Study of the influence of baffles on an artificial debris flow through back-analysis simulations

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ABSTRACT

In this work, we explore the applicability of a novel approach to the full-scale simulation of debris flows, the Lattice-Boltzmann Method (LBM). The main novelty lies in eliminating the need for depth-integrating the conservation equations, which is still a dominant approach in the field. A full 3D model, both for the topography and for the flow itself is therefore developed and employed. The 3D nature of the model allows to accurately reproduce structural countermeasures. An artificial debris flow, generated in real-scale at an experimental site in Korea, provides the basis for a cross-comparison of results. The effects of two arrays of baffles were also tested in the experiment. The flow scale is intermediate between the large natural flows that are usually reported in the literature and a typical experimental apparatus. It is therefore an ideal candidate for an explorative application of the numerical method.

1 INTRODUCTION

Traditionally, numerical approaches to gravity flows have been used to simplify the geometry by considering a three-dimensional topography, a two-dimensional system of equations for the flow itself. For most phenomena, the longitudinal and transversal directions are much larger than the flow thickness. The conservation equations are then integrated over the flow depth, yielding a single mean velocity for every point on the topography. This has proven to yield excellent results for the prediction of the flow path, and of the runout (Pirulli et al. 2017). However, the main hypothesis of a user-defined velocity profile substantially fails when the flow interacts with non-trivial geometries, such as those given by an obstacle, or a steep jump. There is, therefore, still no consensus over the correct way to numerically model the interaction with obstacles (Leonardi et al. 2016).
The development of numerical models has only recently shown some attempt at moving beyond the depth-integration paradigm. The emergence of new Navier-Stokes solvers, such as Smoothed Particle Hydrodynamics (SPH), the Material Point Method (Mast et al. 2014), and the Lattice-Boltzmann Method (LBM) has opened the possibility to simulate phenomena without recurring to integrated equations. In this work, we explore an application of LBM by reproducing in a numerical environment a debris flow triggered and measured in an experimental site in South Korea. The possibility to use the method for the assessment of countermeasures (Choi et al. 2014) is explored, by simulating the effects of two arrays of baffles on the flow path.

2 EXPERIMENTAL SITE DESCRIPTION

The reference debris flow was artificially generated on an experimental site located about 30 km south-west of Gangneung, South Korea, as shown in Fig.1(a). The topography of the initial section of the gully is given in Fig.1(b). The total length of the studied channel is 824 m, but only the first 250 m is analyzed here. On the uppermost point in the valley, a concrete structure for the initiation of a debris flow has been built, with dimensions of $12.6 \times 12.0 \times 6.4\ \mathrm{m}^3$, see Fig. 1(c). The concrete container is able to store up to $614\ \mathrm{m}^3$ of sediment and water in two separate sections. The water can percolate through the soil section, therefore saturating the material, which then reaches an average density of $2.21\ \mathrm{kg/m}^3$. Then, the opening of a steel gate in the direction of the gully triggers the debris flow.

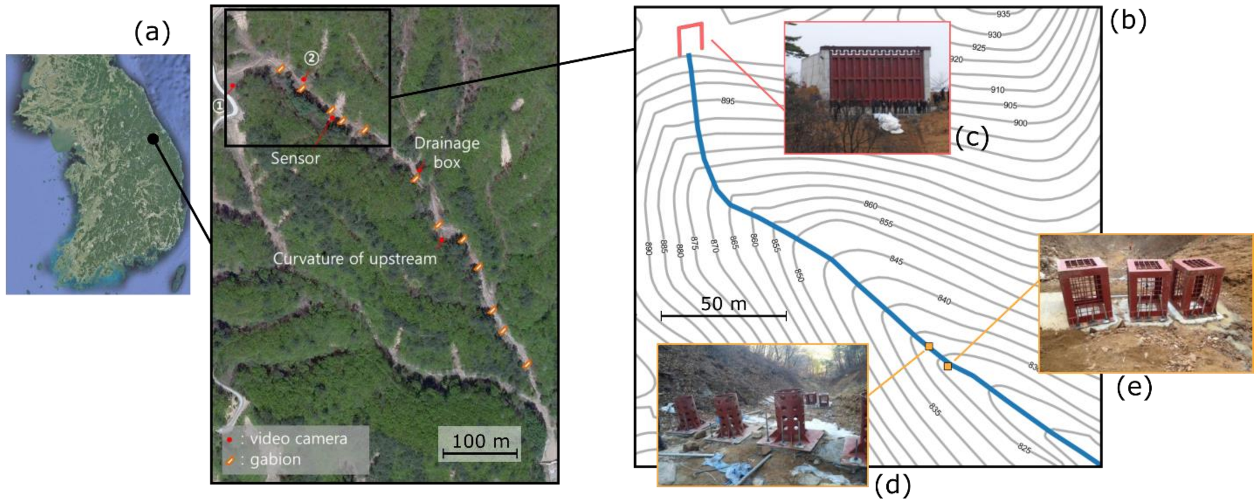

Figure 1: Description of the experimental facilities (a) Location of the site and satellite image, with position of the sensors. (b) Topography of the simulated area, with position and picture of (c) the initiation facility, and (d-e) the two array of baffles.

High-strength geo-textile was installed immediately downstream from the soil and water container in order to prevent excessive erosion in the initial part. At about 150 m from the initiation facility, two arrays of baffles had been installed, see Fig.1(d-e). At the same location, a load cell was installed, mounted on a separate beam element. Several cameras and sensors were placed in the channel, and yield an estimation of the flow depth and the flow surface speed at various chainages. The highly controlled environment, together with the relatively low volume of the flow makes it an ideal candidate for validating the LBM code.

3 NUMERICAL METHOD

LBM is a relatively new approach to fluid dynamics. In this method, the single independent variable is a distribution function $f(\boldsymbol{x}, t, \boldsymbol{c})$ which expresses the probability to find at a given time t and position $\boldsymbol{x}$, a fluid molecule with microscopic velocity $\boldsymbol{c}$. Through the use of a regular lattice for the spatial discretization, and the selection of a limited set of allowed velocities c_i, the evolution of the distribution function can be tracked computationally. Familiar quantities, such as the macroscopic speed $\boldsymbol{u}$ and the fluid density ρ, can be recovered from the distribution function as

$$\rho = \sum f_i; \quad \boldsymbol{u} = \sum f_i \boldsymbol{c}_i / \rho \tag{1}$$

The evolution of the distribution function is controlled by a solution of the Boltzmann equation. The full formulation can be found in Leonardi et al. (2014). It is, however, important to remark that, albeit the peculiar mechanism, a realization of LBM is always equivalent to a solution of the Navier-Stokes equations. One of the major advantages of LBM, in addition to speed and computational simplicity, is that the code performance does not suffer much when implementing complex or irregular boundary conditions, making it an ideal candidate for the simulation of debris flows, and of structural countermeasures.

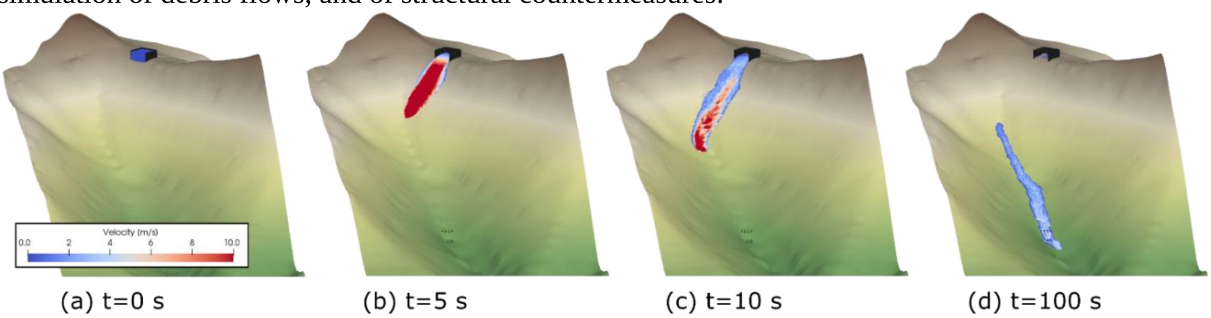

Figure 2: Illustration of the flow as obtained in the simulation, at different time stages. Note the location of the container and baffles.

Debris flows can be simulated using visco-plastic rheological laws, such as the Bingham plasticity ($\tau = \tau_0 + \nu_0\dot{\gamma}$), which is defined by a yield stress τ_0 and a plastic viscosity ν_0. In alternative, frictional laws are also commonly adopted, often including some forms of turbulent dissipation, like the so-called Voellmy rheology, $\tau = \tan\phi\, p + \rho d^2\dot{\gamma}^2$, with ϕ the angle of friction, and d the particle diameter. Additionally, a simpler Newtonian rheology is available, with a turbulence model based on the Smagorinsky approach (Leonardi et al. 2018). In LBM, these constitutive models can be implemented directly without recurring to the integration of an assumed velocity profile, but rather by locally computing at every fluid node the pressure p and the shear rate $\dot{\gamma}$.

The simulation setup aims at reproducing as close as possible the geometry of the experimental site. An example of simulation is given in Fig. 2. The Digital Elevation Model (DEM) of the terrain shown in Fig.1(b) is used to implement the topographical boundary for the flow. The 5 m-spaced grid spacing DEM is resampled to obtain a regular $0.1\ \text{m} \times 0.1\ \text{m}$ grid. The fluid mass is inserted in a box that replicates the storage container, and is instantly released when the computation begins.

4 BACK ANALYSIS

For each rheological model described in the previous section, a preliminary study has been carried out to find the set of parameters that best fits the experimental recording. The most meaningful results obtained for each model are summarized in Table 1. The reference comparison values are the flow height and flow speed before and after the baffles (chainage 147.9m and 166.7m, respectively), where experimental measurements were available.

Table 1: Summary of the calibration of numerical parameters for different rheological models.

	Speed before baffles [m/s]	Speed after baffles [m/s]	Flow depth before baffles [m/s]	Flow depth after baffles [m/s]	Max baffle force (row 1) [kN]	Max baffle force (row 2) [kN]
Experimental	6.92	7.02	1.9	0.8	>27	>27
C1: Turbulent ($\nu = 50\ \text{Pa}\cdot\text{s}$)	7.90	7.92	1.48	1.12	39.73	52.75
C2: Turbulent ($\nu = 60\ \text{Pa}\cdot\text{s}$)	6.43	5.85	1.05	1.10	34.47	46.09
C3: Voellmy ($d = 0.04\ \text{m}, \phi = 0°$)	7.93	7.28	1.46	1.16	72.97	90.28
C4: Voellmy ($d = 0.01\ \text{m}, \phi = 6°$)	8.08	7.64	1.40	1.20	90.28	61.55
C5:Voellmy ($d = 0.01\ \text{m}, \phi = 10°$)	9.00	7.05	1.22	1.21	81.80	82.88
C6: Bingham ($\tau_0 = 1500\text{Pa}, \nu_0 = 60\ \text{Pa}\cdot\text{s}$)	8.81	5.82	1.10	1.21	179.71	60.63

The best fit is obtained with a Voellmy rheology, with no friction (Case 3: $d = 0.04\ \text{m}, \phi = 0°$). For this case, the complete speed- and height profiles are also provided in Fig. 3, together with the available experimental measurement over the simulated channel portion. Additionally, for this case the force on the three cubic baffles are also reported on panel (c). The element supporting the load cell failed during the experiment. The failure load was estimated to be impact load of about 27 kN, indicating that values higher than this were probably exerted to the baffles, a hypothesis substantiated by the numerical findings. Overall, the Voellmy rheology seems to give a very good comparison with the experimental data.

On the other hand, the Bingham rheology correctly reproduces the flow in the first section of the channel. It exhibits premature stoppage of the material directly downstream of the baffles. This was not observed during the experiment, where the material flowed much further, beyond the instrumented section. A secondary effect of the yield stress in the Bingham rheology is the high force registered on the baffles, probably due to the difficulty of the visco-plastic fluid to pass through the narrow spaces between the baffles, which caused them to substantially dam the channel on that section (Choi et al. 2017). For all these reasons, the Voellmy rheology seems better suited to the analysis of the study case than the Bingham model.

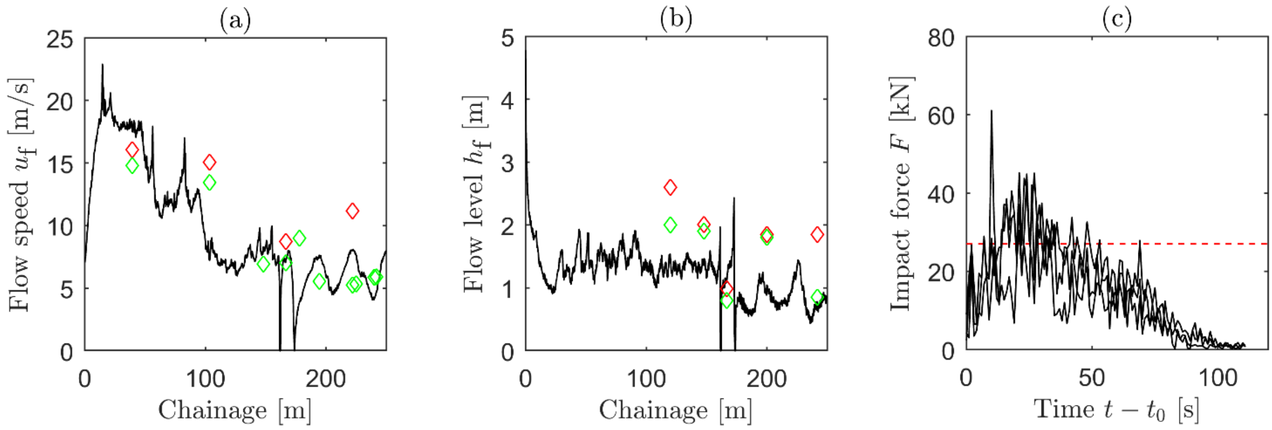

Figure 3: Cross comparison between experimental measurements and simulation data. (a) Flow speed at various chainages. The two drops at ~170m correspond to the location of the baffle arrays. The green and red markers correspond to the tests with/without baffles, respectively. (b) Flow height. Note the hydraulic jump that forms before the baffles. Legend same as left panel. (c) Force measured on each element the second row of baffles, as function of time after first impact. The dotted red line is the minimum estimate provided by the failure of the load cell.

5 CONCLUSIONS

The understanding of debris flow mechanism and the design principles for effective countermeasures could be greatly improved by the development of a reliable numerical tool. In this work, we outlined the preliminary results of applying LBM, a 3D fluid solver, to back-calculate a large-scale experimental debris flow. The results are promising both for what concerns the estimation of the flow features (flow height and speed) and for the estimation of the forces exerted on two arrays of baffles. Overall, a low-friction voellmy rheology reproduces the trend observed in the experiments with good precision. However, further studies are necessary to calibrate the numerical parameters, as the model cannot profit from the experience on integrated models which is dominantly available in the literature.

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