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Volume estimation and assessment of debris flow hazard in Mt Umyeon, Seoul

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ABSTRACT

Debris flows develop rapidly and are widespread, estimating their volumes is difficult. To establish an effective plan for mitigating the hazards of debris flows, estimating the volumes of the potential debris flows is essential. The debris flow volume was estimated using Digital Elevation Models (DEMs) of two different periods. The debris flow caused a volumetric loss of 37882 m3, which passes through the basin outlet. Two dimensional debris flow simulation was used to calculate runout propagation and to find depth and velocity as well. The maximum velocity nearby source area was about 12 m/s. The maximum depth of deposition was found to be 2.8 m in front of Shingdonga Apartment.

INTRODUCTION

In Korea, the frequency of unusual weather events, such as cold waves, heavy snowfall, typhoons, and heavy rainfall, has increased. Data on the frequency of torrential rain have shown a 25% increase in torrential rainfall events and a 60% increase in heavy rain warnings over the past 20 years. Over 75 % of the land of Korea is composed of mountainous terrain with steep and weathered soil slope. In recent years, the growing population and the expansion of settlements and developments over landslide-prone areas are increasing the impacts of landslide disasters on human lives and life-line facilities.

Statistical analyses of the behavior and effects of debris flow have been conducted in several mountainous countries including Asian and European countries. These studies have mainly focused on the estimation of hazard areas (Carrara et al. 1991; Bai et al. 2009; Cervi et al. 2010). Such statistical approaches do not consider the mechanisms that determine slope failures but rather assume that predictions of future landslide areas can be made based on measurements of variables that have led to landslides in the past. Numerical run-out modelling for debris flow assessment is a relatively new research field. The problem in the application of such models is the difficulty in parameterization of the run-out models and the link between the modelling of initiation susceptibility (Chang et al. 2010) and the volume information for the subsequent run-out analysis

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In this research, after identifying the failure source area and estimating volume of the sliding mass with DEM comparison, the run-out behavior was simulated with two-dimensional numerical model of debris flow. To establish an effective plan for mitigating the hazards of debris flows, estimating the volumes of the potential debris flows is essential. Because landslides and debris flows develop rapidly and are widespread, estimating their volumes is difficult. When several events occur simultaneously in different locations, to estimate their magnitudes is expensive and time consuming. The size and volume of the flows must be calculated, but gaining access to the sites is often difficult. In these cases, empirical estimates can be used to evaluate the volumes of the debris flows (Kim et al. 2014).
The debris flow at Umyeon Mountain was initiated by heavy rainfall both antecedent and daily rainfall. Saturated ground moved like a flow and hit residences and vehicles under the slope. The main cause of debris flow in Umyeon area was rainfall, which classify into two different ones based on the temporal variation. Rainfall-induced landslides with slope failure and debris flow occurred in four villages of Raemian, Shingdonga, Jeonwon, and Hyeonchon at Umyeon Mountain. The landslides rapidly expanded into a fast debris flow spreading throughout the narrow and sloping roads. In this study only Shingdonga catchment is considered.

METHODS

Volume estimation

A DEM is a digital cartographic/geographic dataset of elevations in xyz coordinates. The terrain elevations for ground positions are sampled at regularly spaced horizontal intervals. In this study, the volume of debris flow was calculated by topographic changes between two 5×5 m resolution Digital Elevation Models (DEM) of before and after 2011 July debris flow event in Umyeon Mountain as shown in Fig. 1.

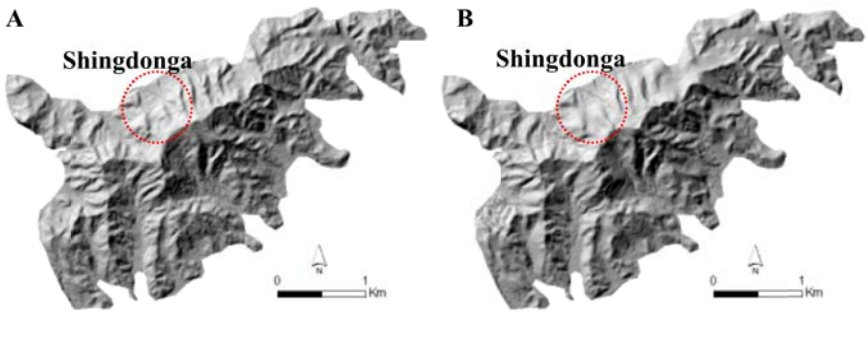

Fig. 1 Hillshade of DEM from (A) before and (B) after debris flow

Two DEMs were overlaid and the change of elevation in each pixel was obtained using raster calculation tool in ArcGIS 10.2 environment. These data sets generally include naturally occurring terrain changes. To minimize uncertainty due to time difference and the most significant terrain changes occurred along the channel, thus only the affected channel of Shindoga catchment was considered to analysis.

Two-dimensional numerical model of debris flow

The key requirements in the assessment of debris flow consists of the prediction of the flow trajectory over the complex topography, the potential run-out distance and the inundation area in order to define a safety zone. The main inputs are topography and initial debris source distribution and its corresponding triggering locations. There is no need to input Manning's n value, but an accurate value for yield stress must be measured from samples. But for a rough estimation, yield stress value can be estimated with grain size and composition.

The governing equations are mass and momentum conservation with shallow water assumption. The coordinate system is the Cartesian coordinate with the average bed elevation as x-axis. The used constitutive relation is the 3-D generalization of Julien and Lan (1991).

$$\tau_{ij} = \left(\frac{\tau_o}{\varepsilon_{II}} + \mu_d + \mu_c \varepsilon_{II} \right) \varepsilon_{ij} \text{, for } \tau_{II} \geq \tau_o \text{,} \tag{1}$$

$$\varepsilon_{II} = 0 \text{, for } \tau_{II} < \tau_o \text{,} \tag{2}$$

where

$$\varepsilon_{II} = \left(\frac{1}{2} \varepsilon_{ij} \varepsilon_{ij} \right)^{1/2} \text{, } \tau_{II} = \left(\frac{1}{2} \tau_{ij} \tau_{ij} \right)^{1/2}$$

$$\text{and } \varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

and $(i, j) = \{x, y, z\}$; ε_{ij} is strain-rate tensor; τ_0 is yield stress; μ_d and μ_c are dynamic viscosity and turbulent-dispersive coefficient respectively. Equation (1) represents the constitutive relation in the region where the shear stress is greater than yield stress; Equation (2) is for the region with shear stress less than yield stress.

After simplification, the resulting governing equations in conservative form are conservation of mass

$$\frac{\partial H}{\partial t} + \frac{\partial (uH)}{\partial x} + \frac{\partial (vH)}{\partial y} = 0 \text{,} \tag{3}$$

and conservation of momentum in x- and y-directions

$$\frac{\partial (uH)}{\partial t} + \frac{\partial (u^2 H)}{\partial x} + \frac{\partial (uvH)}{\partial y} = gH \sin\theta - gH \cos\theta \frac{\partial B}{\partial x} - gH \cos\theta \frac{\partial H}{\partial x} - \frac{1}{\rho} \frac{\tau_o u}{\sqrt{u^2 + v^2}} \text{,} \tag{4}$$

$$\frac{\partial (vH)}{\partial t} + \frac{\partial (uvH)}{\partial x} + \frac{\partial (v^2 H)}{\partial y} = - gH \cos\theta \frac{\partial B}{\partial y} - gH \cos\theta \frac{\partial H}{\partial y} - \frac{1}{\rho} \frac{\tau_o v}{\sqrt{u^2 + v^2}} \text{,} \tag{5}$$

where $H(x, y, t)$ is flow depth; $B(x, y)$ is the fixed bed topography; $u(x, y, t)$ and $v(x, y, t)$ are depth-averaged velocities in x- and y-direction respectively; $\tan\theta$ is the bottom bed slope; τ_0 and ρ are debris-flow yield stress and density, which are all assumed to be constant; g is the gravitational acceleration. The effects of bottom erosion and deposition are not considered in this version.

$$\left(\frac{\partial B}{\partial x}+\frac{\partial H}{\partial x}-\tan\theta\right)^2+\left(\frac{\partial B}{\partial y}+\frac{\partial H}{\partial y}\right)^2 > \left(\frac{\tau_0}{\rho g\cos\theta H}\right)^2. \quad (6)$$

The derivative of B and H represent pressure effect and $\tan\theta$ is the gravitational effect. The right hand side is the resistance from yield stress. As is shown in Equation (6), debris flow can move only if pressure and gravitational effects exceed the yield stress effects.

Finite difference method is applied to discretize the governing equations, i.e., Eqs. (3), (4) and (5). In spatial discretization, the 1st-order upwind method is applied to discretize convective term and 2nd-order central difference method is used for the remaining terms. The explicit 3rd-order Adams-Bashforth method is used for time advancing. During computation, if the maximum velocity in the whole computational domain is less than numerical error, the computation terminates automatically.

RESULTS AND DISCUSSION

The longitudinal and cross-sectional profiles from the most important flow lines were extracted from both DEMs. The analysis showed that extensive slope failures occurred steep slopes. Total changes in elevation was determined by subtracting between DEMs before and after event.

To estimate the total volume each pixel was multiplied by pixel area. The pixel by pixel calculations within the debris flow channels were 49940.75 m^3 of erosion and 12057.6 m^3 of deposition. Thus, the debris flow caused a volumetric loss of 37882 m^3, which passes through the basin outlet. For the event simulation, first four major locations of landslide were first identified. And corresponding estimated soil volume was used.

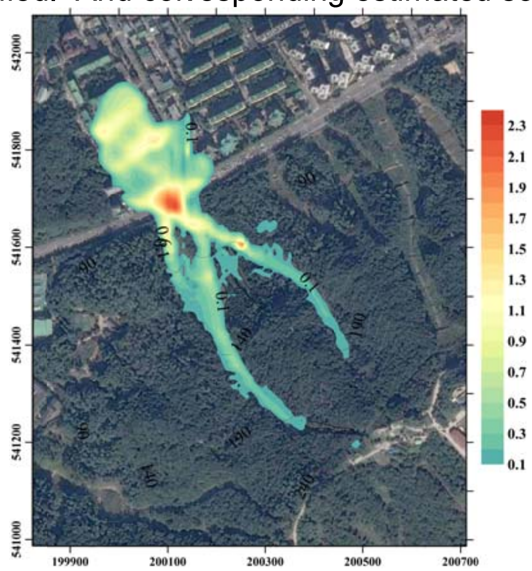

Fig.2 Propagation and maximum flow depth

After debris flow event, the deposition is composed of large quantity of gravels with sand and mud. From the composition of the soil, the yield stress was estimated as 150 pa. Then the time interval of output was set as to be one second real time. One location in front of Shindonga Apartment was selected for result output to observe the flow velocity and flow height in the time at that point. As the simulation result shows, the total process of the transportation of the debris flow was about 133 minutes. The maximum velocity nearby source area was about 12 m/s. The maximum depth of deposition was found to be 2.8 m in front of Shingdonga Apartment as shown in Fig 2. The temporal variation of flow depth in front of Shingdonga Apartment was determined and the maximum depth was about 0.85 m at 150 seconds.

CONCLUSION

This study describes an effective method for estimating the volume of debris using DEMs from before and after debris flow event. The method is applied Shingdonga catchment of Umyeon Mountain in Seoul. Since the actual inundated areas are controlled by the volume of the landslide mass, thus volume estimation is very important. The cell by cell erosion volume was calculated as 49940.75 m^3 and 12056.6 m^3 of deposition. Thus volumetric loss of 3788.2 m^3, which passes through the basin outlet. Most of the debris flows originally occurred in the form of rainfall-induced landslides before they move into the valley channel. The simulation procedure to model potential propagation and inundation area. The result accurately model the historic debris flow. The maximum depth of deposition was found to be 2.8 m in front of Shingdonga Apartment.

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