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Research Paper

A Study on the Debris Flow Hazard Mapping Method using SINMAP and FLO-2D

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Abstract

This study conducted an evaluation of the extent of debris flow damage using SINMAP, which is slope stability analysis software based on the infinite slope stability method, and FLO-2D, a hydraulic debris flow analysis program. Mt. Majeok located in Chuncheon city in the Gangwon province was selected as the study area to compare the study results with an actual 2011 case. The stability of the slope was evaluated using a DEM of 1 x 1m resolution based on the LiDAR survey method, and the initiation points of the debris flow were estimated by analyzing the overlaps with the drainage network, based on watershed analysis. In addition, the study used measured data from the actual case in the simulation instead of existing empirical equations to obtain simulation results with high reliability. The simulation results for the impact of the debris flow showed a 2.2-29.6% difference from the measured data. The results suggest that the extent of damage can be effectively estimated if the parameter setting for the models and the debris flow initiation point estimation are based on measured data. It is expected that the evaluation method of this study can be used in the future as a useful hazard mapping technique among GIS-based risk mapping techniques.

Keywords : Landslide, Debris Flow, SINMAP, FLO-2D, Hazard Mapping

1. Introduction

In july 27, 2011, a catastrophic debris flow happened on Mt. Majeok in the Cheonjeon-ri area in Chuncheon city in Gangwon province, which led to deaths of 10 college students and three adults, and 26 injuries. The catastrophe was caused by torrential rain, itself caused by recent extreme weather. Antecedent rainfall prior to the landslide was approximately 525mm, and rainfall on the day of the incident was 255mm; the recorded rainfall surpassed the landslide alert level. South Korea has a high risk of accidents from landslides, because most land is mountainous, the population density is very high, and housing, roads, and social infrastructure are often close to mountains (Kim, 2013). In addition, most accidents occur in summer when torrential rain frequently occurs, because the country is located in a meteorologically heavy rain area. Since most domestic landslides are caused by torrential rain in the summer, evaluation with a technique that estimates the extent of damage that takes the inherent characteristics into account and reliable simulation techniques both need to be conducted. Oh et al.(2009) analyzed topographical and hydrological effect of debris flow movement which is affected by initiation, flow and deposition using Satellite image. Wie et al.(2010) extracted slope, flow direction and contour from DEM to simulate movement of sediment according to lapse of time using finite different method. Scheuner et al.(2011) simulated the runout distance, velocity, flow depth and impact pressure of debris flows from Mattenbach, Stechelberg in Switzerland using RAMMS two-dimensional debris flow model. LIN et al.(2011) estimated debris flow hazard area using FLO-2D model.

Table 1 shows classification of mass movement simulation model. This study aims to evaluate the feasibility of a GIS technique that considers the soil

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Table 1. Classification of Mass Movement Simulation Model

Model Type	Hydro-topographic/flow models	Dynamic-Physically based flow models	Landslides/ erosion models
Model Name	LAHARZ (Iverson et al.,1998)	FLO-2D (O'Brien et al.,1993)	SINMAP (Pack et al.,2005)
	MSF (Huggel et al.,2003)	Titan-2D (Sheridan et al.,2005)	SHALSTAB (Dietrich and montgomery,1998)
	MTD (Gruber, 2007)	RAMMS (WSL-SLF)	

characteristics of a study area and the rainfall at the time of an accident by estimating the extent of damage of a debris flow and comparing it with an actual case to provide a technique as a future direction for the application of GIS-based hazard mapping.

1.1 Selection of Study Area and Research Methods

This study selects Mt. Majeok as the study area, it is located in Cheonjeon-ri in Chuncheon city in the Gangwon province, and was the site of a debris flow that generated an enormous amount of damage in 2011. The stability of the slope was evaluated using a DEM with 1 x 1 m resolution based on aerial LiDAR survey approach to analyze the debris flow of the study area, and debris flow initiation points were estimated using overlapping analysis with the results of watershed analysis. In addition, a hydraulic simulation of a debris flow was conducted using numerical analysis software based on a rheological model that takes into account the rainfall at the time of accident. A comparative analysis of the simulation results and the actual data from the time of the accident was performed to evaluate the technique's feasibility. Fig. 1 is a flowchart that outlines this study.

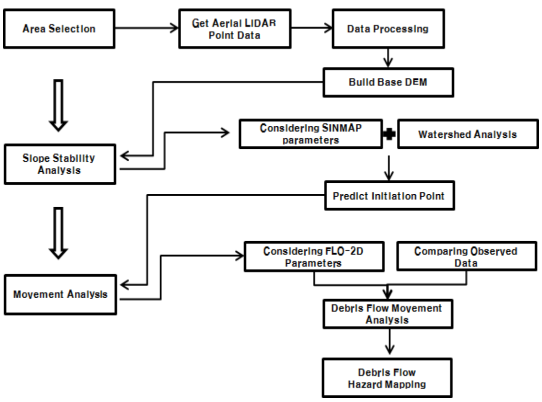


Figure 1. Flow-Chart of Study

2. Causes of Landslides

Prior to the analysis of the debris flow, the causes of landslides, considered a higher-order concept of debris flow, should be examined. Landslides occur due to complex mechanisms of various internal and external factors. Internal factors refer to static factors of environment with little influence such as the terrain, geology, and soil, whereas external environmental factors refer to factors that cause landslides through external impacts such as rainfall and earthquakes (Yang et al., 2007).

This study conducts simulations on the extent of damage of a debris flow by taking into account both the internal factors of terrain, geology, and soil, and the external factor of rainfall.

3. Analysis of Characteristics of Debris Flow Development in Study Area

3.1 Classification of Debris Flow by Type of Development

The most common form of sediment movement caused by landslides in Korea is debris flow. Debris flow can be classified into either hill slope debris flow or channelized debris flow depending on the form of its development (Winter et al. 2005). In a study on the behavior characteristics and sizes of debris flows, Zhang (2010) classified debris flows observed in the Gangwon province, which includes the study area of the present study, into the types described in Table 2. It was determined that the proportion of channelized debris flows in the Gangwon province was 71.1%.

Table 2. Classification of Debris Flow Initiation shape in Kangwondo

Year	Region	Channel	Slope
2008	Inje-Gun	5	
2009	Inje-Gun	5	1
	Jechoen	2	2
2010	Inje-Gun	4	
	Yangpyeong	1	
	YeoJu	1	
2011	Chuncheon		5
	Milyang	2	
2012	Chuncheon	3	1
2013	Chuncheon	4	3
	Hongcheon	2	3
	Hoengseong	2	
	Gapyeong	1	

Figure 2. Observed Initiation Point

The inclination of the slope is also an important factor in the development of debris flow. According to Kim and Chae (2009), landslides occur most commonly at 26–30° and 31–35°; Mt. Majeok (Fig. 2) had two landslides at 15 minute intervals start at a site approximately 150 m in height at inclination 30–35°, which is consistent with the ranges of typical inclinations for landslide development surveyed in the study.

3.2 Initiation Mechanism of Debris Flow

Takahashi (2007) classified the causes of debris flows initiated in the event of torrential rain in mountainous areas with steep hills into the following categories: (1) destruction of a natural slope, (2) scouring and erosion at the bottom and the sides of a valley, and (3) the collapse of a natural dam of sediment. The destruction of a natural slope in Korea

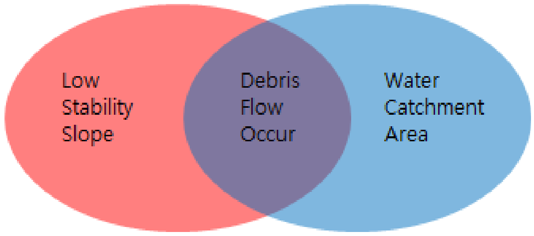


Figure 3. Concept of Debris Flow Initiation

is initiated by increased pore pressure due to the infiltration of rainfall, which is similar to the circumstances encountered in Japan. Taking this into account, this study makes the following assumptions to estimate the initiation points of the debris flow: (1) When it rains, rainwater is primarily collected through a drainage network that temporarily forms with many streams on the slope, into the catchment area, forming a channel and moving on to the slope, and (2) debris flow is likely to develop in areas that are rated low on the Stability Index, the result of the stability assessment of the slope. Fig. 3 shows the concepts used in the estimation process of debris flow initiation points proposed by this study.

3.3 Debris Flowing Mechanism

Made up of fine particles, sediments maintain slopes in a state of cohesion, and the flow of fluid generated from rainfall creates shear stress in four directions. When the shear stress becomes larger than the yield stress limit created by cohesive pressure, sediment particles and water mix move. The flow of debris can be considered as a movement of fluid with cohesive pressure, and rheological features such as yield stress and cohesion can be an important determinant of the fluidity of a destroyed slope (Jeong, 2010).

This study simulated the movement of the extent of damage of debris flow as a function of specific sediment concentrations using FLO-2D model to incorporate the behavioral characteristics of a debris flow. The governing equations of the FLO-2D model are the continuity equation designated as Eq. (1) and the momentum equation explicated by Eqs. (2) and (3).

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}=i \quad (1)$$

h= Depth of debris flow (m),
u= Average flow rate in the direction of the x axis (m/s),
v= Average flow rate in the direction of the y axis (m/s),
i= Rainfall intensity (mm/hr)

$$S_{fx}=S_{bx}-\frac{\partial h}{\partial x}-\frac{\partial u}{g\partial t}-u\frac{\partial u}{g\partial x}-v\frac{\partial u}{g\partial y} \quad (2)$$

$$S_{fy}=S_{by}-\frac{\partial h}{\partial y}-\frac{\partial v}{g\partial t}-u\frac{\partial v}{g\partial x}-v\frac{\partial v}{g\partial y} \quad (3)$$

S_{fx}, S_{fy} : Respective friction slopes in the x axis and y axis directions.
S_{bx}, S_{bf} : Respective bed slopes in the x axis and y axis directions.
g : Acceleration due to gravity (9.81 m/s2)

3.4 LiDAR DEM

A DEM of 1 x 1 m resolution obtained from aerial LiDAR survey method was used to obtain the topographic data used in this study. The aerial LiDAR system generates terrain data on the Earth's surface by shooting laser pulses from an aircraft equipped with a laser scanner, measuring the time required for the pulses to reach the surface, and calculating the three-dimensional coordinates of the spots at which the pulses are reflected. Recently, it has demonstrated an accuracy of 0.089 m ± 0.062 m on average for orthometric heights on conventional digital maps, using a GPS/INS based unified approach, and was found to be superior to 1/1,000 digital maps (Wie et al. 2007).

This method can also produce DEM, DSM, contour lines, and shaded relief maps by extracting the coordinates of point-clouds obtained from aerial LiDAR survey from preprocessing with GPS/INS, and post-processing irregular point data. Fig. 4 shows the DEM of Chuncheon city, which was used in this study.

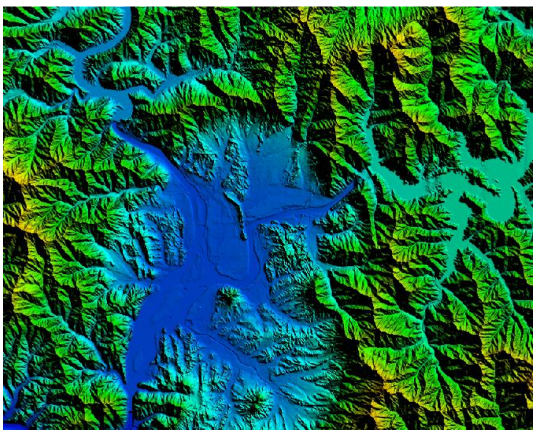


Figure 4. Chuncheon 1m × 1m resolution DEM

4. Slope Stability Analysis

4.1 SINMAP Parameter Setting

This study used SINMAP as a model for evaluating slope stability. Table 3 shows the parameters that were set up based on the results of Seo (2012), which conducted an indoor experiment with soil sampled from two randomly selected spots in the area at which the accident occurred during the landslide, instead of the initial parameter values commonly used in such analysis.

The analysis results are expressed as the Stability Index, which indicates the stability of the slope at each spot in relation to the development of debris flow. The Stability Index indicates relative risk instead of an absolute value for the precise risk, and the red zone shown in Fig. 5 (i.e., the zone of Upper Threshold 0.0 < SI < 0.5) is assumed a low stability zone and designated as a zone with a high probability of flow debris.

Table 3. Parameters of SINMAP Analysis

Variables	Value	Unit
Gravity Constant	9.81	m/s^2
Water Density	1000	kg/m^3
Ratio of Transmissivity	60~200	m
Soil Cohesion	0.1~0.23	t/m^2
Soil Friction Angle	38~40	°
Soil Density	1763	kg/m^3

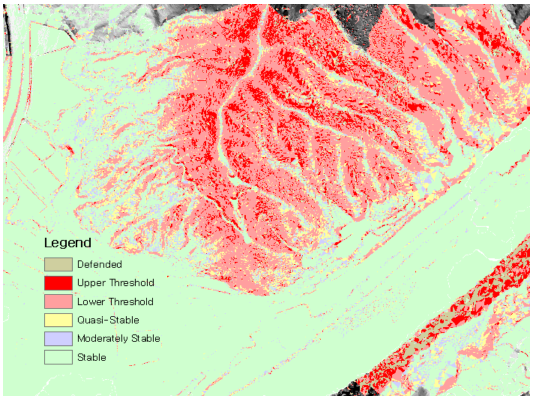


Figure 5. Stability Index of Mt. Majeok

4.2 Watershed Analysis

Based on the concept map of Fig. 3, this study developed a virtual drainage network in all four directions by performing watershed analysis at 1 x 1 m resolution to estimate the catchment area that temporarily forms during a rainfall event. The spot with highest probability of developing debris flow was estimated for each watershed by marking the formed network in blue and performing overlap analysis on the network with the zone of Upper Threshold 0.0 < SI < 0.5 in red, and the area of threshold saturation in green. Fig. 6 shows the debris flow initiation point for each watershed, as estimated from overlap analysis.

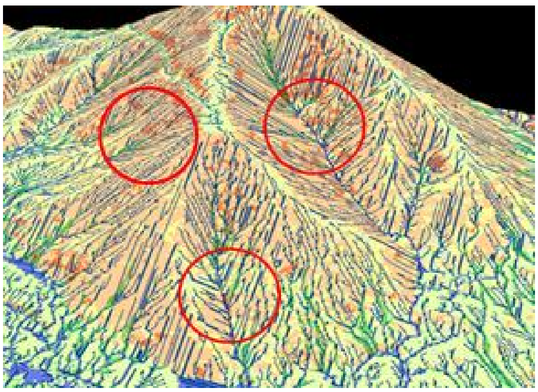


Figure 6. Debris Flow Initiation Point

5. Debris Flow Movement Simulation

5.1 FLO-2D Model Parameter Setting

5.1.1 Sediment Concentration

One of the most important factors in debris flow simulation is sediment concentration. The state of the fluid is determined by the sediment concentration in FLO-2D simulation, and debris flow takes a value of 0.45~0.55 volume concentration according to the classification in Fig. 7. When the concentration is lower, sediment moves faster and spreads wider. A concentration of 0.52 was used in this study, considering that the debris flow took the form of hill slope flow debris, which has relatively larger sediment particles.

5.1.2 Manning's n Value and Laminar Flow K

Since the debris flow that flows down the slope shows the hydraulic behavior of a fluid with viscosity, the hydraulic roughness of the slope as a path must be considered. Manning's n is the value set for each calculation grid to indicate the coating state of the ground surface, and is set at 0.07 based on the data from Woolhiser (1975) in Table 4 and data from a previous study that conducted a geological survey of the site. In addition, the laminar flow resistance parameter K was set at 3500 in consideration of the forestry distribution of the study area.

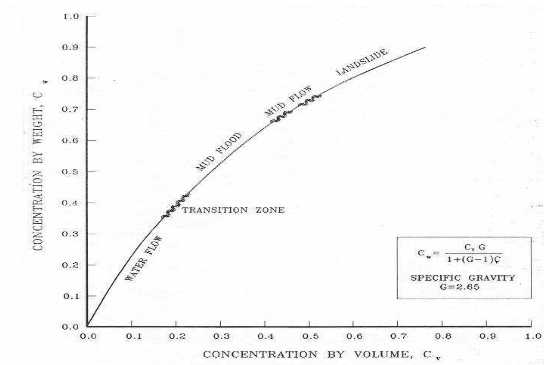


Figure 7. Classification of Flow Status

Table 4. Manning's n Value & K Parameters

Surface	Laminar Flow K	Manning's n
Concrete or asphalt	24~108	0.01~0.013
Bare sand	30~120	0.01~0.016
Graveled surface	90~400	0.012~0.03
Bare clay-loam soil	100~500	0.012~0.033
Sparse vegetation	1,000~4,000	0.053~0.13
Short grass Prairie	3,000~10,000	0.10~0.20
Bluegrass sod	7,000~100,000	0.17~0.48

5.1.3 Yield Stress and Coefficient of Viscosity

The FLO-2D model provides empirical coefficients on yield stress, viscosity, and sediment concentration. O'Brien and Julien (1988) expressed the relationships between the volume concentration Cv and the coefficients obtained from rheological analysis—yield stress and viscosity—as Eqs. (4) and (5).

$$\tau_y = \alpha_1 e^{\beta_1 C_v} \tag{4}$$

$$\eta = \alpha_2 e^{\beta_2 C_v} \tag{5}$$

Hubl and Steinwendtner (2001) concluded that the most important factors in FLO-2D simulation are the digital terrain and rheological parameters (i.e., yield stress and the coefficient of viscosity). When it was impossible to obtain samples from actual sites, previous studies estimated the yield stress and the coefficient of viscosity using O'Brien's empirical coefficients provided by the FLO-2D model; however, the present study's parameters are the estimates for yield stress and volume concentration based on the soil properties of the study area measured using linear regression analysis in "Yield Stress and Viscosity Characteristics of Soils with Liquidity Index" (Kang et al., 2013) to increase the credibility of the parameter selection. In Table 5, Soil Sample Cases 1 and 2 are measurements of the samples obtained from two randomly selected spots in the area of the accident, which were used in SINMAP analysis, and Case 3 is O'Brien's empirical coefficients for Glenwood, which have been used in many previous studies, and are used in the present study for comparison purposes.

Table 4. Parameters of τ_y and η

Soil Sample	$\tau_y = \alpha_1 e^{\beta_1 C_v}$ (Pa)		$\eta = \alpha_2 e^{\beta_2 C_v}$ (Pa·s)	
	α_1	β_1	α_2	β_2
Case 1	0.385	22.67	0.831	12.54
Case 2	0.209	24.37	0.0684	17.64
Case 3	0.077	16.9	0.065	6.20

5.1.4 Intensity of Rainfall

In July 2011, record rainfall was observed for Chuncheon city due to extreme weather conditions, recording 261 mm for 6 hours, and 65 mm/hr. Fig. 8 shows the daily precipitation and cumulative precipitation at the time. This study designated the rainfall flow rate based on the statistics.

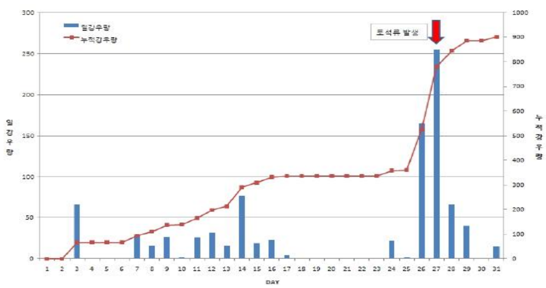
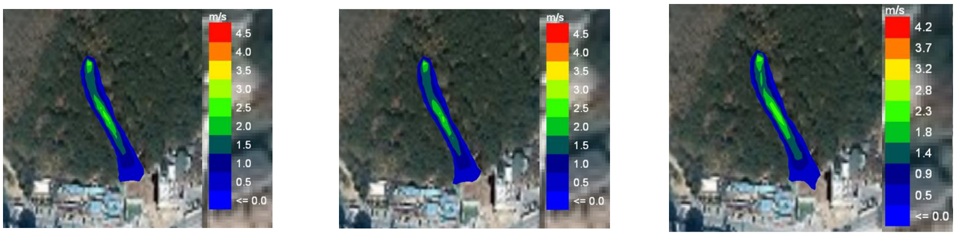


Figure 8. Rainfall data in 27. July. 2011

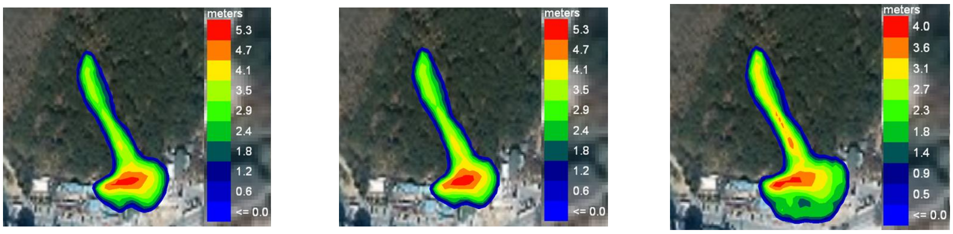
5.1.5 Results of Simulation

Final Flow Velocity



(a) Case 1 (b) Case 2 (c) Case 3

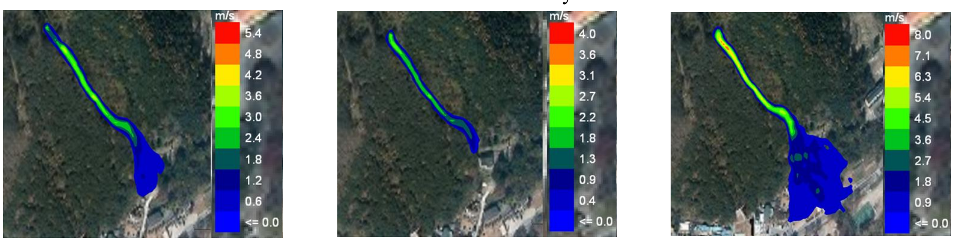
Final Flow Depth



(d) Case 1 (e) Case 2 (f) Case 3

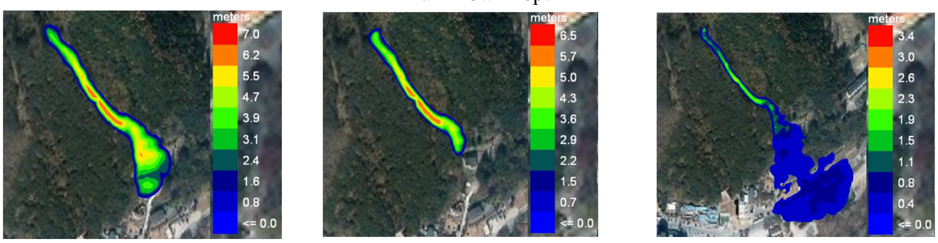
Figure 9. Results of Simulation in Area A

Final Flow Velocity



(a) Case 1 (b) Case 2 (c) Case 3

Final Flow Depth



(d) Case 1 (e) Case 2 (f) Case 3

Figure 9. Results of Simulation in Area B

(a) All cases of Inundation Area

(b) Case 1

(c) Case 2

(d) Case 3

Figure 10. Comparing with Observed Inundation Area

5.1.6 Result Analysis

Debris flow occurred twice at 15 minute intervals in Majeoksan Mountain, and the two areas were designated as Area A and Area B, where experiments were conducted separately. Table 6 shows the summary of input parameters applied to all cases for the two areas.

Fig. 9 shows the results for the final flow velocity and final flow depth obtained from FLO-2D simulation. The final flow velocity in Area A was up to 4.5 m/s for both Case 1 and 2, and 4.2 m/s for Case 3 and the final flow velocity in Area B was 5.4 m/s in Case 1, 4.0 m/s in Case 2, and 8.0 m/s in Case 3.

Table 6. Common Parameters

Inflow Cell Size	3m×3m
K	3500
Manning's n	0.07
Sediment Concentration	0.52
Inflow Time (h)	0.02
Simulation Time (h)	0.05
Sediment Specific Gravity	2.72

The final flow depth results showed that both Cases 1 and 2 in Area A will have deposits of up to 5.3 m on the lower slope, and Case 3 will have a relatively low 4.0 m deposit. In Area A, Cases 1 and 2 showed very similar results, whereas in Area B where the debris flowed down longer slope, Cases 1 and 2 showed noticeable differences: They had respective final flow velocities of 5.4 m/s and 4.0 m/s, and respective final flow depths of up to 7.0 m and 6.5 m.

According to Kim et al. (2013), which evaluated the feasibility of the FLO-2D model using flow debris in the Umyeonsan Mountain, the model produces results for the speed of debris flow that are slower than the actual speed, because it cannot simulate the collapse and change of terrain. The present study is also likely to have estimated the speed as about 50% lower than the actual speed of the debris flow, suggesting that using a simulation to

Table 7. Results of Inundation Area

Inundation Area(m^2)	Area A	Area B
Observed	4154.6	6551.8
Case 1	4393	7069.1
Case 2	4064.9	3942.7
Case 3	5385.5	18485

estimate debris flow speed reliably requires the use of empirical coefficients under the assumption of specific conditions in addition to the use of measurements of the social properties of the accident area. Case 3 in Area B showed simulation results of low sediment concentration and high speed, which suggests that the Glenwood empirical equation is not adequate for the estimation of the deposit area, because the equation does not incorporate Korea's soil properties.

Fig. 10 shows the results of comparison between the data obtained from the area where the actual debris flow was observed and Cases 1, 2, and 3; the numerical values for each are summarized in Table 7.

In Area A, Case 1 resulted in a τ_y of 50710.49 Pa, and η of 564.35 Pa·s, which was 5.7% larger than the actual deposit area. Case 2 resulted in a τ_y of 66634.58 Pa, and η of 658.80 Pa·s, which was 2.2% smaller than the actual deposit area. In contrast, Case 3 resulted in a τ_y of 504.74 Pa, and η of 1.63 Pa·s, which was 29.6% larger than the actual case and showed a large difference from Cases 1 and 2. In Area B where the flow distance of the debris flow was much longer than in Area A, Case 1 showed a 7.9% difference, Case 2 showed a 39.8% difference from those of Area A, and Case 3, which did not incorporate local soil properties, showed a massive difference of 182%.

6. Conclusions and Discussion

This study evaluated the extent of debris flow damage in Majeoksan Mountain in Chuncheon, where a debris flow incident occurred in July 2011. Specifically, the study investigated the feasibility of an evaluation technique in which simulation was conducted with measured data of the soil from the area damaged by the flow debris using a slope stability model, SINMAP, and a flow movement model, FLO-2D, by comparing the simulation results with the actual data from previous damage. The values of τ_y and η that were calculated based on measured data in Area A were 50710.49 Pa and 564.35 Pa·s for Case 1, and 66634.58 Pa and 658.80 Pa·s for Case 2, and the results for Area B also showed a relatively accurate representation of the actual damage. In contrast, Case 3, which used empirical coefficients commonly used in previous studies, resulted in respective τ_y and η values of 504.74 Pa and 1.63 Pa·s, showing a large difference from the actual values. This suggests that further research is crucial to obtain adequate empirical coefficients for the area in which debris flows develop in Korea is crucial. Although the technique has the limitation of underestimating the flow rate of debris flows due to the limitation that the model cannot simulate the collapse of sediment, it is concluded that the technique is appropriate for the evaluation of the extent of sediment deposits and damages by incorporating actual soil properties. It is expected that the technique can be used as a hazard mapping technique for risk assessment that considers risk factors within the damage area in the future.

Acknowledgements

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