The impact of debris flow on mitigation structures: a novel depth-averaged and three-dimensional coupled model for the flow dynamic simulation

Debris flows are characterized by rapid movement of a mixture of water, mud, and unsorted debris along natural channels due to gravity. With propagation speeds exceeding 5 m/s and lack of premonitory signals, evacuating local populations is challenging, mitigation measures like barriers become necessary . The current difficulties in designing barriers regard the simplified methods employed that overlook event variability, hindering optimal structural design.

In this study, continuum numerical models, specifically depth-averaged (DA) and three-dimensional (3D) models, are employed to investigate debris flows. DA models depth-average Navier-Stokes equations, reducing the number of variables, allowing for efficient analyses of entire mountain valleys in a short timeframe. However, due to depth-averaging, essential details of vertical momentum transfer are missing, crucial for studying flow-structure interaction (FSI). By contrast, 3D models faithfully replicate FSI but are computationally demanding, making their application challenging for valley-scale flow propagation studies.

The study proposes a novel approach by coupling DA and 3D models to comprehensively investigate a flow propagating in a mountain valley and impinging against barriers. This approach combines the efficiency of DA models with the precision of 3D models, without neglecting upstream flow evolution. The DA model is employed when the flow is far from barriers, and a coupling section is placed upstream of a barrier, with the DA results as input for the 3D model to study the FSI.

The DA-3D coupled model is validated through replicating a laboratory experiment and a real-world event, with the same rheological law in DA and 3D frameworks for consistency.

A laboratory experiment with glass beads in a flume was replicated. Using $\mu(I)$ rheology, the study initially compared 3D results with the original experiment. Subsequently, the DA-3D model, employing $\mu(I)$ rheology, replicated the experiment. Striking similarity were found in DA-3D results when compared with 3D and experimental results. Additionally, forces on the barrier were compared between the 3D and DA-3D models, affirming results consistency and effectiveness of the DA-3D model.

In the site-scale investigation of an event occurred in St. Vincent (Aosta Valley, Italy), the study focused on a filter barrier installed to mitigate the risk associate to debris flows in the area. Field data are available because the barrier was monitored to evaluate forces. In this scenario, the DA-3D model was utilised, avoiding the the $\mu(I)$ rheology due to calibration challenges and because it was formulated for dry flows. Instead, the study opted for Voellmy rheology, extensively used in DA frameworks and specifically adapted for the 3D framework. The examination of debris flow impact on the barrier involved a comparison of field data with numerical values. The findings highlighted the realistic representation of FSI and forces by the DA-3D model at the site scale, emphasizing its potential for the comprehensive study of debris flows.

Acknowledgments

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005) – SPOKE VS 2.