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Multiscale modeling of multiphase flow interaction with mitigation structures

Marina Pirulli[1], Andrea Pasqua[1,2], Alessandro Leonardi[2]

Abstract

Debris flows are multiphase flows consisting of water, fine-grained, and coarse-grained sediments, whose complex behavior poses challenges for understanding the process dynamics, and mitigating the effects on the territory. Standards for designing effective protection measures are lacking, and are unlikely to become available soon. A variety of simulation methods exist, ranging from microscopic to macroscopic scales, offering tools to model multiphase flows and address the above challenges. Discrete methods represent flows as assemblies of colliding particles. They are useful for studying particle clogging, but appear inadequate for capturing the entirety of events due to computational demands. Continuum-based numerical methods, such as depth-averaged and three-dimensional models, offer more comprehensive simulations. Depth-averaged models efficiently simulate the entire process, but struggle with flow-structure interactions. In contrast, three-dimensional models, while more complex, excel at studying specific aspects like the impact of debris flow against mitigation structures. This study focuses on the Gran Valley catchment, leveraging historical data and existing mitigation structures. It explores how different modeling approaches contribute to understanding the dynamics of debris flows and their interaction with protective measures. By examining both the process dynamics and structural interactions, the research aims to provide insights into effective mitigation strategies

Keywords

Debris flows, numerical modelling, mitigation structures

Introduction

Debris flows represent a significant natural hazard, characterized by the rapid movement of a mixture of water, fine-grained, and coarse-grained sediments down steep slopes. These events are often triggered by intense rainfall, snowmelt, or seismic activity, posing threats to communities, infrastructure, and the environment in mountainous regions worldwide. The heterogeneous composition and complex behavior of debris flows make them challenging to model accurately. Advanced numerical techniques and extensive field observations are then required to understand their dynamics and mitigate their impacts.

Effective protection measures against debris flows rely on a comprehensive understanding of their behavior and interaction with mitigation structures. While physical barriers, such as slit-check dams and retention basins, can help reduce the risk posed by these events, their design and implementation require a careful consideration of local topography, flow dynamics, and sediment characteristics. Numerical modeling plays a crucial role in assessing the effectiveness of mitigation measures, providing insights into flow patterns, deposition zones, and potential failure scenarios.

In this paper, we explore the contributions of discrete and continuum-based numerical techniques to the understanding of debris flow dynamics and their interaction with mitigation structures. Drawing on data from the Gran Valey catchment - a region with a history of debris flow events and with installed mitigation measures - we conduct a comparative analysis of different modeling approaches. By examining their strengths, limitations, and potential synergies, we aim to develop a multiscale framework, with the final goal of increasing our ability to predict and mitigate the impacts of debris flows in vulnerable areas.

Numerical modeling

Discontinuum-based approach

Discrete numerical modeling approaches represent debris flows as interacting particles (Fig. 1), allowing for detailed analysis of particle motion, collision, and aggregation (e.g., Cundall and Strack, 1979; Galindo-Torres, 2013). These models simulate individual particle behaviour, considering factors like size, shape, density, and surface roughness (e.g., Zhou *et al.*, 2016). While highly accurate at capturing particle-level interactions, they are computationally demanding, leading to a struggle in simulating large-scale debris flow processes (e.g., Leonardi, 2015).

A key strength of discrete modeling is its ability to simulate particle clogging in mitigation structures, such as barriers and check dams (e.g., Shen *et al.*, 2018), by tracking individual particle movements and interactions. This helps assess barrier effectiveness and identify potential failure modes. Discrete models also investigate flow stratification, sediment segregation, and the formation of levees and lobes during debris flow propagation (e.g., Zhou *et al.*, 2016).

However, scaling up simulations for large-scale events is challenging due to the high computational cost of simulating numerous, limiting the model spatial and temporal resolution. This can hinder the accurate representation of long-distance propagation, channel avulsion, and the interaction of multiple debris flows merging downstream (e.g., La Porta *et al.*, 2024). Despite these limitations, discrete modeling is valuable for understanding particle-scale processes and evaluating the performance of mitigation structures at the local level.

Continuum-based approach

Continuum-based numerical models represent debris flows as continuous fluid-solid mixtures (Fig. 1), using balance equations for mass, momentum, and energy (e.g., Pudasaini, 2012). These models simulate flow dynamics over large spatial and temporal scales (e.g., Pirulli, 2010) and can be divided into depth-averaged models and three-dimensional models.

Depth-averaged models, or two-dimensional models, simplify debris flow dynamics by averaging flow properties over the vertical dimension (e.g., Savage & Hutter, 1989). They are computationally efficient and can simulate the entire debris flow process from initiation to deposition (e.g., Pirulli et al., 2011), making them suitable for large-scale hazard assessment (e.g., La Porta *et al.*, 2024). However, they cannot capture three-dimensional flow features or flow-structure interactions, potentially oversimplifying flow dynamics.

In contrast, three-dimensional models provide a detailed representation of debris flow dynamics, accounting for spatial variations and topographic features (e.g., Leonardi, 2015), by solving the full three-dimensional Navier-Stokes equations. These models can simulate complex flow phenomena (e.g., Gray and Tang, 2018) and flow-structure interactions, providing insights into energy dissipation, pressure distribution, and structural loading (e.g., Pasqua *et al.*, 2022). However, they are computationally intensive and require high-resolution topographic data (e.g., Pastor *et al.*, 2011), making them challenging to apply over large spatial domains. These models also require a more detailed parameterization of turbulence, sediment transport, and bed roughness, which may introduce uncertainty and complexity into the modeling process (e.g., Mangeney *et al.*, 2010). Despite these challenges, three-dimensional modeling offers valuable insights into specific aspects of debris flow behavior, such as flow-structure interaction and sediment deposition patterns.

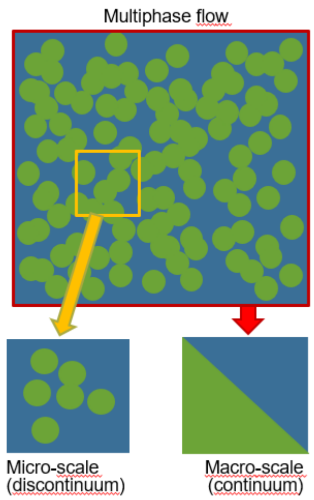

Fig. 1 Discrete (micro) vs. continuum (macro) representation of a multiphase flow.

Comparative analysis

In this section, we conduct a comparative analysis of discrete and continuum-based numerical modeling approaches applied to debris flows, using data from the Gran Valey catchment as a case study. We examine their performance in replicating past debris flow events, predicting the effectiveness of mitigation structures, and capturing the overall dynamics of debris flow propagation. By comparing the strengths and limitations of each modeling approach, we aim to identify opportunities for improving hazard assessment and risk management in vulnerable areas.

The Gran Valley catchment serves as a valuable testbed for evaluating debris flow models and mitigation strategies due to its history of past events and installed mitigation measures. In this section, we provide an overview of the catchment characteristics, past debris flow events, and implemented mitigation measures. We then conduct a detailed analysis of debris flow dynamics and interaction with mitigation structures using both discrete- and continuum-based numerical models.

Gran Valey Catchment

The town of Saint-Vincent, nestled at the base of Mount Zerbion in Aosta Valley Region (Italy), is prone to rapid landslides due to the steep slopes and fractured rock that characterize the upper Grand Valey basin. Historical records detail frequent debris flows often triggered by intense rainfall in spring or summer, involving thousands of cubic Glendameters of material (Leonardi & Pirulli, 2020). To safeguard Saint-Vincent and surrounding areas from such events, defense structures were constructed along the Grand Valey channel. These include two check dams near the Pèrriere hamlet (Figs. 2 and 3), with a couple of steel net barriers and a terminal check dam further downstream.

Fig. 2 Grand Valey catchment. A: main release channel; B: secondary release channel; Area 1, Area 2: triggering areas; (1) the two check dams located close to Perrière. The arrow indicates the confluence of the two channels (modified after Leonardi and Pirulli, 2020).

To assess the impact forces of debris flows on defense structures, the Aosta Valley Region government, in collaboration with Politecnico di Torino, implemented a monitoring system. This system equips the upper check dam with sensors, converting its 18 vertical steel beams into transducers capable of measuring horizontal loads from the flowing mass. These sensors monitor both the impacts and intervals between them, recording strain at the base of the steel beams at preset intervals. Upon detecting a sudden strain change, the system captures continuous high-speed data streams, enabling a time-history of force measurements even during rapid events such as debris flows (Leonardi & Pirulli, 2020).

Two debris flow events recorded by the above described monitoring system are used here: on June 9th and July 11th 2016 (Fig. 3), respectively.

The mass mobilized in both events was retained almost completely by the two filter barriers at Perrière. For this reason, the estimation of the involved volumes was made on the basis of the material removed from the basins after each event: 1875 m^3 in the June event and 4420 m^3 in the July event (Leonardi *et al.*, 2021). The available data was used for comparison with the different numerical approaches proposed in the following section.

Fig. 3 The check dams in Perrière filled afted the July 11th 2016 debris flow event.

Numerical results

Depending on the aspect to investigate, the most appropriate numerical approach has to be selected to obtain useful and meaningful results.With this in mind, different numerical methods have been applied to analyse the dynamic behavior of flow movements occurring along the Grand Valey catchment.

The first approach was devoted to an overall analysis of the process dynamics. As detailed in the numerical section, depth-averaged continuum models are well suited to these purposes. In the last decades, these methods have been widely validated and it has been proven their capability to reproduce the entire debris flow process, despite the loss of in-depth information concerning the velocity profile during movement. The depth-averaged RASH3D code

(Pirulli, 2010) has been then used to reproduce the Grand Valey event that occurred on July 11th 2016. This event caused the filling of the two basins existing upstream of the 2 check dams located near Pèrriere. It was also characterized by the release of material from both branches in which the Grand Valey splits in the upper part of the slope (Area 1 and Area 2, Fig. 2). Branch B activates only during the most intensive rainfall events.

An intriguing aspect that emerges is that, despite the material being released simultaneously from Area 1 and Area 2, the flow from Area 2 is delayed compared to Area 1 (Leonardi *et al.*, 2021). This behavior aligns with the site survey interpretations. The initial surge from Area 1 likely caused clogging of the first barrier. Approximately 300 seconds later, a subsequent surge carrying woody debris arrived from Area 2, flowing over the deposit in the retention basin soon after the initial event, and clogging the second barrier (Fig. 4).

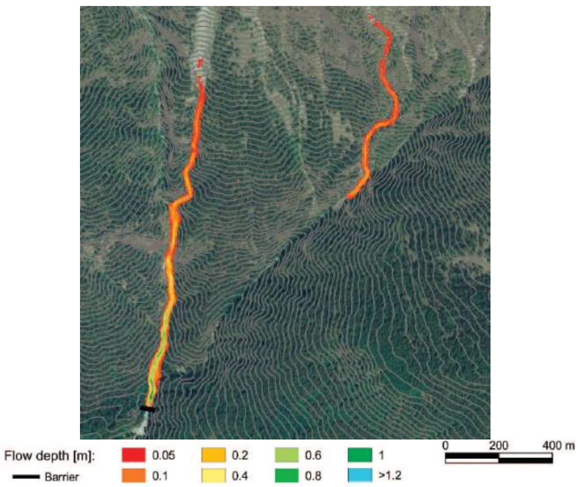

Fig. 4 Modeling of the event on July 11 with a Voellmy rheology (modified after Leonardi *et al.*, 2021)

Moving to the analysis of the flow-structure interaction, especially with reference to the check dam equipped with the monitoring system. It emerged the need of moving to a fully three-dimensional approach that guarantees a detailed description of the mass in-depth velocity distribution. To retain the capability of simulating the entire debris flow process, a coupling between a depth-averaged and a fully three-dimensional model was proposed (Pasqua *et al.*, 2022). This allows to have a computationally efficient tool and an appropriate level of accuracy when the flow impact the structure. A comparison between monitoring recordings and numerical results is given in Figure 5 to highlight the good match between measured and computed forces acting on the central elements (07, 08 and 10) of the filter impacted by the flow in Pèrriere.

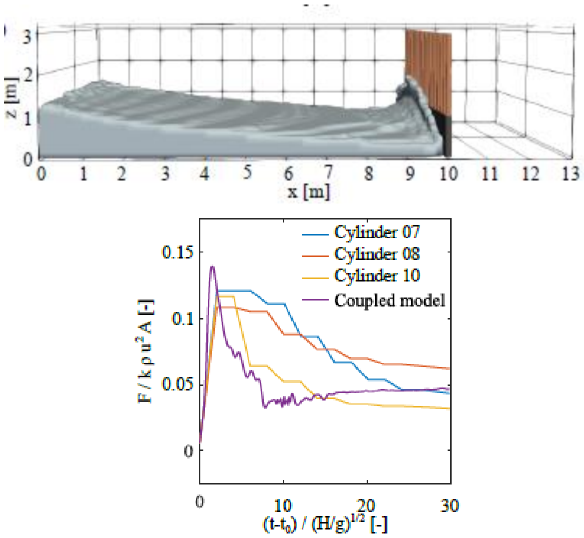

Fig. 5 Numerical results obtained with the coupled depth-averaged and three-dimensional continuum-based numerical model for the July 11 debris flow event. Comparison between measured and simulated impact force F against the Perrière monitored check dam. The forces are scaled to the dynamic load applied to barrier cross-section, while the time is scaled with the time of first impact (t_0) (modified after Pasqua, 2023).

Focusing on the flow-structure interaction, some aspects are however uncatchable by a continuum model, even if three-dimensional. This mainly concerns the possible clogging of the barrier filter and its sizing on the basis of the granulometric composition of the flowing mass. This analysis requires that the numerical model is able to describe particles that are part of the movement and their behavior. For this reason, a discrete-based numerical model is necessary. This allows to investigate the possible clogging of the filter and its development over time, in reason of the granulometric characteristics of the moving mass.

In order to give an interpretation to the signals recorded on St. Vincent site, the discrete element method (DEM) is here proposed. The type of load exerted on the barrier is evaluated by assuming the barrier itself is hit by a single surge of grains (Fig. 6).

The output is plugged into a finite-element model (FEM) of the barrier as a time-history of external actions. A dynamic analysis is then performed, studying how the bending moments at the base of the beams evolve. The strain at the base is then compared to the site recordings. the main factor that determines amplitude and sign of ε_{zz} is M_x, rather than M_y. This is confirmed by the FEM computations of ε_{zz}. Notwithstanding the many simplifications adopted in the procedure, the model is able to capture the order of magnitude of the recorded strains (Fig. 7).

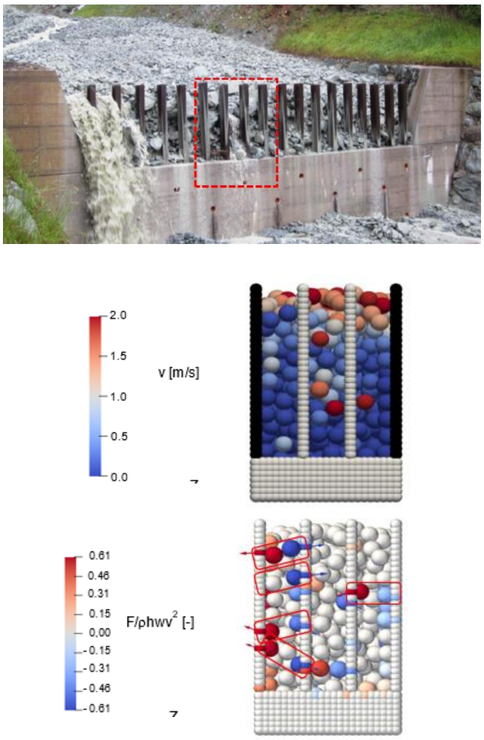

Fig. 6 Schematic of the mechanism of force transmission to be barrier, and corresponding strain field on the beams. The strongest granular arches are highlighted with red boxes (modified after Leonardi *et al.*, 2019).

Conclusions

Debris flows are complex natural phenomena that pose significant risks to human life, property, and infrastructure in mountainous regions worldwide. Effective mitigation of these hazards requires a thorough understanding of their dynamics and interaction with mitigation structures. In this paper, we have provided a comprehensive analysis of discrete and continuum-based numerical modeling approaches applied to debris flows, using data from the Grand Valey catchment as a case study.

Our analysis highlights the strengths and limitations of each modeling approach, as well as their potential synergies in providing comprehensive insights into debris flow dynamics and mitigation strategies. While discrete models excel in capturing particle-level interactions and clogging phenomena, continuum-based models offer a broader understanding of flow dynamics and can simulate the entire debris flow process. By integrating these approaches into comprehensive analyses, we can enhance our ability to predict and mitigate the impacts of debris flows in vulnerable areas.

Moving forward, future research should focus on refining numerical models, integrating data-driven approaches, validating models with field data, improving mitigation structure design, and increasing public awareness and community engagement. By addressing these challenges and embracing emerging technologies and methodologies, researchers can contribute to the development of more effective debris flow mitigation strategies, ultimately saving lives and protecting communities from the devastating effects of debris flows.

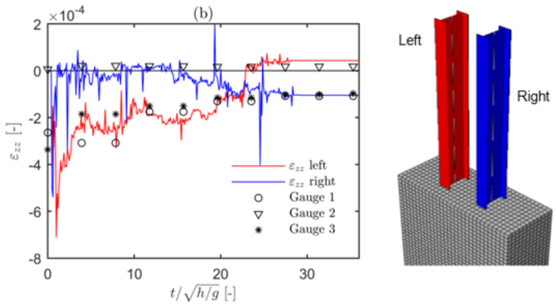

Fig. 7 Time-history of the bending moment registered at the location where the strain gauges are installed, and comparison with the results of the DEM numerical simulations (modified after Leonardi *et al.*, 2019).

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