Analysis of mitigation effect of the open- and closed-type check dam

Seungjun Kim, Hyunuk Kim, Minseok Kim

Abstract. Debris flow caused by intense rainfall can damage a range of properties and endanger human life. Therefore, constructing a check dam is essential to mitigating the damage scale (casualties and property damage). However, the optimal siting conditions for the two types of check dams vary and is difficult to determine. Therefore, we sought to reduce debris flow damage through optimally siting the two types of dams.

1 Introduction

Landslides and debris flows can transport sediment and boulders over long distances and comprise one of the most frequent natural disasters. However, because they combine water, sediment, boulders, and flotage, simulation and analysis is difficult.

Various methods for analyzing and predicting the debris flow have been developed, in keeping with the development of computing power. These can be divided into numerical modeling and artificial intelligence (AI)-machine learning. Further, numerical models are divided into physical and conceptual–empirical models. The physical model is advantageous because it considers physics-based parameters, such as soil depth, water content in the debris flow, density of particles, and rainfall intensity. Therefore, it may be useful in elucidating the physical mechanism behind debris flow. However, representing the physical parameters is challenging. Moreover, applying it to a warning system is challenging because of the excessive computation time. In contrast, the statistics-based AI model requires a short computation time to calculate the debris flow. However, utilizing it when there records of debris flow are limited is problematic. Using a numerical model based on a conceptual–empirical algorithm to figure out the flow process may be difficult. However, this method was validated over the past three decades by adequately simulating debris flow. Further, the simulation time is short. Therefore, we chose the numerical model based on a conceptual–empirical algorithm to simulate the debris flow.

The warning system based on numerical and AI modeling can shorten the evacuation time and lower casualties. However, it is impossible to reduce property damage using a warning system. Therefore, constructing a check dam is essential to mitigating the damage scale (casualties and property damage). However, the optimal siting conditions for the two types of check dams varies and is difficult to determine. Therefore, we sought to reduce debris flow damage through optimally siting the two types of dams.

2 Material and methods

2.1 Governing equation and numerical modeling

In this study, Deb2D, which was developed by An et al. [1], was used to simulate the debris flow. This model is based on a hyperbolic conservation form of the mass (shallow-water equation). Please refer to An et al. [1] and An et al. [2] for detailed definitions and calculation methods for discrete terms.

This study focuses on a one-phase modeling approach due to its simplicity and applicability. Further, the widely used Voellmy, Bingham, and Coulomb-viscous rheological models, as well as Takahashi models, are considered here. The Voellmy friction is expressed as follows:

$$S_v = \mu_v gh + \frac{g|\mathbf{v}|}{\zeta}$$

(3)

where $\mu_v$ is the Coulomb friction coefficient, and $\zeta$ is the turbulent friction coefficient. The Bingham friction is expressed as follows:

$$S_v = \frac{\tau}{\mu_v} + \frac{\mu_v |\mathbf{v}|}{h}$$

(4)

$$S_v = \frac{\tau}{\mu_v} + \frac{\mu_v |\mathbf{v}|}{h}$$

(5)
where $\rho$ is the mass density, $\tau_b$ is the yield stress, and $\mu_b$ is the Bingham viscosity. The Coulomb-viscous friction is expressed as follows:

$$S_a^b = g h \frac{\phi + \frac{\mu_b}{\rho}}{\rho} \frac{V}{h}$$

where $\phi$ is the friction angle between the bed material and surface, and $\mu_b$ is the Coulomb-viscous viscosity. Finally, the Takahashi model calculates the resistance by classifying the characteristics of debris flow into 1) stony, 2) immature, and 3) turbulent-muddy debris flows. The Takahashi friction for a stony debris flow ($C \geq 0.4C_s$) is expressed as follows:

$$S_a = \frac{d_m}{h} \left( \frac{C + (-C) \rho_s/\rho}{(C_s/C) - 1} \right) \frac{V}{h}$$

Immature debris flow occurs when $C$ is less than 0.4$C_s$, and the resistance at the bottom of flow is expressed as follows:

$$S_a = \frac{d_m}{h} \left( \frac{C + (-C) \rho_s/\rho}{(C_s/C) - 1} \right) \frac{V}{h}$$

A turbulent-muddy flow occurs when $C$ is less than 0.02, and the bottom flow resistance is expressed as follows:

$$S_a = \frac{\rho_m h^3}{\rho_b h^3} \frac{V}{h}$$

where $d_m$ is mean sediment diameter, $C$ is the sediment concentration in the flow, $C_s$ is maximum sediment concentration in the basal, $\rho_s$ is the density of water, $\sigma$ is the density of the sediment particle, $\rho_T$ is mixture density ($\rho_T = \sigma C + (1 - C) \rho_s$), and $n$ is the Manning’s roughness coefficient of the channel. More details can be found in the work of Takahashi [3]. We use the algorithm proposed by Lee et al. [4], which is based on Lee et al. [5]. It can simulate erosion, entrainment, and deposition. Please refer to [4] for details on the algorithm.

Before simulating the debris flow event to analyze the check dam, we validate the four rheological models using Sun et al.’s experimental procedure [6].

### 3 Validation

We compare the simulation results from the four rheological models with the experiment results. Fig. 1 presents the experimental condition. Using six check-dam designs, we validate the simulation performance in each case. The simulation and experiment results of each rheological model are depicted in Fig. 2. The Voellmy and Takahashi models exhibit reasonable performance. The former is advantageous for parameters calibration, so we use it to simulate the debris flow.

### 4 Study area

Several debris flows occurred (rainfall amount: 500 mm/day; maximum rainfall intensity: 80 mm/h) in the Umnyeon Mountain area on July 26 and 27, 2011 due to torrential rainfall. The water-laden debris flows caused significant property damage in the downtown areas. We simulate the Raemian apartment basins, for which field data are abundant (Fig. 3).

Landslides-debris flows occurred at four points, marked in red, in the Raemian apartment basin [7]. The observed channel lengths in the Raemian basins were reported to be 610 m. The final volume of deposited sediment was 26,000 m$^3$. The maximum velocity was determined from CCTV footage and dashboard cameras in cars. It was estimated as 28 m/s in the Raemian apartment blocks. These debris-flow events caused direct damage to the 3rd floors of the Raemian apartment [7]. In this study, the erodible soil depth is between 2 m and 5 m [7]. A digital elevation model, utilizing light detection and ranging (1 m × 1 m), was used to build the terrain. The initial volume of debris flow was measured as 350 m$^3$.

The check design was divided into 1) closed type: 1.1) height (5, 10 m); 1.2) distance from initiation zone (section 1–7); 2) open type: sections 1–7. However, sections 6 and 7 were too wide for the construction of a check dam. Therefore, the mitigation effect of the check dam, located in sections 1–5, was analyzed to identify the best construction location according to the check dam design (design type, height, and location). The thickness of the check dam was fixed at 4 m.
5 Results

Fig. 4 presents the simulation results when the closed-type check dam was designed with a height of 5 m. The damage scale in the absence of the check dam was 26 310 m$^3$ (Fig. 4a), which is close to what was observed (26 000 m$^3$). This finding was used as the standard for analyzing the mitigation effect. Fig. 4b–f presents the simulation results. Fig. 4b–d shows that the check dam located in the upper part of the basin achieved decent performance. Specifically, the check dams located in sections 1 and 2 achieved mitigation ratios of 11.35% and 10.76%, respectively. However, efficiently reducing the damage due to debris flow using a 5 m check dam proved challenging.

The simulation result for a 10 m-high closed-type check dam is depicted in Fig. 5. Fig. 5a presents the simulation result in the absence of a check dam, and Fig. 5b–d shows the results of the check dam being located in the upper part of the basin, with decent performance being realized. Notably, the check dam located in section 2 achieved a mitigation ratio of 48.71% (Fig. 5c). The check dams in sections 1 and 3 also realized decent mitigation effects (44.31% and 42.21% of mitigation ratio).

Thus, the mitigation effect was approximately 35% higher when the check dam was designed with a height of 10 m rather than 5 m. Figs. 4 and 5 reveal that it is preferable to construct a closed-type check dam in the upper part of the basin.

Fig. 6 presents the simulation result for a 10 m high open-type check dam. The open type also achieved decent performance when the check dam was constructed at section 1 (Fig. 6b), which is located in the upper part of the basin. Siting the check dam in section 1 yielded a 12.99% mitigation ratio. However, the check dam located in section 5 achieved the worst mitigation effect of approximately -7.89%, implying that installing the check dam made the damage worse.

According to Figs. 4–6, the mitigation effect was best when the check dam was close to the initial dam area, regardless of the design of the check dam.

6 Conclusions

The two types of check dams were hypothesized in a debris flow catchment in South Korea to analyze the mitigation effect. Although we divided the design of the check dam, when we hypothesize the check dam on the upper side of the catchment, it presents the best performance. However, in order to effectively reduce debris flow damage, a check dam needs to be constructed at a height above a certain level. Because the Raemian apartment debris flow was water-landed, the open-type check dam cannot reveal a decent mitigation effect. The closed-type check dam presented a high mitigation effect, which has an advantage in effectively trapping the water-laden debris.
However, we simulated only one debris flow event (water-laden), so it will be necessary to analyze different events in the future to precisely and comprehensively figure out the effect of the check dam.

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References