Debris Flow Impact Mitigation Using Dual Flexible Barriers: Experimental and Numerical Study

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Abstract: Debris flows pose severe threats to infrastructure and lives globally. Multiple flexible barriers offer a sustainable alternative to single rigid structures by progressively retaining and decelerating debris flows. This study investigates dynamic interactions between debris flows and dual flexible barriers through physical flume tests and numerical back-analysis. A 9.0 m³ debris flow impacts two flexible barriers in a 28-m flume, revealing mechanisms like frontal impact, runup rollback, overflow, and landing. The numerical model captures key kinematics and stress evolution. Results show the first barrier significantly reduces peak impact pressure on the second barrier, enhancing design efficacy for multi-barrier systems.

Keywords: ***Debris flows, Flexible barriers, Impact, Flume experiment.***

Introduction

Debris flows, classified as flow-like landslides, consist of rapidly moving mixtures of soil, rock, water, and debris, endangering infrastructure and human life worldwide (Froude and Petley, 2018). Traditional mitigation relies on single large concrete barriers, but multiple smaller flexible barriers along flow channels provide a promising alternative by intercepting and retarding debris progressively, stabilizing gradients and minimizing environmental impact (Kramer et al., 2025). Existing guidelines for rigid barriers (SWCB, 2019; NILIM, 2022) address spacing but overlook dynamic flow-barrier interactions, particularly for flexible types that are lightweight, sustainable, and less carbon-intensive than rigid structures.

Flexible barriers have become popular for mitigating geophysical flows in steep terrains due to their robustness and non-intrusive nature. However, field measurements of responses to debris impacts are limited and numerical studies on multiple barriers are scarce (Ng et al., 2024), with designs often ignoring velocity effects like Froude number. Few cases document interactions with series installations allowing overflow (Wendeler et al., 2008). The challenge of understanding debris flow interaction with multiple barriers is intensified by the limited availability of rigorously validated numerical simulations on debris flow interactions with flexible barriers (Lam et al., 2022), none of which explore responses in multi-barrier configurations. Thus, a comprehensive analysis is essential to clarify the performance of multiple flexible barriers arranged sequentially in a flow path that accommodates overflow during debris impacts. This study combines physical and numerical modeling to examine dual flexible barrier responses to dynamic debris flow, focusing on impact mechanisms, forces, and deformations.

Research Methodology

Physical experiments modelled debris flow impact on dual flexible barriers in a 28-m-long flume facility with 2 m width and 1 m height, featuring a transparent sidewall for high-speed imaging. Debris (9.0 m³) was prepared in a concrete mixer and released via dam-break from a 5-m-long, 30°-inclined storage container into a 15-m-long, 20°-inclined transport zone, ending in an 8-m horizontal runout pad. Figure 1 shows the side elevation schematic diagram of the test setup in the 28-m long flume. The first barrier (FB1), 0.8 m high and 2.0 m wide steel ring net, was placed 6 m from the gate, supported by two horizontal cables with load cells. The second (FB2), 1.5 m high and 3.6 m wide, was 13 m downslope, anchored to a steel frame with three cables and load cells. Flow depth, velocity, and kinematics were measured using laser/ultrasound sensors and UAVs. Details of the flume facility including instrumentations and the debris material used in this study is the same as that used by Ng et al. (2020). The flexible barrier is the same as reported in Poudyal (2024).

Numerical back-analysis employed a 3D coupled Arbitrary Lagrangian-Eulerian and Finite Element Method (ALE-FEM)) to model debris flow flexible barrier interactions. Debris was simulated with a Drucker-Prager constitutive model (friction angle 12°, cohesion 1.0 kPa, density 2150 kg/m³) in total-stress formulation. The barrier's ring net used elastoplastic behavior (Young's modulus 200 GPa, yield strength 800 MPa), while cables were elastic (100 GPa). The flume was analytically rigid. Model geometry matched the physical setup, capturing three-dimensional effects like spillover. Details of constitutive models and modelling procedures are provided in Poudyal (2024).

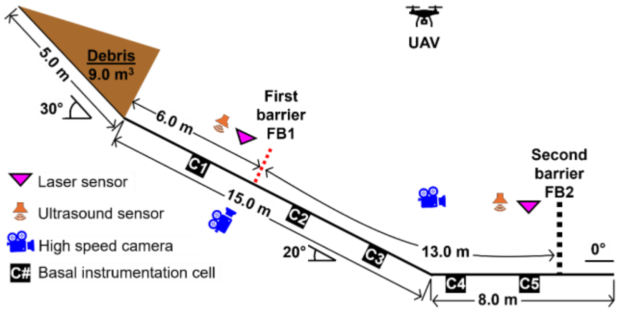

Figure 1, Schematic of test setup in the 28-m flume.

Results

Observed impact kinematics revealed debris front reaching FB1 at 6.0 m/s and 0.53 m depth, causing runup, rollback, and overflow with fines discharging through the mesh. Overflow spilled laterally and landed 6.4 m downslope, reducing incoming momentum to FB2. At FB2, impact began at t=3.0 s, with higher runup but no overflow, leading to deposition by t=8.0 s; the numerical model captured deformed shapes and deposition volumes, though underestimating velocity due to constant friction coefficient used in the material model.

Debris pressures evolved dynamically: at FB1 impact (t=0.0-1.0 s), peak 28 kPa (1.7 times hydrostatic) indicated passive stress from compression. Overflow (t=2.0 s) sustained 24 kPa drag on deposits, with landing compression dropping as flow accelerated. By t=4.0 s, FB2 registered 10 kPa near the base; final pressures reduced to hydrostatic 16 kPa at FB1 and 8 kPa at FB2 (active state), a sixfold reduction versus single-barrier cases. The first barrier mitigated downstream pressures through deceleration and overflow.

Conclusions

The dual flexible barrier system effectively managed 9.0 m^3 debris flow, with FB1 reducing peak pressure on FB2 by up to six times via overflow and momentum loss. Barrier deformation and mesh perviousness drove runup rollback and fines discharge, while passive stresses dominated initial impacts. Numerical ALE-FEM back-analysis validated kinematics and elucidated stress evolution. Computed results of pressure within the debris revealed that the peak impact pressure is governed by a passive state of stress in the material due to compression from overriding flow. The first barrier in a dual flexible barrier system is shown to reduce peak impact pressure on the second barrier by up to six times. These findings support optimized, low-carbon multiple flexible barriers as useful tools for mitigating debris flow hazards.

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