GEODISASTER-INDUCED LANDSLIDES AND DEBRIS FLOWS IN REGIONAL SCALE AREA

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Abstract

Globally, damages from debris flows have been reported in mountainous areas. Various studies indicate that increases in landscape exploitation and climate instability can grow up the incidence and impacts of debris flows. Therefore, the prediction of possible hazardous areas by debris flows is a public and private concern. In this study, a proposed method for a regional-scale analysis combining landslides and debris flows has been described, and the Umyeonsan (Mt.) landslides and debris flows, Seoul, Korea in 2011 were simulated to validate initiation points by landslides analysis and flow paths of debris flows. The recorded rainfall causing the landslides was applied to the simulation. All the simulation results of the landslides prediction and the propagation of debris flow were compared with the observations, and it has been confirmed that the regional-scale analysis conducted in this study can provide a meaningful prediction of possible hazardous areas by the rainfall-induced landslides and debris flows.

Keywords: Regional-scale analysis, Landslide, Debris flow, Rainfall

Introduction

Damages from debris flows have been reported in mountainous areas worldwide. Debris flows can demolish mountainsides, impregnate run-out plains, and cause losses of property and human life. Various studies indicate that increases in landscape exploitation and climate instability can increase the incidence and impact of debris flows (Pierce et al. 2004; Stoffel and Beniston 2006; Jakob and Friele 2010; Hong et al. 2018). Therefore, the prediction of possible hazardous areas due to debris flows is a public and private concern. Various studies have been conducted to predict the occurrence, size, runout distance, speed or velocity, impact force, potential damage and other parameters needed to quantify risk for the prevention of damage to urban areas by debris flows (Jakob et al. 2005; Pastor et al. 2014; Rahman and Konagai 2017; Bru et al. 2017).

Debris flow is a phenomenon that occurs in mountainous and steep slopes and is generally caused by extended landslides. Landslides are caused by deterioration of the slope stability due to rainfall, earthquakes, etc (Kim et al. 2017; Jeong et al. 2018). In particular, landslides caused by rainfall extend to debris flows containing soil and water such as sand, gravel, clay and silt. In this study, a combined method was proposed to analyze rainfall-induced landslides and debris flows.

A combined method for regional scale analysis of landslides and debris flows

The combined numerical method for rainfall-induced landslides and debris flows proposed in this study is a simplified depth-integrated method that performs debris flow simulation. All of the input data, including rainfall, material properties and topographical data, are constructed as a GIS dataset. All of the analytical procedures are conducted on the geometry determined by the presented GIS dataset. First, rainfall-infiltration analysis is performed to calculate the distribution of the wetting front depth based on rainfall data and the hydrological characteristics of the soil beds. The wetting front depth is applied

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as the initial wetting condition in the slope stability analysis and entrainment analysis. The location and thickness of the slope failure (landslides) are estimated from the slope stability analysis. The location and volume of the landslides can be defined as the initial source of debris flow. Fluid mobility and soil erosion are considered in the simulation of debris flows. The Navier-Stokes momentum equation and continuity equation are used to simulate the fluid mobility, and the solution is estimated using the finite volume method. A rheological model (Herschel-Bulkley fluid model) for non-Newtonian fluid is applied to consider the variation of viscosity in accordance with the strain rate. The soil erosion and entrainment by debris flow are also calculated at each cell (point) and time. The erosion depth is estimated based on a modified infinite slope stability model that applies the weight of debris, and the wetting front depth is also considered in this calculation.

Governing equation

In this study, modeling of the debris flow mobility is defined based on continuum mechanics and includes the mechanical and hydrological behavior. Debris flow is defined as a mixture of debris and water and is assumed to be incompressible, unsteady, and characterized by continuous flow. Therefore, the continuity equation (Eq. 1) and the Navier-Stokes equations (Eqs. 2-4) are applied to the governing equations of debris flow mobility.

$$\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz}=0 \tag{1}$$

$$\rho_d\left(\frac{du}{dt}+u\frac{du}{dx}+v\frac{du}{dy}+w\frac{du}{dz}\right)=-\frac{dp}{dx}+\mu\left(\frac{d^2u}{dx^2}+\frac{d^2u}{dy^2}+\frac{d^2u}{dz^2}\right) \tag{2}$$

$$\rho_d\left(\frac{dv}{dt}+u\frac{dv}{dx}+v\frac{dv}{dy}+w\frac{dv}{dz}\right)=-\frac{dp}{dy}+\mu\left(\frac{d^2v}{dx^2}+\frac{d^2v}{dy^2}+\frac{d^2v}{dz^2}\right) \tag{3}$$

$$\rho_d\left(\frac{dw}{dt}+u\frac{dw}{dx}+v\frac{dw}{dy}+w\frac{dw}{dz}\right)=\rho_d g-\frac{dp}{dz}+\mu\left(\frac{d^2w}{dx^2}+\frac{d^2w}{dy^2}+\frac{d^2w}{dz^2}\right) \tag{4}$$

Where u, v and w are the velocity components of the x, y and z directions, ρ_d is the density of the debris flow, μ is the dynamic viscosity, p is the pressure, g is the gravitational acceleration, and t is the time. For debris flow with height h ($=\zeta-\zeta_b$), the governing equations are integrated from $z=\zeta_b$ to $z=\zeta$ for simplification, where ζ_b is the bottom of the debris, and ζ is the top of the debris.

First, the depth-integrated model, which represents the modeling of debris flow in this study, has the geometry of the majority of fast-propagating debris flows, including a low depth-to-length ratio, implying a small vertical velocity component and particles smaller than flow depth, and thus it is possible to use a depth integration approximation. The integrated continuity equation is Eq. (5) and the integrated Navier-Stokes momentum equations are Eqs. (6) and (7).

$$\frac{d}{dx}(FL_x)+\frac{d}{dy}(FL_y)+\frac{dh}{dt}=0 \tag{5}$$

$$\frac{dFL_x}{dt}+\frac{\alpha}{h}\frac{d(FL_x{}^2)}{dx}+\frac{\alpha}{h}\frac{d(FL_xFL_y)}{dy}=-\frac{dH}{dx}gh+\frac{\mu\beta}{\rho_d}\left(\frac{d^2FL_x}{dx^2}+\frac{d^2FL_x}{dy^2}\right)-\mu\sqrt{gh}cos\delta_x tan\varphi-\left(\frac{gFL_x{}^2}{\xi h^2}\right) \tag{6}$$

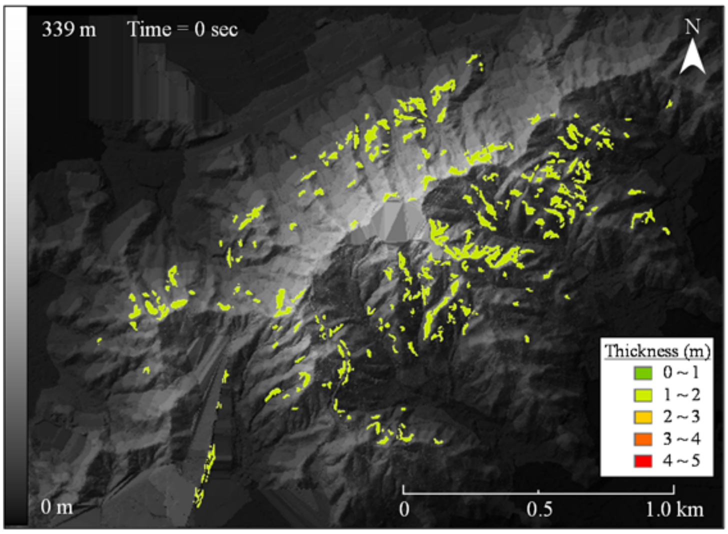
$$\frac{dFL_y}{dt}+\frac{\alpha}{h}\frac{d(FL_xFL_y)}{dx}+\frac{\alpha}{h}\frac{d(FL_y{}^2)}{dy}=-\frac{dH}{dy}gh+\frac{\mu\beta}{\rho_d}\left(\frac{d^2FL_y}{dx^2}+\frac{d^2FL_y}{dy^2}\right)-\mu\sqrt{gh}cos\delta_y tan\varphi-\left(\frac{gFL_y{}^2}{\xi h^2}\right) \tag{7}$$

Where, $FL_x=\int_{\zeta_b}^{\zeta}u\ dz=\bar{u}h$, $FL_y=\int_{\zeta_b}^{\zeta}v\ dz=\bar{v}h$ and $\mu\sqrt{gh}cos\delta tan\varphi-\left(\frac{gFL^2}{\xi h^2}\right)=\frac{\tau_b}{\rho_d}$ is the total resistance between the debris and residual soil defined as a combination of viscous-Coulomb friction flow resistance with normal stress and a turbulent drag resistance with the square of the velocity (Voellmy 1964).

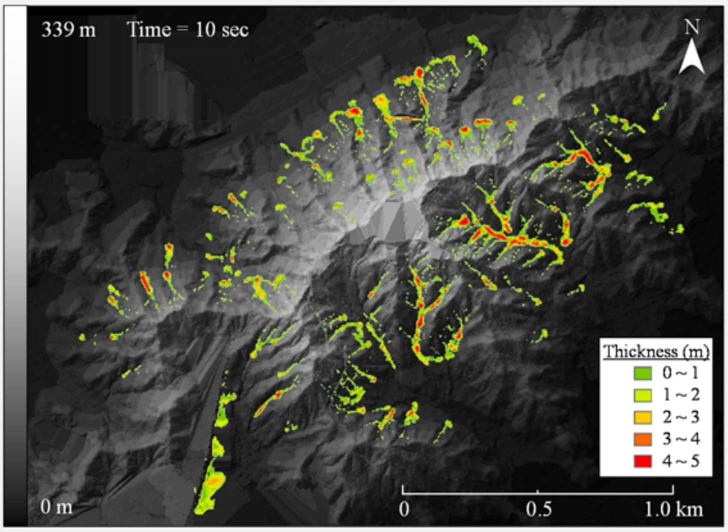
Modeling and numerical results of regional-scale analysis of landslides and debris flows

The study area of Umyeonsan (Mt.) is located in the south-east of Seoul, Korea with a total area of 418 ha and an altitude ranging from 50 to 312 m. This area is also located in a temperate monsoon zone, and most precipitation falls in the summer. Between 8:30 to 8:50 a.m. on July 27, 2011, many landslides and debris flows occurred simultaneously in the study area. A total of 151 landslides and 33 debris flows expanded from one or more landslides were reported (Jeong et al. 2015). According to the Korea Meteorological Administration, the Seoul Observatory recorded 341 mm of rainfall for a period of 72 hours from July 24 to 27, 2011, and 307 mm of rainfall was also observed for the 24 hour period ending at 9 a.m. on July 27. Such heavy rainfall has been noted as a cause of landslides. The hazard had a great impact on property and people because the mountain is located at the center of an urban area, and it led to careful scrutiny of the hazard area and the causes of landslides and debris flows. In this study, simulation of the Umyeonsan (Mt.) landslides and debris flows was conducted based on the observed rainfall information at the time of the landslide occurrence, the site investigation results, and the simulation results were compared with the measured data. The comparison of the results was conducted for the landslide location and the debris flow path.

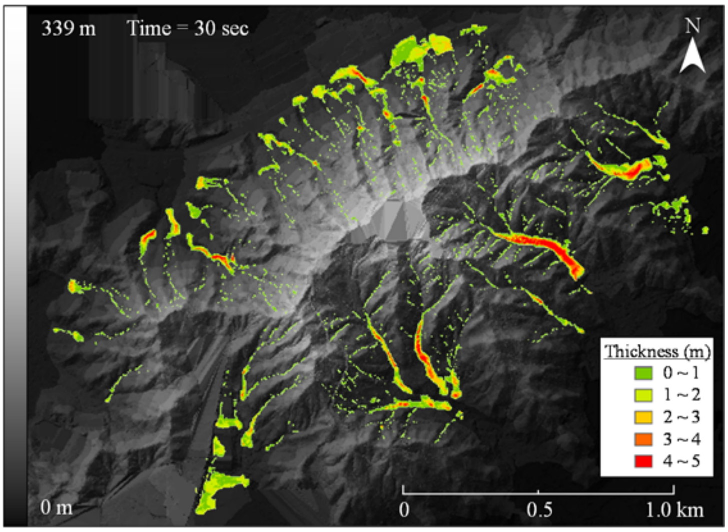
Figure 1 shows the debris flow propagations of the entire study area after the landslide initiation (t = 0). The debris flow from the upstream to the middle of the mountain reaches the downstream after approximately 20 seconds. The sporadic landslides merge into the valley and flow downstream, and the thickness of the debris flow increases due to entrainment with time. Figure 2 shows the predicted landslide and the debris flow paths, and these results are also compared with the measured data reported by Jeong et al. (2015). As shown in Figure 2, the simulation results from the proposed method in this study show good agreement with the historical landslide and debris flows, especially within the detailed site investigation information. However, a difference is observed between the predicted and measured results for the outlying area.



(a) Time = 0.5 sec



(b) Time = 10 sec



(c) Time = 30 sec

Figure 1 Debris flow propagations of the study area from the landslides initiation to 30 sec

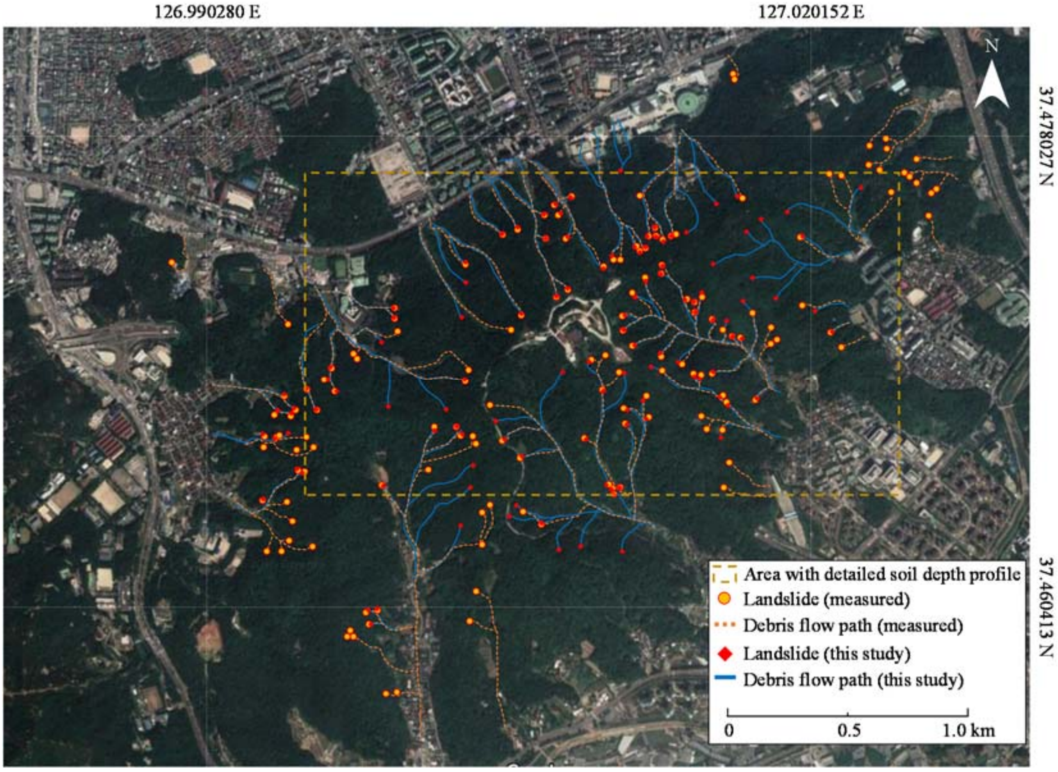


Figure 2 Comparison of the predicted landslides and the debris flow paths with measured data

For quantitative analysis, the confusion matrices of the prediction results are shown in Table 1 with the total area, the area with detailed soil depth profile, and the outlying area. The threat score, which is generally known as the critical success index, is used to verify the prediction results. Three parameters are used to calculate the threat score (TS): area correct (Ac), area forecast (Af), and area observed (Ao). Using the calculated Ac, Af, and Ao parameters, the threat score (TS) is defined as shown:

$$Threat\ score\ (TS) = \frac{Ac}{Af+Ao-Ac} \tag{8}$$

Where Ac is the number of correct predictions, Af is the number of predictions for which the landslide or debris flow occurred, and Ao is the number of all observations. TS ranges from 0 to 1, where 0 indicates no skill, and 1 is the perfect score.

Table 1 Confusion matrices and threat scores of the landslides and debris flows predicted

Confusion matrix				**Threat score (TS)**	**Description**
Landslides	Positives	Negatives	Total	0.717	Area with detailed site investigations and laboratory tests
Prediction (Y)	86	15	101		
Prediction (N)	19	-	19		
Total	105	15	120		
Debris flows	Positives	Negatives	Total	0.810	
Prediction (Y)	17	1	18		
Prediction (N)	3	-	3		
Total	20	1	21		
Landslides	Positives	Negatives	Total	0.288	Area without detailed site investigations and laboratory tests
Prediction (Y)	15	6	21		
Prediction (N)	31	-	31		
Total	46	6	52		
Debris flows	Positives	Negatives	Total	0.214	
Prediction (Y)	3	1	4		
Prediction (N)	10	-	10		
Total	13	1	14		
Landslides	Positives	Negatives	Total	0.587	Whole area
Prediction (Y)	101	21	122		
Prediction (N)	50	-	50		
Total	151	21	172		
Debris flows	Positives	Negatives	Total	0.571	
Prediction (Y)	20	2	22		
Prediction (N)	13	-	13		
Total	33	2	35		

As a result of the threat score calculation, The TS values for the whole area are 0.587 for landslide prediction and 0.571 for debris flow prediction. Specifically, in the case of landslide prediction with detailed site investigations and laboratory tests, TS is estimated as 0.717 and that of debris flow prediction is 0.810. However, in the case of the area without detailed site investigations and laboratory tests, TS is 0.288 for landslide prediction and 0.214 for debris flow prediction.

Conclusion

The major purpose of this study is to propose a combined numerical method for analysis of rainfall-induced landslides and debris flows. The term "combined" means a combination of landslide and debris flow analysis, and it is completed by considering the results (landslides prediction and the wetting condition) of landslide analysis in the debris flows analysis as the initial source of debris flows and the initial wetting condition for entrainment analysis. The following conclusions can be summarized from the findings of this study:

(1) A numerical method was proposed to simulate landslides and debris flow by combining rainfall-infiltration analysis and slope stability analysis with consideration of debris flow mobility and soil entrainments. These calculation processes were developed based on GIS for a regional-scale analysis.

(2) By using the model developed in this study, it is possible to simulate not only reverse analysis after events but also the expandable debris flow induced by the input rainfall applied in engineering practice.

(3) As a result of the threat score calculation for the case of Umyeonsan (Mt.) debris flows, the TS values for the entire area are 0.587 for landslide prediction and 0.571 for debris flow prediction. Specifically, in the case of landslide prediction with detailed site investigations and laboratory tests, TS is estimated as 0.717 and that of debris flow prediction is 0.810. However, the TS is 0.288 for landslide prediction and 0.214 for debris flow prediction, in the case of the area without detailed site investigations and laboratory tests for mechanical and hydrological properties of soils.

Acknowledgements

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2018R1A6A1A08025348).

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