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Roles of barrier location for effective debris flow mitigation: assessment using DAN3D

Shin-Kyu Choi[a], Tae-Hyuk Kwon [a,*], Seung-Rae Lee[a] , and Joon-Young Park[b]

[a]*Dept. of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Daejeon 305701, KOREA*
[b]*Geo-Environmental Hazards Research Center, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Daejeon 34132, KOREA*

Abstract

Debris flows can travel at rapid velocities and can cause economic and societal damages. Accordingly, barriers that can dissipate the energy of debris flows are frequently installed as a mitigation measure. However, the effect of barriers on debris-flow behavior is not fully understood. In this study, we used DAN3D to investigate the interactions between a debris flow and barriers, and evaluate the effect of barrier location on debris-flow velocity and volume. We chose a study site in Seoul, Korea, where a debris-flow event occurred in 2011. At the site, we numerically installed a closed-type barrier at four different locations along the flow path in the watershed. We then simulated the debris flow while monitoring debris-flow velocity and volume. The barriers decreased the velocity and volume of the debris flow compared to a simulation with no barrier. In particular, installation of the barrier at the upstream portions of watersheds resulted in the greatest reduction in velocity. Installation of the barrier at downstream portions of watersheds resulted in the greatest deposition of volume. These results contribute to a better understanding of debris-flow behavior associated with the installed barriers as a mitigation measure, and can be used for optimum and efficient design of the debris-flow barriers.

Debris flows; Debris-flow barrier; Location; Velocity; Volume; Entrainment

1. Introduction

Recently, damage caused by landslides has increased due to heavy rainfall. Debris flows, a flow-like type of landslides can travel at extremely rapid velocities and entrain basal channel materials with scouring. Installing debris-flow barriers that can dissipate the energy of debris flows is one of the frequently used methods for preventing damages.

Many researches have conducted small-scale experiments to verify the effect of debris-flow barriers (Wenbing and Guoqiang, 2006; Lim et al., 2008; Takahara and Matsumura, 2008; Canelli et al., 2012; Kim et al., 2013; Xie et al., 2014; Ng et al., 2015; Choi et al. 2018). Also, research on flow patterns of debris flows using numerical analysis has been carried out (Remaître et al., 2008; Kwan et al., 2014), but only a little research has been done on analyzing the influence debris-flow barriers on debris-flow characteristics (Remaître et al., 2008; Jeong et al., 2015). Therefore, there is a need for research on this topic.

In this study, we explored the influence of a debris-flow barrier on characteristics of a debris flow that occurred during heavy rainfall in Woomyeon Mountain, Korea in 2011. A closed-type barrier that traps all of the debris-flow sediment and water was numerically installed separately at four locations along the debris-flow channel, and 2011 debris flow was then simulated. The effect of the closed-type barrier on characteristics of the debris flow was evaluated with respect to velocity and volume. In all cases, the closed-type barrier significantly reduced velocity and volume compared to the 2011 debris flow without the barrier. Our results contribute to a better understanding of debris-flow behavior associated with installed barriers as a mitigation measure, and can be used to determine an optimum and efficient design for debris-flow barriers.

* Corresponding author e-mail address*: t.kwon@kaist.ac.kr*

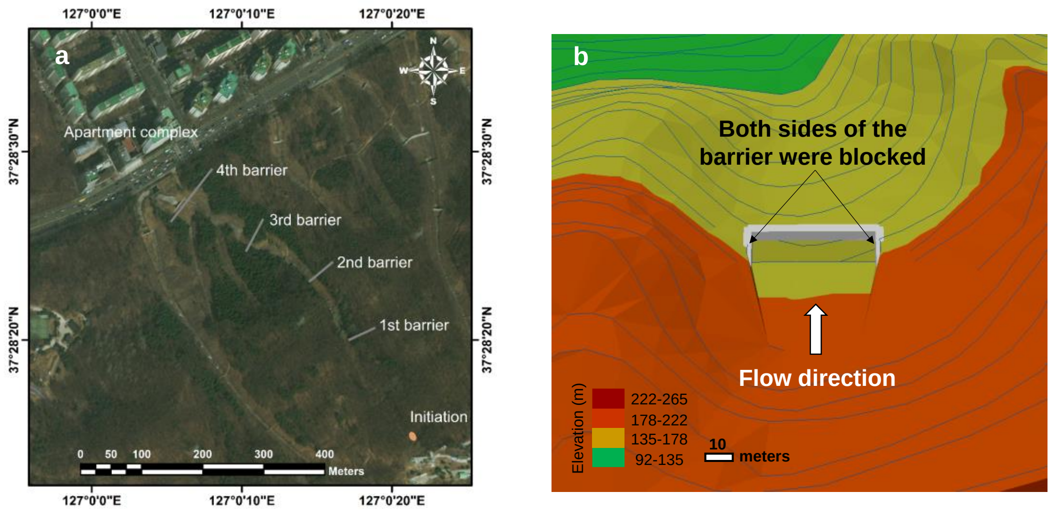

Fig. 1. (a) Locations of the numerical barriers and debris-flow initiation area; (b) Schematic description of barrier installation

2. Numerical code

2.1. Governing equation

DAN3D (Dynamic Analysis of Landslides in Three Dimensions; McDougall and Hungr, 2004, 2005) is a commercially available code that simulates the flow dynamics of viscous, liquid-like debris. This numerical code is based on a smoothed particle hydrodynamics (SPH) method that was first developed by Hungr (1995). Changes in a complex 3D terrain cause non-hydrostatic, anisotropic internal stresses, which strongly affect landslide dynamics. The governing equations of DAN3D are composed of mass conservation equation and momentum conservation equations.

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}\right)=\frac{\partial b}{\partial t} \tag{1}$$

$$\rho h\frac{\partial v_x}{\partial t}=\rho h g_x+k_x\sigma_z\left(-\frac{\partial h}{\partial x}\right)+k_{yx}\sigma_z\left(-\frac{\partial h}{\partial y}\right)+\tau_{zx}-\rho v_x\frac{\partial b}{\partial t} \tag{2}$$

$$\rho h\frac{\partial v_y}{\partial t}=\rho h g_y+k_y\sigma_z\left(-\frac{\partial h}{\partial y}\right)+k_{xy}\sigma_z\left(-\frac{\partial h}{\partial x}\right)+\tau_{zy}-\rho v_y\frac{\partial b}{\partial t} \tag{3}$$

Where, h is the bed-normal flow depth, ρ is the material bulk density, t is time, v is flow velocity, b is the bed-normal erosion-entrainment depth, g is the acceleration due to gravity, k is the stress coefficients.

DAN3D simulates the local divergence (or convergence) of landslides flowing over complex 3D topography by using Rankine's earth-pressure theory (Rankine, 1857). The DAN3D code can incorporate the increase in debris-flow volume based on the effect of momentum transfer between the main flow and the bed materials, assuming that the exponential growth in volume is correlated with the displacement of the debris flow. This code can utilize any of five different rheology models: Newtonian, Plastic, Bingham, Frictional, or Voellmy.

2.2. Rheological model

The volume increases due to entrainment phenomenon at the bottom of the channel can be considered with erosion rate and the flow characteristics (velocity and deposition) can be controlled by the rheological models. Among the rheology models, many researchers have used the Voellmy model for analysis of the debris flows. The voellmy model was originally developed to analysis snow avalanches (Voellmy, 1955; McDougall, 2017). However, the model began to be used for landslide analyses because ranges in the velocity and thickness of snow avalanches are similar to landslides (Korner, 1976; McDougall, 2017). The Voellmy model requires frictional and turbulence coefficient values as input parameters. The frictional coefficient is related to the deposition characteristics of debris flows, and the turbulence parameter is related to the velocity of debris flows (McDougall, 2017). For debris flows, the frictional coefficient previously used was in the range of 0 to 0.3 and the turbulence parameter was in the range of 0 to 1000 m/s^2. Most debris flows in Korea have extremely rapid velocity (measured maximum velocity was 28 m/s) due to high water content from heavy rainfall. In order to satisfy these high-velocity characteristics, a low frictional coefficient and a high turbulence parameter were used in this study.

3. Case study

3.1. Research area

The study area was Mt. Woomyeon, located in Seoul, South Korea. Mt. Woomyeon has a maximum elevation of 293 m above sea level and is surrounded by buildings and roads within an area of 5,104,162 m^2 (Park, 2014). Korean Society of Civil Engineers (KSCE) reported that 33 debris flows occurred from ~150 landslides on July 26–27, 2011. The estimated financial loss was approximately US$15 million, with sixteen lives lost (KSCE, 2012).

One of the debris-flow events occurred in the Sindonga watershed, Mt. Woomyeon was chosen for this study. This event has been previously investigated by KSCE (2012). For the Sindonga debris flow case, the watershed area, runout length, average slope angle of the channel were 214,400 m^2, 633.6 m, and 17.5°, respectively. The event consisted of three debris flow that coalesced in the main watershed channel and had a total combined volume of 45000 m^3. All input parameters used for the back-analysis were based on the field investigation (KSCE, 2012). The debris flow reproduced by the back-analysis had the frictional coefficient of 0.03, the turbulence parameter of 800 m/s^2 and the erosion rate of 0.0078 m^{-1}. A debris flow that flowed out to the Sindonga apartment complex was selected as a reference case (Case REF) for numerical modeling in this study (Fig. 1a).

3.2. Condition of debris flow barriers

The effect of location of barrier installation was examined numerically. The distance (L) between the debris source and the roadway near to the Sindonga apartment was 596 m (Fig. 1a). Four locations along the debris-flow channel were determined; thereby, a barrier was placed at 0.3L (i.e., 179 m far from the debris source; Case 1), 0.5L (i.e., 298 m far from the debris source; Case 2), 0.7L (i.e., 417 m far from the debris source; Case 3), or 0.9L (i.e., 537 m far from the debris source; Case 4). The barriers were created by numerically increasing elevation values in the topography file to achieve the desired shape and size using ArcGIS 10.5 (Fig. 1b). The barrier was installed to be perpendicular to the debris flow direction. The barrier width was determined to be two times wider than the width of the front part of the reference debris flow occurred in 2011; it resulted in 48 m wide (Case 1), 50 m wide (Case 2), 60 m wide (Case 3), and 110 m wide (Case 4). The height and thickness of all barriers were set to be 7 m and 3 m, respectively (Table 1). Surface erosion near the barrier was prevented by setting the no erosion zone which was 50 m long and 50 m wide in the upstream and downstream sides of the barrier. Total five simulations, one without the barrier (or reference case; REF) and four with the barrier (Cases 1-to-4), were conducted, as shown in Table 1.

4. Results

Figure 2a shows temporal changes in velocities of the modeled debris flow with respect to the barrier locations, respectively. Herein, as the SPH method was used, the velocity of moving debris flows was determined from the average velocity of all moving particles. When any overflow was observed in some cases, the velocity represented the average velocity of the overflowed particles. The results indicate that debris-flow velocity gradually increased to approximately 7 m/s due to the steep slope angle in the upper part of the flow path, then gradually decreased as the debris flowed downslope. Each time that the debris collided with a barrier, the velocity decreased over time compared to the actual debris flow. Particularly, debris flows were not transferred to downstream in Case 1. In Case 4, debris flows were almost entirely deposited and only about 131 m^3 of material was transferred to downstream locations. Immediately after the collision of barriers, velocities decreased to zero in the front part, but debris flows continuously come in. When volume of debris flows exceeded allowable deposition of the barrier, overflow was generated and velocities increased as it passed downstream due to the steep slope. This tendency occurred frequently in the downstream locations because volume of the debris flow grow further by entrainment to the downstream. In Cases 2 and 3, the overflowed debris slightly gained their velocities, mainly due to the steep slope after the barriers, and their volumes also increased due to the entrainment as those flowed downslope along the flow path. If there was no entrainment effect, the overflowed volume is expected to stay constant while the velocity is primarily determined by the slope of the channel.

Table 1. Barrier conditions

Case name	Number of barriers	Width of the reference debris flow (m)	Width of the barrier (m)	Height of the barrier (m)	Thickness of the barrier (m)	Distance from the source (m)
1	1	24	48	5	3	179
2		25	50			298
3		30	60			417
4		55	110			537
REF	0	-				

Figure 2b shows the volume of the moving segments (or particles). The debris reached a volume of 4100 m^3 as it approached the downstream roadway at 85 s in Case REF. Upon the barrier installation, the debris volume was significantly reduced to less than 1000 m^3 in all cases with the barrier. As the debris overflowed the barrier in Cases 2, 3, and 4, the volume slightly increased.

Toward the downstream area, the barrier became huge because of the increased debris volume and the widened channel width. The volume of the deposited debris (e.g., 200 m^3 for Case 1, 600 m^3 for Case 2, 1200 m^3 for Case 3, and 2800 m^3 for Case 4) progressively increased as the barrier location became more distant from the source area. These results implies that it is better to install a barrier near the source location, if it is predictable, before the debris grow further by entrainment. However, it is a daunting task to predict the source location, and thus, either multiple barriers along a debris flow channel or one gigantic barrier at the downstream is expectedly required, when the large-scale debris flow is predicted.

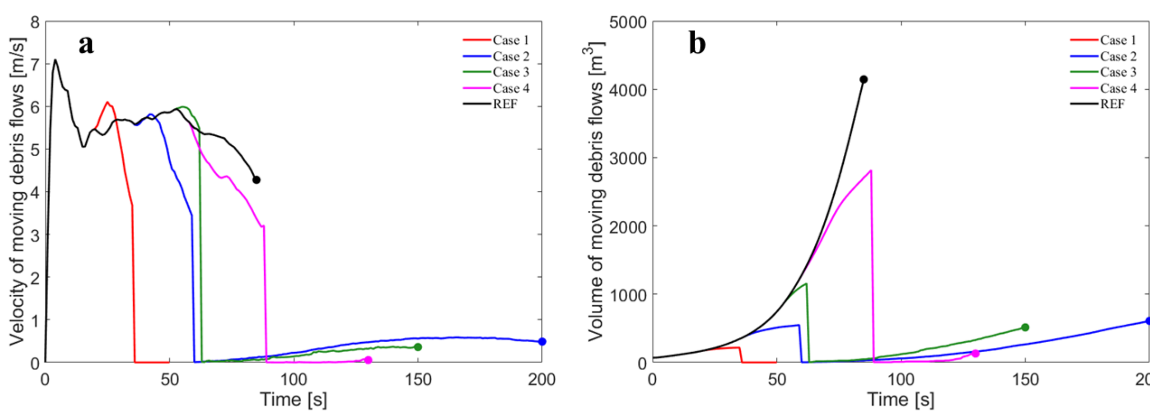

Fig. 2. (a) Changes of the average velocity; (b) Distribution of the volume of moving debris flows. Dots indicate the time of access to the village

5. Conclusion

The effects that barrier locations along a channel have on debris-flow behavior have been explored using the DAN3D numerical code. Temporal changes in debris-flow velocity and volume were observed for scenarios with and without barriers. The velocity of the debris flow significantly decreased at barriers and small volume (< 600 m^3 in Case 4) of the debris flow was transferred to downstream locations. After collision with the barrier, the velocity of the overflowed debris flow increased again due to the steep slope after the barrier. Our work shows that it is possible to prevent debris flows from being transferred downstream by installing one barrier in a proper location when the scale of debris flow is small (< 200 m^3 in Case 1). Because volume of debris flows around the source and the width of the channel are small, the debris flow can be adequately blocked by small-sized barrier. However, it is difficult to install due to problems with the access road. Large-sized barrier should be installed because the volume increases by entrainment and the width of the channel grows as progressed downstream. For this reason, optimum location is required. These results can be used for optimum and efficient design of the debris-flow barriers.

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