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ECP-DEBRIS-BARRIER: OPTIMAL DEBRIS-FLOW BARRIER DESIGN FRAMEWORK

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The risk of damage from debris flow hazards can be mitigated by installing barriers, such as check dams and baffles, at channel or mountain bases. Current barrier mitigation design frameworks often rely on advanced three-dimensional computational fluid dynamicsmodels to simulate debris flow runouts and to evaluate the mitigation performance of barriers against debris flow. However, these dynamic modelsare inefficient due to significant computation time, leading to sub-optimized design solutions or requiring costly hardware.This study introduces the ECP-debris-barrier, a streamlined framework for designing effective mitigation barriers with these steps: (1) performing a runout analysis to evaluate debris flow dynamics with an efficient ECP-debris runout model, (2) using a clustering analysis to quantify the debris flow propagation into a network data structure,(3) usinga search optimization algorithm to lay outan optimal barrier design based on engineering and sustainability criteria. The ECP-debris model uses core principles like entrainment and energy conservation to track debris flow paths and characteristics like speed and volume.The tabu stochastic optimization algorithm is implemented to finalize the optimal design based on multiple weighted criteria. The debris flow case studyat Mt. Umyeon in 2011 demonstrated the effectiveness of the ECP debris barrier for runout analysis and optimal barrier mitigation design. The sensitivity analysis assessed the influence of criteria weighting on determining optimal barriers. The developed platform is an ideal tool for preliminarymitigation design for debris flow hazards.

Keywords: Debris flow, Runout, Optimization, Network, Mitigation, Software.

1. General Appearance

Debris flow hazards are considered one of the most destructive geohazards due to their difficulty in prediction and damage to humans and infrastructures (Jakob and Hunger 2005). Therefore, passive solutions, such as check dams, baffles, and slit walls placed in flow channels, have been popular for their reliability in effectively mitigating damage risks posed by debris flow. However, these passive solutions have major disadvantages regarding environmental impact and cost. Barrier constructionnegatively impacts the environment by removing the forests and disrupting the natural flow of streams and surrounding wildlife. Furthermore, each barrier has a high cradle-to-grave cost due to material price, challenging construction environment, and maintenance. In order to maximize the sustainability and cost-benefit ratio of using barriers as mitigation against debris flow disasters, the proposed design should achieve mitigation effectiveness with the minimum number of barriers.

The barrier mitigation design procedure requiresthree-dimensional (3D) computational fluid dynamic (CFD) numerical models capable of simulating debris flow runout while accounting for the interactions between barriers and debris flow. The model assesses barrier performance by measuring debris volume retention and the kinetic energy dissipation of debris flow. The traditional design approach determines a suitable barrier design by iteratively modifying the suggested barrier design until the evaluated barrier performance exceeds the minimum threshold. However, simulating the complex interactions between barriers and debris flow in 3D CFD models requires very short intervals of time steps to maintain numerical stability and accuracy. Hence, utilizing 3D CFD to simulate the mountain-scale debris flow runout and analyzing barrier design would require significantcomputational time and hardware resources. Therefore, engineers would have to purchase expensive computation hardware or limit the number of barrier design iterations, increasing uncertainty in the proposed design's optimality.

This study proposes a streamlined barrier design framework, ECP-debris-barrier. The framework performs a runout analysis and proposesoptimal barrier designs that minimize the cost and environmental impact. A debris flow case study in Mt. Umyeon, Seoul, South Korea, was used to validate the proposed framework and demonstrate its applicability in mitigation design.

2. ECP-debris-barrier

The developed ECP-debris-barrierframework is a simplified design framework from the SPEC-debris-barrier developed by Cheon (2022). The ECP-debris-barrierframework, which is implemented with Python programming, streamlinesthe design procedure of effective mitigation barriers with these three steps:

(i) ECP-debris runout model– performs a runout analysis to evaluate debris flow dynamics,
(ii) Clustering analysis – stores the ECP-debris results into a network data structure,
(iii) Optimal barrier search – determines the optimal barrier design that meetsdesign criteria.

2.1.*ECP-debris model*

The ECP-debris model is a simplified runout model based on SPEC-debris (Cheon 2022) that determines the path of debris flow propagation in the channels or valleys and computes the debris flow characteristics, such as speed, volume, and impact pressure. In the ECP-debris model, the debris flow is discretized into particles and is governed by the following equations: energy conservation, collision, and pathway algorithm. The model accounts for the resistance using Veollmy rheology (Voellmy 1955). The entrainment phenomena, where debris volume grows due to eroded loose topsoil merging with debris mass, is modeled with Hungr's (1995) model. The energy conservation model, entrainment model, rheological base resistance, and collision in ECP-debris are similar to the SPEC-debris modelas the details of these equations are described in Cheon's (2022) paper.

The ECP-debris utilizes a simplified pathway algorithm that determines debris flow propagation based on the steepest gradient descent and inertia principle:

$$\vec{\nabla} = \begin{bmatrix} \nabla_x \\ \nabla_y \end{bmatrix} = w_g \vec{\beta} - w_u \vec{u} = w_g \begin{bmatrix} \beta_x \\ \beta_y \end{bmatrix} - w_u \begin{bmatrix} u_x \\ u_y \end{bmatrix}, \quad (1)$$

$$\begin{bmatrix} x_f \\ y_f \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} - \frac{s}{|\vec{\nabla}|} \vec{\nabla}, \quad (2)$$

where $\vec{\nabla}$ is the gradient vector, $\vec{\beta}$ is the terrain gradient vector, $\vec{u}$ is the velocity vector,w_g is the weighting factor of gravity, w_u is the weighting factor of inertia, and$s$is the distance traveled between iterations. Subscripts*0* and *f* are the positions before and after movement. The weight factors ($w_g$and w_u) are computed by Eq. (3) to (5):

$$\begin{bmatrix} x_{uf} \\ y_{uf} \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} - \frac{s}{\sqrt{u_x^2 + u_y^2}} \begin{bmatrix} u_x \\ u_y \end{bmatrix}, \quad (3)$$

$$E_{ratio} = \frac{\left(u_x^2 + u_y^2\right)}{2g\left(z_{uf} - z_0\right)}, \quad (4)$$

$$w_g : w_u = \begin{cases} 1:2, & E_{ratio} \geq 1 \text{ and } \left(z_{uf} - z_0\right) \geq 0.175 \\ 1:1, & \text{else} \end{cases}, \quad (5)$$

wherez_0 and$z_{uf}$are the elevation at (x_0, y_0) and (x_{uf} , y_{uf}) coordinates, respectively.

2.2.*Clustering Analysis and Debris Flow Network*

The ECP-debris modelsimulates the propagation of debris flow with particles. Instead of tracking individual particles, the clustering analysis (Cheon et al. 2020 and Cheon 2022) classifies these particles as part of a cluster using the K-mean clustering, an unsupervised machine learning model. The debris flow propagation tracks these clusters and computes the following collective properties: centroid location, total volume (V), average velocity (u), and impact pressure (P). Additionally, the clustering analysis computes the closest distance between the debris flow cluster location and a road, i.e., distance-from-road (D), to represent the accessibility. Further details are described in Cheon et al. (2020) and Cheon (2022) papers.

After performing the clustering analysis, the propagations of debris flow clusters aresummarized into the debris flow network data structure (Cheon 2022). The network structure is a tree structure consisting of nodes and directed edges. The nodes represent the locationsof the debris flow clusters at each iteration. At each node, the collective properties of debris flow clusters are stored. The directed edges represent the progression of debris flow clusters. For example, a directed edge connecting node A to node B represents the movement of the debris flow cluster from location A to B. Thenetwork structure forms chains of directional linksstarting from the source, the initial landslide failure location, and ending at the terminus, the edges of mountain bases.Further details on the debris flow network can be found in Cheon (2022).

2.3.*Optimal Barrier Design Selection*

The ECP-debris-barrier framework utilizes the debris flow network and stochastic tabu search algorithm to quickly check the viability of aproposed barrier design and determine the optimal barrier designs (Cheon 2022). The stochastic tabu search algorithm is a meta-heuristic optimization algorithm that performs a random greedy optimization search. The algorithm keeps track of previously proposed barrier designs and prevents analyzing a previously checked design to gain efficiency. The optimal barrier design is a design that minimizes the optimization cost ($), which is computed by Eq. (6):

$$\$ = \sum_{j=1}^{N_C+N_O} \left[w_V \widehat{V_j} + w_P \widehat{P_j} + w_D \widehat{D_j}\right] + w_C N_C + w_O N_O, \quad (6)$$

where $N_i$is the number of barriers, andw_j is the weighting factor. The V, P, D, C, and O refer to volume, impact pressure, distance-from-road, closed-type barrier, and open-type barrier, respectively. Symbols below a hat symbol ($\hat{V}$, $\hat{P}$, $\hat{D}$) refers to a normalized quantity that varies from zero to one. Normalized quantities were utilized since the volume, pressure, and distance-from-road units and scales differ.

The volume (V) and impact pressure (P) indirectly represent the approximate size and reinforcement required for each barrier. The distance-from-road (D) represents accessibility during construction and maintenance; therefore, lower D means it is easier to access the barrier site and would have lower construction and maintenance costs. The optimization weighting factor (w_j) should all sum to one. The w_j allows engineers to set different prioritiesfor each $j$factor (V, P, D, C, and O). A higher value of w_j results in the optimization algorithm prioritizing to minimize the cost ($) effect of the j factor.

The details of the optimal barrier design procedure are described in Cheon (2022).

3. Mt. Umyeon 2011 Debris Flow

3.1.*Verification of ECP-debris*

The developed ECP-debris model was verified by comparing its simulation results with the SPEC-debris model (Cheon 2022)forthe debris flow case study at Mt. Umyeon. In July 2011, extreme rainfall triggered debrisflow at Mt. Umyeon in Seoul,South Korea, and caused 16 human fatalitiesand extensive damage to surroundingbuildings (Yune et al. 2013). ECP-debris and SPEC-debris models used the same terrain and base rheological parameters: frictional (f_b) = 0.05 and turbulence (f_t) = 0. The pathway traced by the movement of debris flow clusters from the ECP-debris model was plotted with the SPEC-debris model (see Fig. (1)).

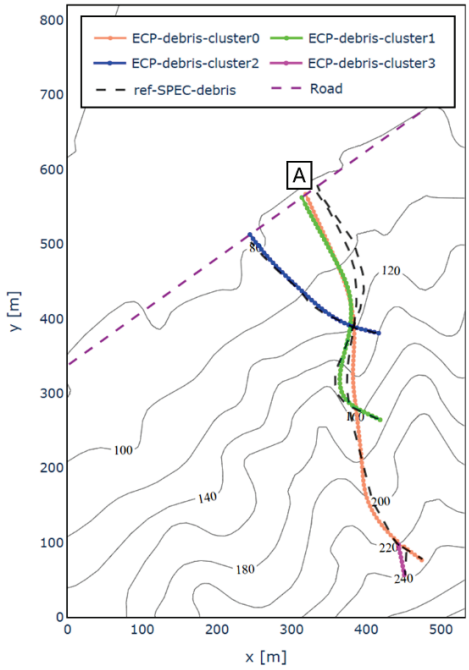


Fig. 1.The pathway traced by debris flow clusters from ECP-debris and SPEC-debris models at Mt. Umyeon Raemian region

As shown in Fig. (1), the pathway traced by the ECP-debris and the SPEC-debris models showsimilar results. The slight differences in pathways of clusters 0 and 1 arise due to the ECP-debris model not considering the internal pressure of debris flow. The internal pressures exert force going outwards from the cluster centroid; therefore, the degree of spreading is lower in ECP-debris. However, both models produce very similar results in valleys or channels where spreading is limited. Furthermore, video footage recorded debris flow reaching a speed of 28 m/s at location A (see Fig. (1)). Both ECP-debris and SPEC-debris models computed the debris flow speed to be 28.6 m/s, which matched well with the observed debris flow. The simulation of Mt. Umyeon 2011 debris flow verifies the accuracy of the developed ECP-debris model by agreeing with the observation and another existing model.

3.2.*Effect of Optimization Weighting Factors*

A parametric study with the developed ECP-debris-barrier framework examined the effects of different optimization weighting factors (w_j). The optimal closed-type barrier designs were compared using three cases of weighting factors.Fig. 2 presents thelocation, the cumulative debris volumethat needs to be retained (V), the impact pressure from colliding debris flow (P), and barrier's distance-from-road (D) at the optimal barriers for each case.

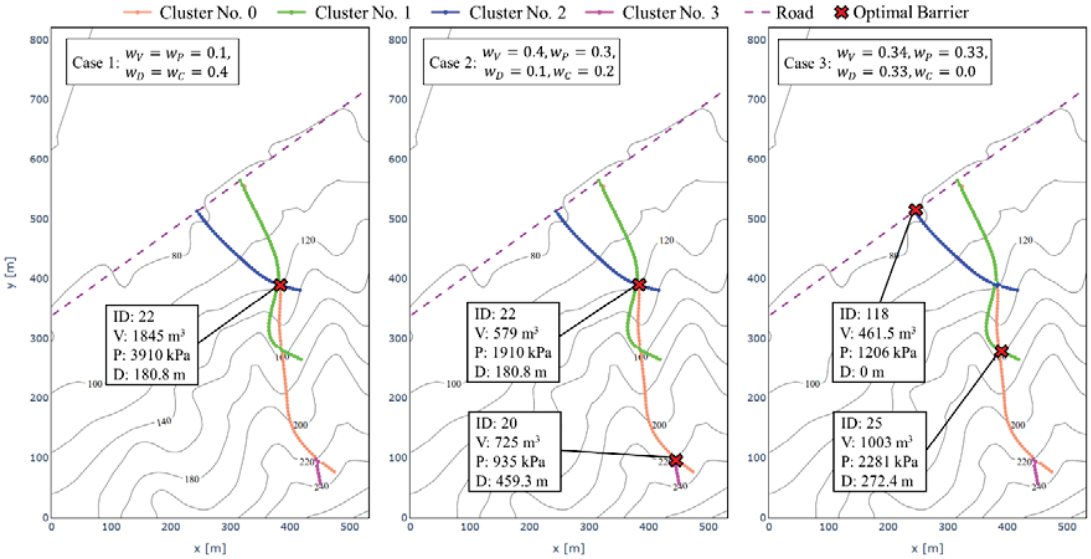


Fig. 2.The optimal barrier designs determined by the ECP-debris-barrier framework based on different weighting factors (w_i)

Case 1 prioritizes the construction and maintenance aspectby minimizing the number of barriers (*Nc*) and maximizing the accessibilityindirectly through distance-from-road (*D*); therefore, the developed framework selects a single large barrier to be optimal. However, case 2 prioritizes barrier design, such as the size and structural integrity. A smaller barrier would be sufficient if a smaller volume retention capacity (*V*) is required. Additionally, smaller impact pressure from debris flow (*P*) signifies using less steel in reinforced concrete walls and thinner walls required for gravity-type retaining walls. Hence, case 2 selects two optimal barriers with smaller *V* and *P* than the single barrierin case 1. Case 3 balances thebarrier design, construction, and maintenance aspects; therefore, the barriers in case 3 are closer to the road than case 2, while having smaller *V* and *P* than the single barrier in case 1.

Based on theparametric study,the optimization weighting factors (w_i), whichnumerically quantifies design priority, are shown to be correctly considered in the ECP-debris-barrier framework.The optimal barrier designs reflected the design criteria and priorities. Additionally, since the entire runout simulation and barrier design procedure in the ECP-debris-barrier framework are automated using Python programming, it becomes a quick and convenient tool for designing mitigation against runout disasters, such as debris flow and avalanches.

6. Conclusion

This study presents the ECP-debris-barrier framework that streamlined the barrier design procedure for mitigation against debris flow disasters. The frameworkfollows these main procedures to achieve optimal initial barrier design: simulate debris flow runout with the ECP-debris model, construct debris flow network data structure, and search for optimal barrier design. The novelty of the developed framework is its efficiency in barrier design through an accurate, quick ECP-debris model and design optimization algorithms. With the 2011 Mt. Umyeon debris flow case study, the accuracy of the ECP-debris model was validated by matching well with the site observations and the results of the SPEC-debris runout model (Cheon 2022).The parametric study on the ECP-debris-barrier framework has demonstrated its capabilities to consider various design priorities to propose optimal barrier designs.

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References

Cheon, E. (2022). (A) new simulation model for optimal location selection and performance evaluation of barriers as mitigation against debris flow.Doctoral dissertation, KAIST.

Cheon, E., S. R. Lee, andD. H. Lee (2020). Hazard Assessment Based on the Combination of DAN3D and Machine Learning Method for Planning Closed-Type Barriers against Debris-Flow. *Water12(1)*, 170.

Hungr, O. (1995). A model for the runout analysis of rapid flow slides, debris flows, and avalanches.*Canadian Geotechnical Journal 32(4)*, 610–623.

Jakob, M. and O. Hungr (2005). Debris-flow hazards and related phenomena. Springer, Berlin, Heidelberg, 1-7.

Voellmy, A. (1955). Über die Zerstörungskraft von Lawinen.*SchweizerischeBauzeitung 73*, 212–285.

Yune, C.Y.,Y. K. Chae, J. Paik, G. Kim, S.W. Lee, H. S. Seo(2013). Debris flow in metropolitanarea—2011 Seoul debris flow. *Journal of Mountain Science10*, pp. 199–206.