flows

As discussed, two models were used to assess the impact force of the debris, namely, the hydraulic model and the dynamic impact force model. A wide range of studies applied these models to assess the debris flow impact.

Fig. 6 Comparison between the results of the simulations (Case 1) without the structures and (Case 6) with the structures in terms of the flow depth and the impact force of the debris flow: A comparison between the flow depth in (black plot) Case 1 and (brown plot) Case 6; and B comparison between the impact force in (orange plot) Case 1 and (green plot) Case 6; (s) mean is structures
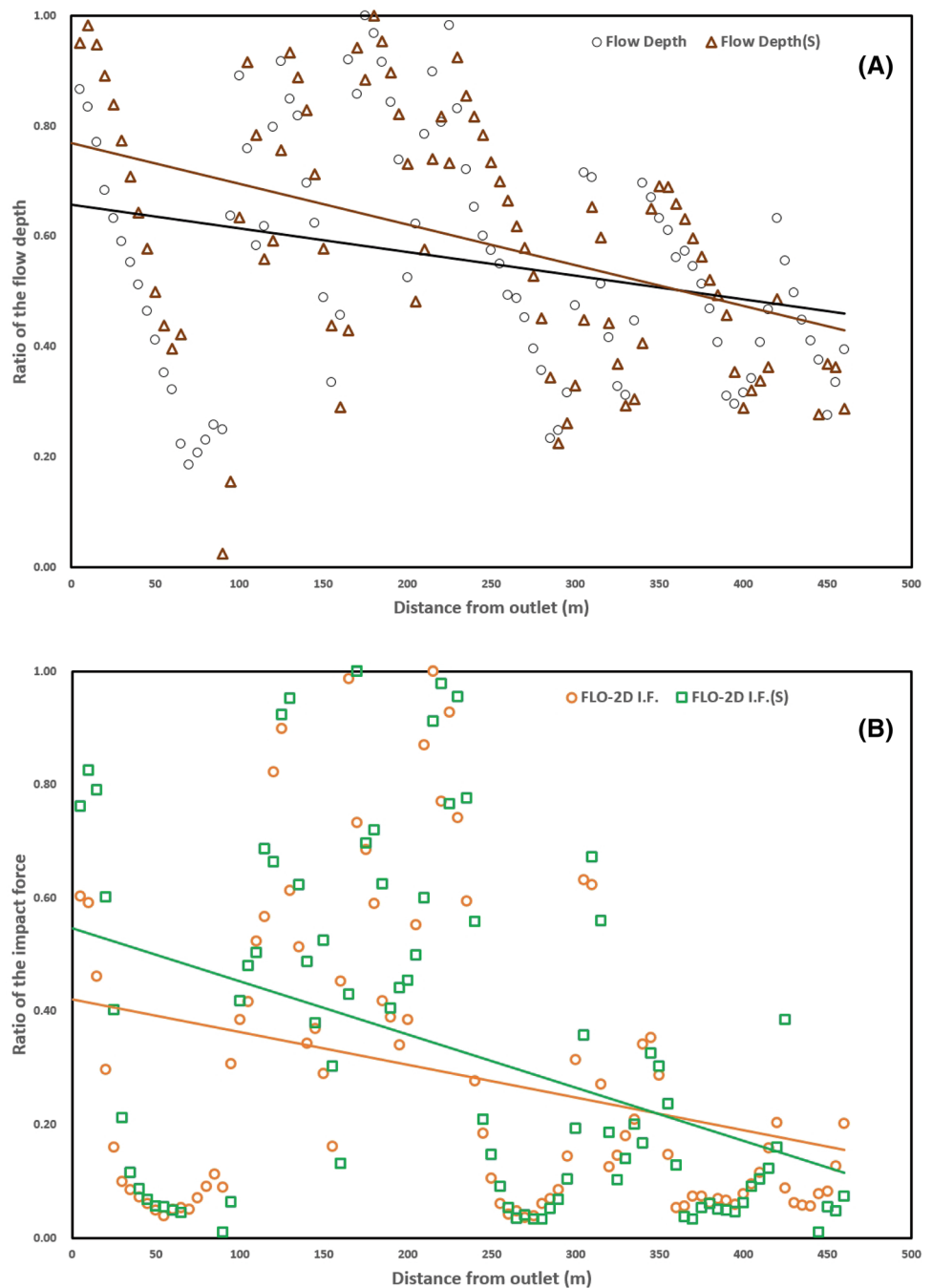
In this study, a dynamic model was adopted to estimate the impact force of debris flows as seen in Eq. (11).

$$p_{max} = k\rho V^2 \tag{11}$$

Density (ρ) is the value obtained by dividing mass by volume. To estimate the density of debris flows, it was adjusted using the densities of soil and water, excluding the mass of air in accordance with the concentration of debris flows.

$$p_f = \delta C_v + (1 - C_v)\rho_w, \tag{12}$$

where δ is the density of sediment, C_v is the sediment volume concentration, and ρ_w is the density of water. The dynamic model can be modified as follows by applying the adjusted density.

$$P = k\{\delta C_v + (1 - C_v)\rho_w\}V^2 \tag{13}$$

There are various equations for the estimation of the flow velocity (V) of debris flows. In this study, the velocity was adjusted using the Manning's equation. The Manning's equation, which is similar to the Chézy's equation, is known to be practical and useful for the estimation of
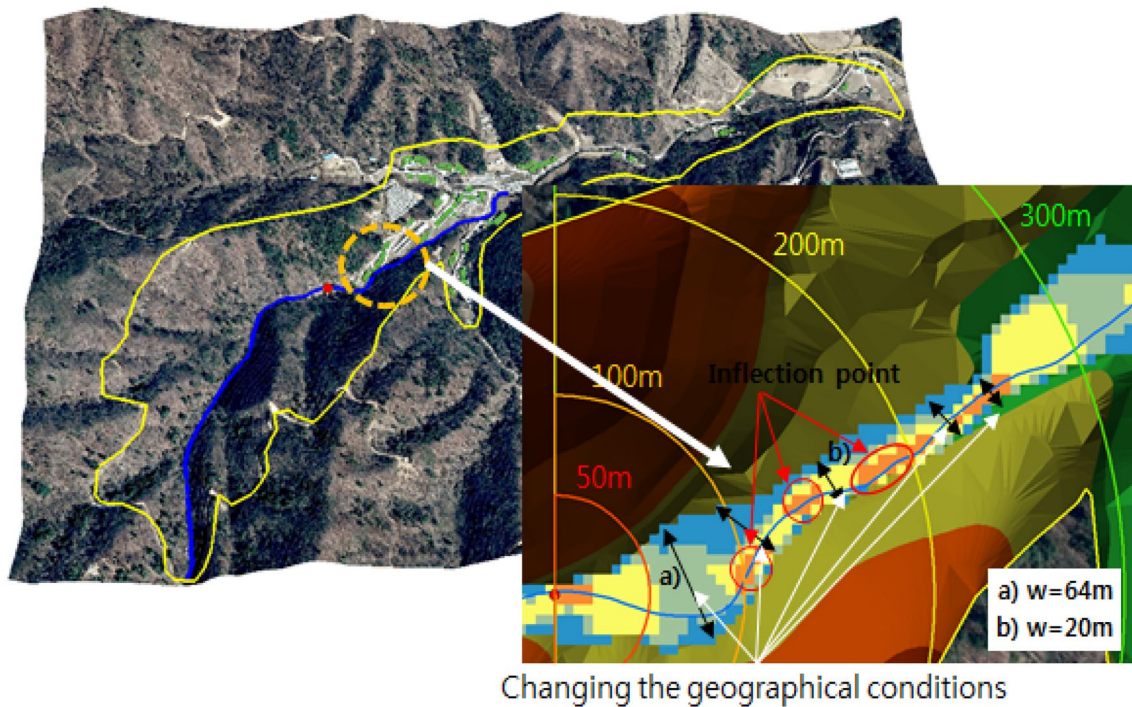
Fig. 7 Increasing the debris flow depth caused by a change of the geographical length (red circles are inflection points of the main stream)
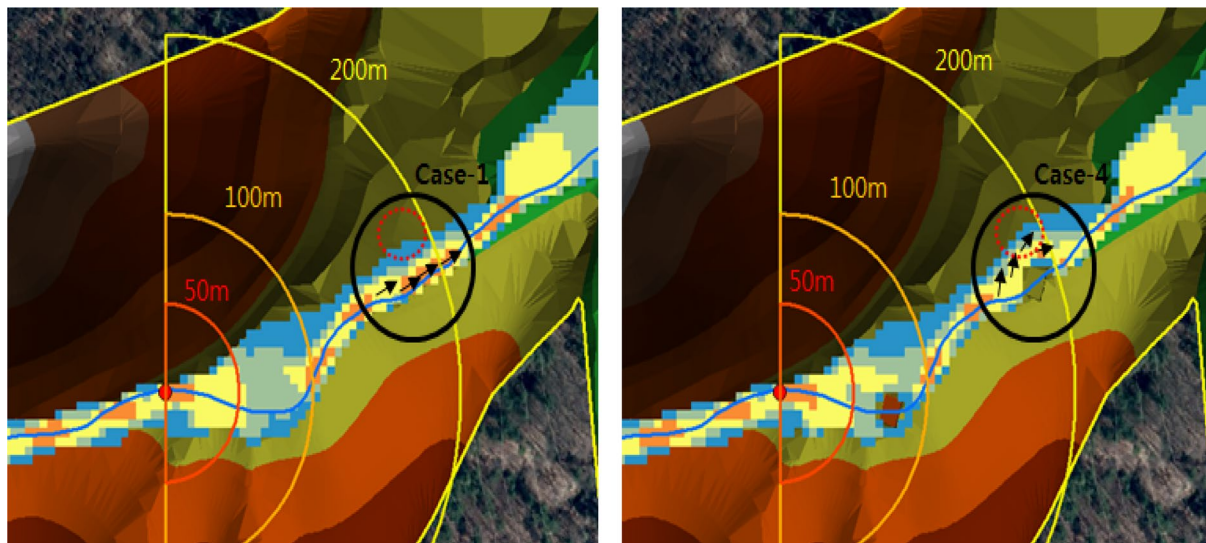

Fig. 8 Change in the direction of the debris flow caused by the structures and the topographical change on the main stream in Cases 1 and 4 (the black arrows mark the direction of the debris flow)

the average velocity of a river or a waterway (Holland 2016).

$$P = k\{\delta C_v + (1 - C_v)\rho_w\}\left(\frac{1}{n}R^{2/3}I^{1/2}\right)^2, \tag{14}$$

where n is the roughness coefficient, R is the wetted parameter, and I is the hydraulic gradient. The impact force

equation suggested through the adjustment to the density and flow velocity may overestimate the impact force of debris flows in accordance with input variables such as the width of a mountain torrent, flow depth of debris flows, and roughness coefficient. According to Hübl et al. (2009) and Moriguchi et al. (2009), it was reported that the impact force of debris flows ranged from 5 to 250 kN/m².
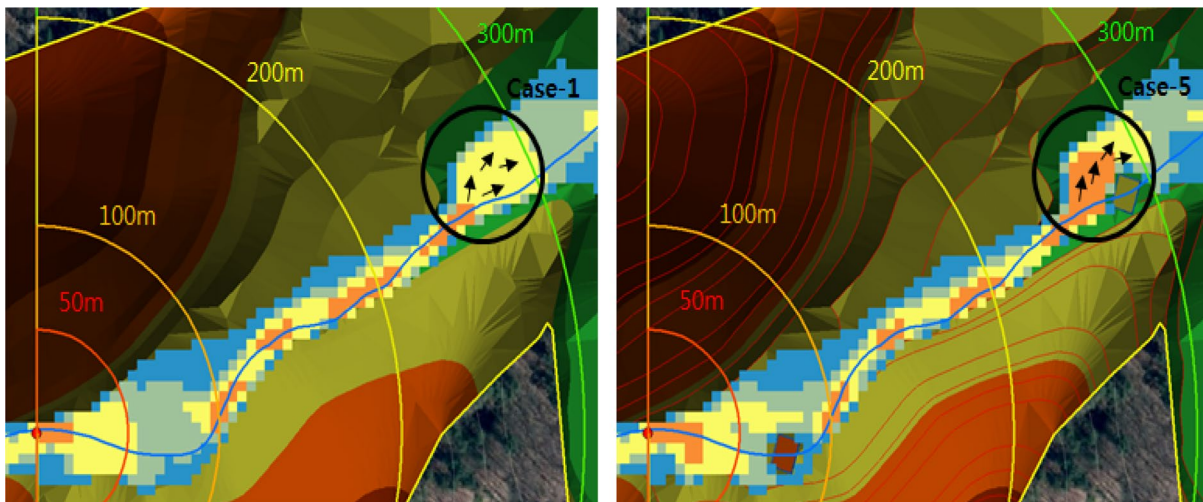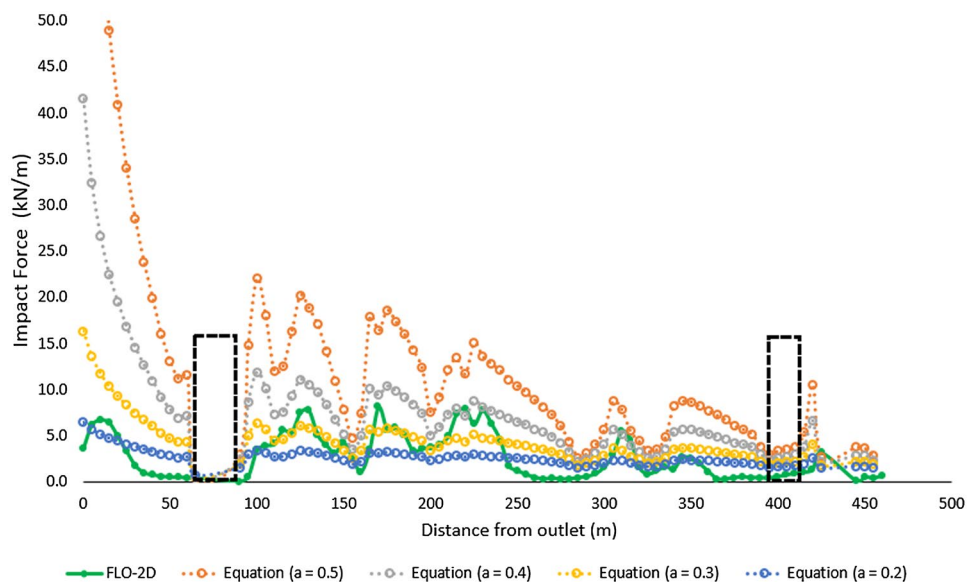
Fig. 9 Change in the direction of the debris flow caused by the structures and the topographical change on the main stream in Cases 1 and 5 (the black arrows mark the direction of the debris flow)

In this study, the impact force of debris flows was corrected by introducing the correction index α to avoid the overestimation of the impact force. The range of the correction index α was proposed through the verification with the FLO-2D simulation. Furthermore, the impact force equation for debris flows can take into account the amount of the impact forces that are canceled in accordance with the direction in which the debris flows run into the structure, by applying the direction angle (sinβ) between the flow direction of the debris flows and the structure.

$$P = \left[k\left\{ \delta C_\mathrm{v} + \left(1 - C_\mathrm{v}\right)\rho_\mathrm{w} \right\} \left(\frac{1}{n} R^{2/3} I^{1/2} \right)^2 \right]^{\alpha} \sin\beta, \qquad (15)$$

where α is the impact force correction index.

Correlation analysis of the suggested impact force equation for debris flows

Determination of a range of *a* with a pattern of the plot and correlation analysis

The reliability of the suggested impact force equation was verified by comparison between the impact forces estimated by the suggested equation with the analysis results obtained from Case 6 and the FLO-2D simulation results.

Figure 10 shows the variation of the impact force at each distance from the outlet, the impact force obtained from Case

Fig. 10 Trend analysis of the impact forces from the FLO-2D simulation and the data obtained using the proposed equation in this research (green plot: FLO-2D impact force; black box: structures; other plots: impact force equations with different values)

6, and the impact force obtained by the suggested equation are plotted for each value of α. The analysis results showed that the impact forces obtained by the FLO-2D simulation and estimated by the suggested equation had highly similar trends. In particular, the trend was similar to the relation between the flow depth and impact force, showing a similar pattern to the FLO-2D simulation results when α was 0.3–0.4; there were sections in which the impact force was overestimated. It was judged that this phenomenon resulted from the fixed values of the geographical factors, such as the width, roughness coefficient, and slope, in estimating the impact force.

The correlation analysis with respect to the impact forces estimated by the suggested equation in this study and obtained by the FLO-2D simulation was performed. This method enables the clear and objective relation between two variables, and the degree of relation is presented by a number called the coefficient of correlation. The positive correlation coefficient indicates two variables are positively correlated with each other, the negative correlation coefficient indicates they are negatively correlated, and the zero value of the correlation coefficient indicates they are uncorrelated.

In the correlation analysis, the correlation coefficient was the largest when the correction index (α) was 0.2, but the accuracy was low because of the large distortion of the estimated impact force. It was judged that the correlation coefficient was the smallest when α was 0.5, and the impact force tended to be overestimated. Namely, it was judged that the impact force was appropriately estimated when α ranged from 0.3 to 0.4. As seen in Table 4, all of the values of the correlation coefficient for each value of α were equal to or larger than 0.4, which indicated that impact forces from the FLO-2D simulation and obtained by the suggested equation were correlated.

This indicated that there was a similar relation to the proportional relation in which the impact force increased as the flow depth increased, by comparison with the FLO-2D simulation results. The impact force equation for debris flows is suggested in Eq. (16) with the determination of the range of α through the reliability verification of the two types of the impact force.

$$P = \left[k \left\{ \delta C_\text{v} + (1 - C_\text{v})\rho_\text{w} \right\} \left(\frac{1}{n} R^{2/3} I^{1/2} \right)^2 \right]^\alpha \sin\beta, \ (0.3 \leqslant \alpha \leqslant 0.4)$$

(16)

Table 4 Comparison of correction analysis results between impact forces from the FLO-2D simulation and the suggested equation

Correction index (α)	Coefficient of correlation	Index of correlation relationship
0.5	0.45	0.0–0.1: none or very weak
0.4	0.49	0.1–0.3: weak
0.3	0.53	0.3–0.5: moderate
0.2	0.56	0.5–1.0: strong

Verification of equation validity by comparing the relationship between the flow depth and impact force

The study compared the relationship between the flow depth and the impact force of the debris flow using the FLO-2D simulation results to verify the impact force equation for which the correction index is applied. In general, the impact force of the debris flow is relative to the flow depth, but the impact force is considered unchanged when it has the same ratio as the flow depth. The relationship between the flow depth and the impact force of the debris flow is illustrated in Fig. 11 (without structures) and Fig. 12 (with structures). The value applied was fixed at 0.4.

As shown in Fig. 11, where there were no structures, the coefficient of determination (R^2) of the proposed equation for the impact force and the flow depth is 0.6169, which is slightly smaller than that of FLO-2D (i.e., 0.6315). The smaller number for the relationship between the impact force and the flow depth may have been obtained because the proposed equation reflects an additional factor, that is, the directional angle to consider the structures that influence the impact force of the debris flow when it was estimated.

In contrast, in the simulation where structures were present, as shown in Fig. 12, the coefficient of determination (R^2) of the proposed equation for the impact force and the flow depth is 0.7350, which is larger than that of FLO-2D (i.e., 0.4949). This value indicates that the suggested equation more sufficiently reflects the change in the impact force with the changing flow depth when structure(s) were present in the direction where the debris flow is moving, as compared to the result of FLO-2D simulation. In addition, the structures influence should be taken into account in finding ways to prevent the overestimation of the impact force being calculated.

Conclusions

In this study, the variation of the flow characteristics of debris flows in the presence and absence of structures was investigated on the research area using FLO-2D, a debris flow simulator, and the flow depth, and impact force of the debris flows were analyzed for each distance on the basis of the outlet. In particular, the flow variation of the debris flows was investigated by analyzing the flow characteristics of the debris flows in the presence of the structure at a constant distance from the outlet. Through this, an impact force equation for debris flows was suggested with the adjustments of the density and flow velocity based on the impact force analyzed from FLO-2D and the dynamic model. Furthermore, the reliability verification was performed for the suggested impact force equation for debris flows through the relation between

Fig. 11 Comparison of the relationship between the flow depth and the impact force based on FLO-2D and the proposed impact force equation (unstructured condition; correction: $a = 0.4$)
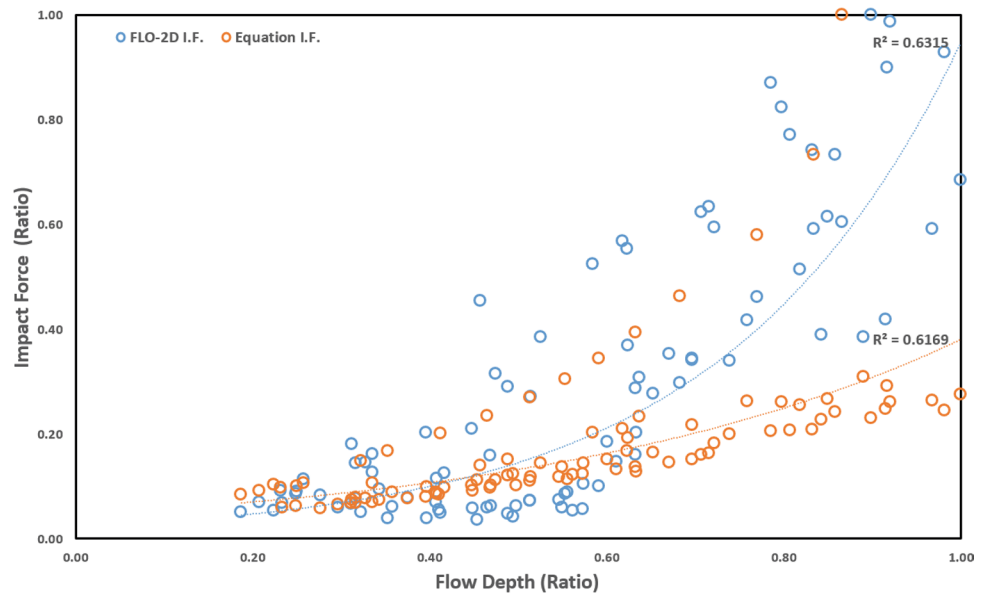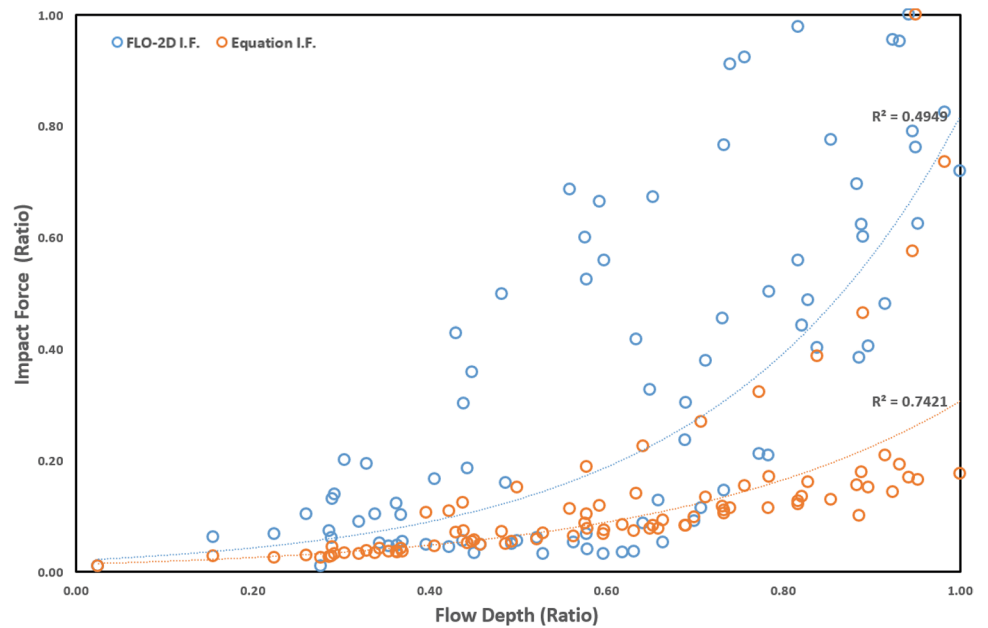

Fig. 12 Comparison of the relationship between the flow depth and the impact force based on FLO-2D and the proposed impact force equation (setup of the structured condition; correction $a = 0.4$)

the flow depth and impact force, correlation analysis, etc., based on the FLO-2D simulation.

This study was able to confirm that the flow characteristics of the debris flows varied by the presence and absence of structures, and their variations did not have a constant pattern. The flow depth and impact force of the debris flows tended to slightly increase ahead of the structure(s), but the flow velocity tended to gradually decrease ahead of the structure(s). However, in general, the debris flow movement slows down as the flow goes farther away from the outlet. In addition, based on the evaluation, the debris flow rate instantly drops when there are structures in the flow's path.

At some sections, significant and irregular increasing or decreasing tendencies in the flow characteristics were observed. The structure(s) can be taken into account as a geographical factor, along with the surrounding topography, and the changes in topography caused by the structure(s) affected the variation in the debris flow characteristics. Furthermore, the variation of the debris flows occurred by general geographical changes, such as the decrease of the dispersion range and inflection points, other than the structure(s). Therefore, it turned out that the dispersion distance of the debris flows as well as

surrounding geographical factors needs to be taken into account, to estimate the impact force of the debris flows.

The suggested impact force equation adopted the correction index (α) to avoid the possibility of overestimating the impact force, and it appeared that it was correlated with the impact force from FLO-2D, with the correlation coefficient equal to or larger than 0.4. This showed similar trends to the relations with the flow depth and impact force from FLO-2D with the range of α: $0.3 \leq \alpha \leq 0.4$.

In cases where structures are present, the coefficient of determination (R^2) of the proposed equation is 0.7350 for the impact force and the flow depth, which is larger than that of FLO-2D (i.e., 0.4949). Therefore, the proposed equation sufficiently reflects the factors that influence the debris flow, such as debris, water density, concentration, decreasing coefficient with a directional angle, and Manning's coefficient.

In addition, the equation is useful because it can estimate the impact force of the debris flow without the use of complex simulations, and it only requires relatively simple data on topography and the physical properties of rocks, which can be easily obtained by a field investigation, for instance. In particular, as it shows a correlation as high as 0.7 for the relationship in the changes between the depth flow and the impact force, it can be widely used as basic data for further studies on the impact force of debris flow.

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