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Coupled Eulerian-Lagrangian Debris Flow Model with Flexible Barrier

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Abstract. Natural hazards such as large debris flow events can have catastrophic effects on the environment and critical infrastructure, posing a significant threat to human life. Debris flows often exhibit high velocity, high-pressure discharges due to their bulk volume, and the capacity to transport considerable volumes of large rocks, boulders, and woody debris. Although debris flow run-out simulations are commonly performed using hydraulic modelling software, these environments are seldom capable of assessing the interaction between the debris fluid, transported material, and protective structures. In this research, large deformation numerical models are calibrated using input parameters from hydraulic modelling software. Due to the computational cost of the large deformation models involving fluid-solid-structure simulation with flexible net barriers, an equivalent stiffness method is implemented to provide comparable performance through a membrane structure. The Coupled Eulerian-Lagrangian Finite Element method is used to model the impact forces of rocky boulders on the membrane, exhibiting damage characteristics consistent with flexible ring-net protective structures. The Coupled Eulerian-Lagrangian model results highlight the performance of the simplified membrane, as shown through a benchmark simulation of debris flow with boulders.

1 Background

Debris flow events are a perilous form of landslide due to their high velocity, considerable impact forces and long-runout distances. It is considered to be a mixture of soil and water, coupled with detritus such as gravel, boulders and driftwood. To mitigate potential debris flow hazards, two categories of protective structures are commonly implemented: rigid structures such as check dams, fences and racks, and flexible barriers such as wire ring nets, hexagonal nets, and water drop-shaped meshes.

In recent times, advanced Finite Element Method (FEM) techniques have been developed to overcome convergence issues for large deformation analysis by combining Lagrangian and Eulerian methods. At a reasonable computational cost, numerical methods such as Coupled Eulerian-Lagrangian (CEL) can evaluate large deformation behaviour while accurately capturing fluid-structure interactions. The CEL method has been applied to a range of geotechnical applications, including soil slope stability analysis [1], in-situ cone penetration tests [2] and large deformation geotechnical laboratory tests [3]. Several studies have employed CEL to simulate debris flow, including Crosta et al. [4] and Sha et al. [5], where the advantages of the CEL method were demonstrated for debris flow simulations, avoiding mesh distortion and modelling multiple materials. Similarly, Jeong and Lee [6] employed the CEL method to simulate a check dam subjected to debris flow, taking into account the entrainment of the sediment, whereby it was concluded that the method performs well in simulating the dynamic impact force acting on the rigid or deformable structures. It is worth noting that current research has predominantly focused on flow behaviour and entertainment within the sedimentary soil layer rather than fluid-structure interaction. In terms of modelling flexible barriers, a number of scholars have introduced several approaches to simplify complicated models by using shell or membrane elements [7-10]. However, these simplified models are rarely well studied and developed, especially for the simulation of flexible ring nets subjected to debris flow with various shapes of boulders.

In this research, an equivalent simplified numerical model using membrane elements (referred to as a membrane model) is proposed as an efficient alternative to the more traditional numerical model using beam elements (called a ring net model). Several benchmark analyses, including direct tensile tests, sphere/cylinder loading tests, and sphere drop tests, were performed on the ring net model to map the deformation-force curves and the failure loads for calibration and validation of the membrane model. The CEL method was employed to simulate the interaction between debris flow material and the flexible barrier in the ABAQUS/Explicit [11] modelling environment. The performance of the flexible barrier with membrane elements subjected to debris

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flow incorporating boulders was investigated, indicating that such a numerical approach can be efficiently applied, replacing complex models of flexible ring nets while significantly reducing the computational cost.

2 Numerical Models and Validation

2.1 Modelling of debris flow

The initial model geometry for the CEL debris flow model to be simulated is provided in Fig. 1, material parameters summarised in Table 1 [5]. The debris flow is modelled with the Bingham visco-plastic material, behaving as a solid at low stresses and a viscous fluid at higher stress levels. The bedrock over which the debris flows is modelled as a rigid body, while the check dam in the path of the viscous fluid is considered linear elastic, with a fixed base tied to the bedrock. In the simulation of both the bedrock and check dam, ABAQUS Explicit type C3D8R 8-node linear brick reduced elements were used. EC3D8R 8-node Eulerian linear brick reduced elements were implemented to simulate CEL Eulerian behaviour.

To examine the performance of the simulation methods, the results of CEL simulations were compared with numerical simulations performed by Joeng and Lee [6]. As shown in Fig. 2, the impact pressures were obtained from 16 nodes with an interval of 0.05 m placed along the central line on the check dam at simulation times of 2.5 seconds for the CEL simulations, providing good agreement with the results of Joeng and Lee.

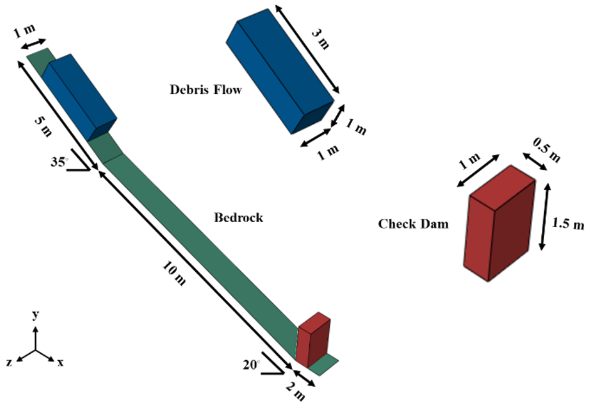

Fig. 1. The geometry of the debris flow model.

Table 1. Material parameters [5].

Material parameter	Debris flow	Bedrock	Check dam
Constitutive model	Bingham	Rigid body	Linear elastic
Density ρ (kg/m^3)	1500	-	2500
Young's Modulus E (GPa)	-	-	24
Poisson's ratio ν	-	-	0.25
Yield stress τ_y (Pa)	100	-	-
Viscosity η (Pa·s)	100	-	-

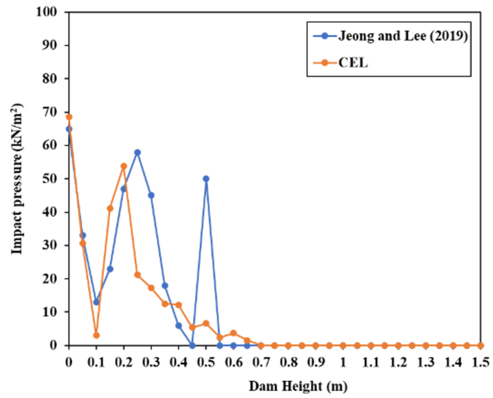

Fig. 2. Comparison of model impact pressures with Jeong and Lee [6].

2.2 Modelling of flexible ring net

The modelled flexible ring net is made of 11 × 11 plus 10 × 10 steel wire rings (221 rings in total) with a single ring diameter (d_0) of 14.6 mm and an internal diameter (D) of 300 mm. Each wire ring is modelled using 8-elements beam elements and is attached to four separate rings within the net by 8 nodes, in which 4 nodes are from the ring itself, and the other 4 are from the four attached rings, as shown in Fig. 3a to 3c. To simulate the ring-to-ring contact properly, the pin type of Multiple-Points Constraint (MPC) is used to connect the two points between every two rings. This type of MPC provides a pinned joint between two nodes, making the global displacements equal but leaving the rotation.

As discussed, finite membrane elements have been previously used to simulate flexible ring nets [10, 12, 13]. To do so, the equivalent model is idealised as a closed homogeneous surface discretised with plane-stress finite membrane elements. As shown in Figure 3d, the nodes (shown in red) are defined as boundary points at which translation fixities are applied. Therefore, the red dashed square region can be considered as the effective area of the ring net that undergoes impact loads and deformation. Hence, the length of the effective area (L_e=4.455 m) can be used as the geometrical size of the membrane model (Fig. 3e). The key geometry and material parameters for the ring net model and the membrane model are referred to [14].

Based on the performance of the ring net model, the membrane model is calibrated and verified through a series of analyses, including direct tensile tests, sphere/cylinder loading tests, and sphere drop tests. The equivalent elastic modulus and tensile strength of the membrane model are calibrated based on the results of the reaction force and deformation obtained from FEM analyses of the ring net model, providing a good agreement with the behaviour of the membrane and ring net models, as shown in Fig. 4.

To investigate the computational efficiency of the membrane model, the processing time of the simulation for the two models is compared in Fig. 5. As shown in this figure, the simulation of the membrane model is almost 9 times more cost-efficient than the ring net model. Considering the agreements between the ring net

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and membrane models found from the direct tensile, loading and drop tests, also considering the substantial computational efficiency of the membrane model, it is concluded that the proposed membrane model can be used as a reliable, accurate and efficient alternative for the simulation of flexible ring net barriers.

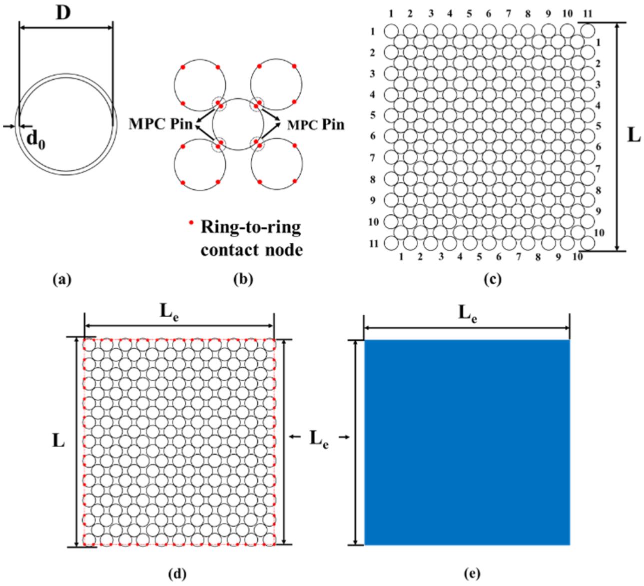

Fig. 3. Specifications of the ring net model: (a) Single wire ring; (b) Ring-to-ring contact; (c) Flexible ring net (L=4.543 m); (d) Effective area of the ring net model (red dashed square, L_e=4.455 m); (e) Equivalent simplified model (membrane model).

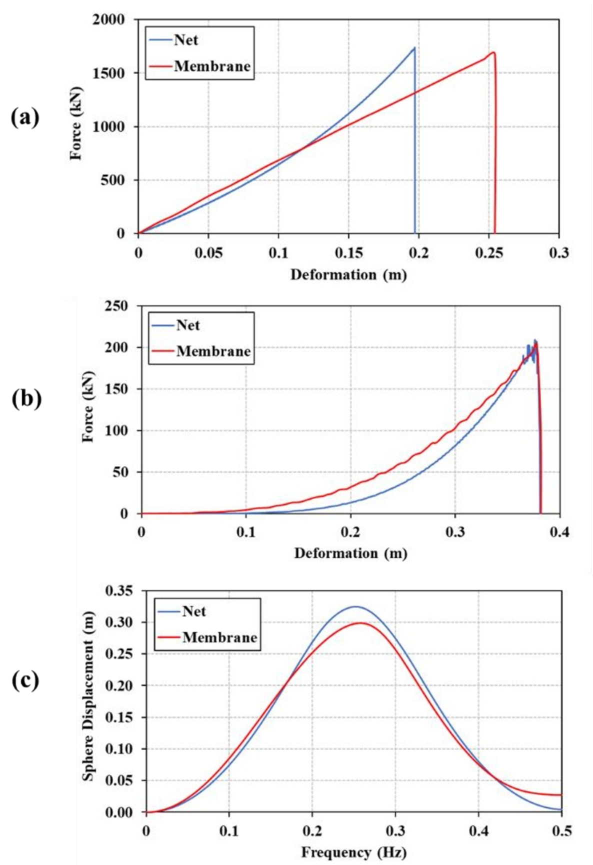

Fig. 4. Comparison of the force and deformation response of the ring net model and the membrane model: (a) the direct tensile test; (b) the loading test; (c) the sphere drop test.

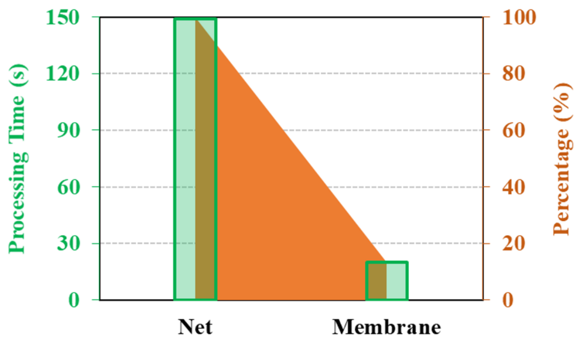

Fig. 5. Comparison of the computational cost between the ring net and membrane models in the sphere drop test.

3 Benchmark Simulations of Debris Flow Incorporating Boulders

The geometry for the CEL debris flow model with a randomised assortment of boulder shapes, orientations and locations is provided in Fig. 6. As discussed in Section 2.1, the debris flow is modelled with the Bingham visco-plastic material, behaving like a solid when stresses are low and a viscous fluid when the yield stress is reached. The ramp and boulders are modelled as rigid bodies, while the membrane barrier is identical to the membrane model discussed in Section 2.2. To simulate both the ramp and boulders, Abaqus Explicit type R3D4 4-node 3-D bilinear rigid quadrilateral elements were employed. EC3D8R 8-node linear Eulerian brick elements with reduced integration and hourglass control were used to simulate CEL Eulerian behaviour.

The membrane barrier is treated as a flexible ring net barrier. In this case, it is assumed that there is no interaction between the debris flow and the membrane barrier, which means the debris flow can pass through the barrier, as is expected for a ring-net barrier. Furthermore, these two components indirectly interact through a proxy interaction with the boulders, as each component exhibits a boulder contact definition, thereby transmitting hydrodynamic forces to the protective structure. A contact penalty definition with a friction coefficient of 0.1 was chosen for the contact between the boulders and both the debris flow and membrane barrier. A gravity load was applied to the model. To investigate the impact of the flow velocity on the performance of the membrane model, continuous initial flow velocities of 1 m/s, 3 m/s and 5 m/s were applied in three simulations. A duration of 6 seconds was simulated for each case.

Fig. 7 presents the reaction forces imposed by the boulders on the barrier at three different flow velocities. From this Figure, the peak impact force generated by boulders is 29, 69, and 103 kN at the simulation time of 5.8, 2.7, and 2.1 seconds for the cases with flow velocities of 1, 3 and 5 m/s, respectively. Based on the simulation results, the faster the flow velocity acted on the boulders, the higher the impact force imposed on the barrier. However, as the boulders vary in size, weight, and location, the reaction forces obtained from each case show irregular fluctuations with time.

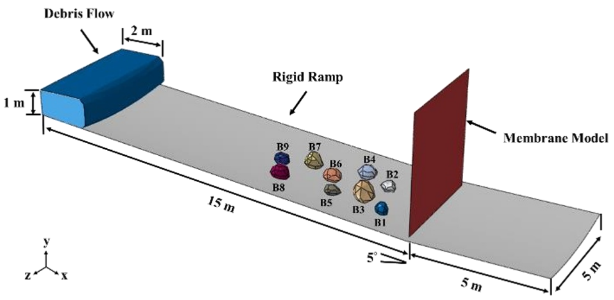

Fig. 6. Geometry of debris flow with boulders model.

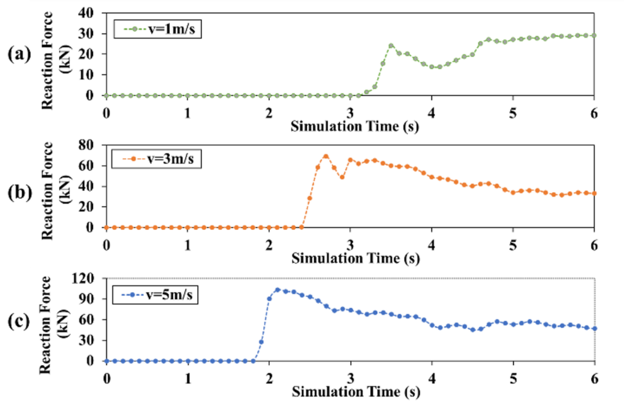

Fig. 7. Reaction force versus time at various flow velocities: (a) 1 m/s; (b) 3 m/s; (c) 5 m/s.

4 Conclusions

Numerical simulation of large deformation problems for debris flow is a challenging task that often requires complex numerical methods commonly attributed to computational fluid dynamics such as CEL. As one of several protective structure types applied for mitigating debris flow, flexible netting barriers exhibit complex nonlinear behaviour when subjected to dynamic impacts. Although flexible barriers are widely used in engineering practice, the analysis of flexible netting models using an equivalent simplified model has not been well studied in the literature. In particular, the interaction between flexible barriers, debris flow fluids and boulders has been rarely investigated. In this research, a simplified model for the simulation of flexible net barriers was proposed, and its performance was studied comprehensively through several numerical analyses.

The simulation results highlight the performance of an equivalent stiffness model using membrane elements, showing good agreement with the ring net model regarding force-displacement response. Based on the performed fully dynamic sphere drop test, the proposed membrane model can be efficiently applied to replace complex models of flexible ring nets and significantly reduce the computational cost. In addition, a benchmark analysis was conducted to investigate the proposed membrane model subjected to debris flow with boulders at various flow velocities. The results showed that the faster the flow velocity acted on the boulders, the higher the peak impact force imposed on the barrier.

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