E3S Web of Conferences **415**, 02024 (2023) https://doi.org/10.1051/e3sconf/202341502024
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Shear-thinning, Coulomb friction and grain collisions in debris-flow waterfalls: Applications of a 3D phase mixture model with a single calibration parameter and a complex 4-way coupled resolved CFD-DEM approach

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Abstract. Shear-thinning is a common flow-feature of fine sediment suspensions. Mixed with gravel, Coulomb friction drives the energy dissipation between small grains while collisions become more and more important with larger grains. The interaction of the flow with local geometries of the channel can enforce each of these three key features, making the design analysis of channel sections with obstacles a highly back-coupled system. This paper addresses the numerical simulation of debris flow material under extreme flow conditions at planned protection measures. Mixtures with small grain sizes are modelled with a single calibration parameter using the 3D CFD phase mixture software debrisInterMixing and compared with laboratory experiments. To further investigate the scaling of the results, a coupled code of YADE and debrisInterMixingLP is applied accounting for the 4-way coupling to the coarse boulders at the front with resolved CFD-DEM, reaching beyond the possibilities of debris flow experiments.

1 Introduction

Debris flows assemble sediments of different grain-size and compound them with water. The interstitial fine sediment suspension between grains can be treated as a Herschel-Bulkley fluid. In cases with homogeneous flow patterns and high share of fine material, the interstitial fluid damps grain collisions and Coulomb friction drives the grain-to-grain contact. Such mixtures composed of fines typically form the tail part of debris flows. In most cases, debris flow experiments fulfil this constraint, too. As a consequence, such flows can be reproduced with the CFD code debrisInterMixing [1] accounting for the shear-thinning by using a Herschel-Bulkley exponent close to $n = 1/3$, leading to a single calibration parameter [1][2]. However, field observations and numerical investigations show that mechanisms of segregation under the influence of fluid forces accumulate larger grains at the flow front, making grain collisions a driving factor of the flow process at the front. The collisions then cause grain accelerations that lead to strong deviations between the velocity of the particle and the surrounding fluid, creating drag forces that cannot be neglected. This coupled process of grain-to-grain, grain-to-fluid, fluid-to-grain and grain-to-wall force interaction is denoted as four-way coupling in CFD-DEM particle laden flow modelling. A local average of the surrounding fluid velocity filed applies sufficiently for coarse gravel and pebbles particle-fluid interactions. In contrast, the large boulders transfer momentum between distant regions of the flow field by their rigid body dynamics. When the fluid force is resolved locally on the (e. g. non-spherical) particle surface, the resulting detailed coupling of the grain and fluid dynamics is referred to as resolved CFD-DEM coupling. Here we address an extreme case of shear thinning, pressure fluctuations and collisions found at the Fellbach torrent in Canton Valais, Switzerland, were the debris flow passes a series of high waterfalls before hitting a protection measure which is currently planned below the last cascade.

First, we show how simple single-parameter CFD simulations at the real-world scale agree with small-scale, mid-scale and large-cale debris flow experiments. Then we compare the laboratory experiments of the Fellbach torrent with the full-scale single-parameter CFD simulation to shed some light on the scalability. Finally we present the resolved CFD-DEM approach of DIMYade, a four-way coupling between debrisInterMixingLP [4] and the high-precision discrete element code Yade [5] already used for hillslope debris flow simulations [6].

2 Applications with a single calibration parameter neglecting grain collisions

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https://doi.org/10.1051/e3sconf/202341502024

2.1 Lab-scale experiments and simulations

Lab-scale debris flow and hillslope debris flow experiments contain e. g. high shares of fine material suspensions. Most can thus be modelled in 3D using a Herschel-Bulkley rheology law for the slurry in combination with a pressure dependent Coulomb-viscoplastic rheology for fine gravel, in a mixture model like debrisInterMixing [1]. Good results were obtained with just a single calibration parameter, even without readjusting it to other material compositions. The angle of repose of the gravel sample was used as its friction parameter. The Herschel-Bulkley parameters were derived as defined in [1] with a shear-thinning parameter $n \approx 1/3$. Only one grid-dependent parameter remains for calibration. Examples can be found in [2] or [3].

2.2 Simulation of lab-scale experiments in full scale

To shed light on some aspects of the scaling of laboratory experiments to the real scale, two planned debris flow protection measures were modelled in full scale and compared with the laboratory experiments. Both protection measures deflect the debris flow into a discharge channel, resulting in a complex interplay of shear, pressure, and details of the 3D-geometry. Both cases were modelled with the single-calibration parameter approach using debrisInterMixing [1]

Debris flow discharge channel at Lienzerbach, Altstätten (Switzerland)

The first case was to optimize a planned construction geometry at the Lienzerbach near Altstätten in the canton St. Gallen, Switzerland. It was modelled and the design was altered accordingly prior to the experiments. The material composition was given by the geological survey and the parameter tau00 was calibrated to match the pre-defined flow height of the scenario in an upstream bend. Fig. 1 shows the comparison of simulation and experiment, in the moment where a second surge develops and reaches the protection barrier that deflects the flow to a lateral channel and finally to the fan apex. Simulation and Experiment agree well.

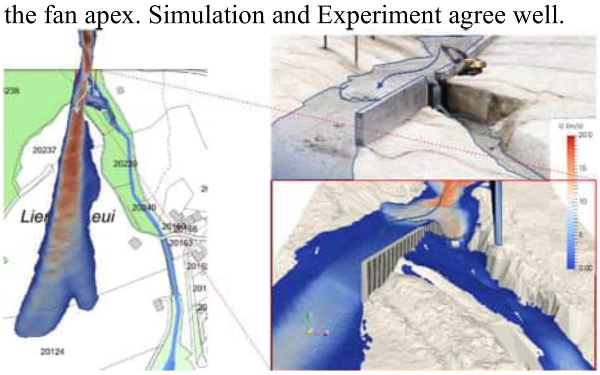

Fig. 1. Left: Situation of the spill with the spread of simulated debris flow material into the deposition slope, right: view upstream on the spillway at the moment when a second surge evolved. The wall heights in the experiment (right top) were altered according to the simulation results (right bottom), where too much debris tops over.

Simulation of debris flow at the Fellbach waterfall cascade, Saas-Balen (Switzerland)

The second case is situated at the Fellbach torrent in Saas-Balen, canton Valais, Switzerland. It contains a series of waterfalls upstream of the planned protection measure, with extreme conditions in terms of pressure peaks, shear and large temporal and spatial gradients (Figure 2 left).

Fig. 2. Left: The cascade of three waterfalls before hitting the village in a moderately inclined, narrow channel. Right: Experiment with corresponding protection measure – a wall with lateral discharge channel to bypass the village.

The situation was examined with laboratory experiments [7] (Figure 2 right). Two numerical models were created, one with and one without protection measures. The parameters were based on the lab test material and tau00 was calibrated to match the simulated travel time with the measured travel time between the upstream end of the first waterfall and the beginning of the village housings. However, this calibration was only done once based on the experiments and model of the current state without protection measures. The comparison with the experiment including the planned dam and spillway is thus seen as a quite independent validation for the complex flow processes involved. The match in flow structure and flow front velocity is astonishing (Figure 3 and 4), indicating that a scaling of the lab experiments in the range of 1:50 seems to produce adequate results.

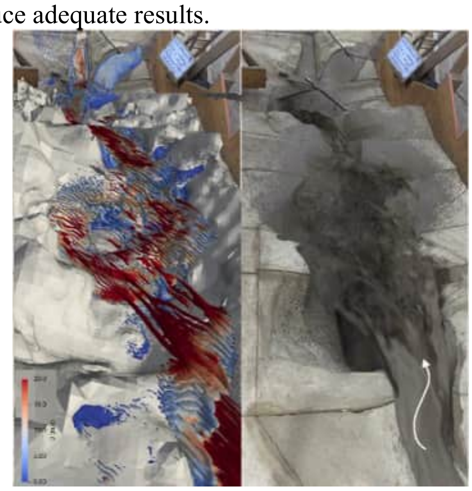

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Fig. 3. Top view of the waterfalls including the planned protection measure at the end, with the simulated surface (left) and the lab experiment (right).

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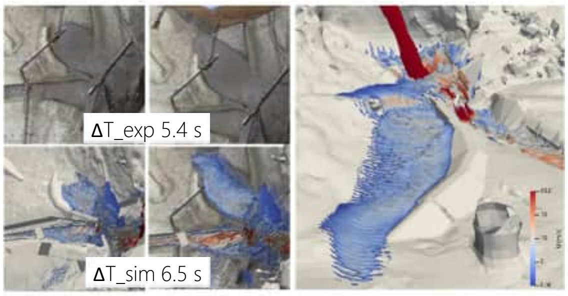

Fig. 4. Closeups of the spreading within the discharge region at two different times (top rows) and a snapshot of the simulated spilling process (bottom) with a perspective corresponding to the lab experiment shown in Fig. 2. The colour legend indicates surface velocity as computed by the model.

2.3 Simulation of field test sites without particle coupling

However, both full-scale models and the corresponding experiments lack the effect of larger grain collisions, which brings us to large-scale outdoor experiments and simulations with coupled particles. In larger scale, with a certain amount of grain collisions being part of the flow process, flume experiments at the USGS test site were performed [8][9]. The debris-flow mixture of large scale experiments was composed of slurry and gravel with only few larger grains, and thus could be modeled with the single-calibration parameter approach. The difference between the flow and deposition of a Sand-Gravel-Loam mixture compared to a pure Sand-Gravel mixture was covered as well as the change in flow dynamics due to the introduction of a rough bumpy bed (Figure 5 and 6).

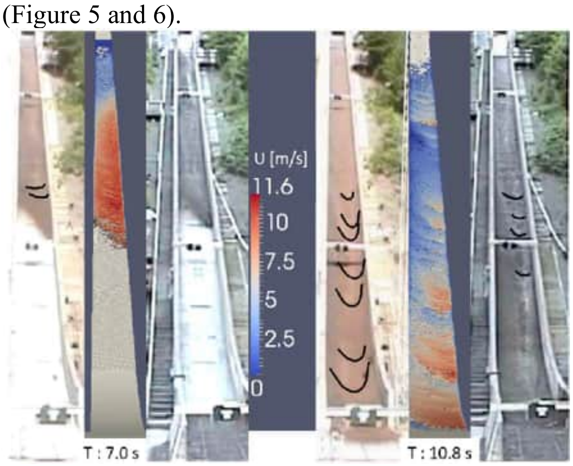

Fig. 5. Front view of two rough-channel experiments with sand, gravel and mud with 20% loam content (SGM-Mixture) and the corresponding simulation in between, 7 s (left half) and 10.8 s after release. Black lines indicate surface waves at the experiment that appear in the model, too.

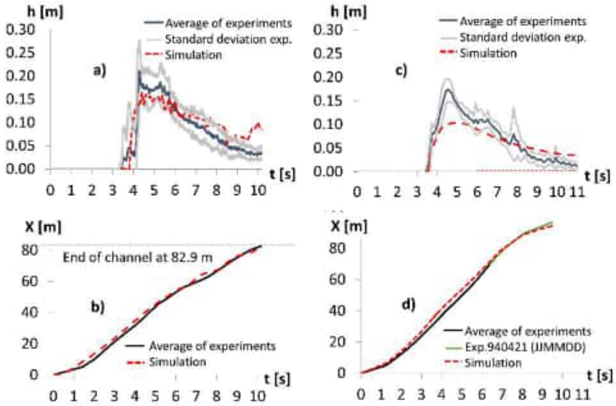

Fig. 6. Left panels: SGM Mixture in the rough channel: a) flow height over time 32 m downstream from the release gate and b) flow front position over time. Right panels: Corresponding results for sand and gravel (SG-Mixture) with water in the smooth channel.

3 Simulations with DEM-Particles

The presence of larger particles reduces the shear-thinning of the overall material mixture. One solution is to adjust the shear-thinning parameter of the slurry rheology in debrisInterMixing as presented in [3]. An alternative is to add large particles with a four-way coupling technique. With the aim to stick to the single calibration parameter strategy, particles with fixed standard parameter properties were included, and the calibration was restricted to the interstitial fluid phase mixture. We modelled a 2 m wide section of a coarse-gravel dominated experiment at the outdoor test site in Veltheim (Switzerland) [10] with symmetric lateral boundary conditions including the grainsize distribution between 10 and 67 mm with a CFD-DEM solver debrisInterMixingLP [4], see Fig. 7. We applied the same solver but with single sized particles to the Lienzerbach debris flow channel. Besides higher impact pressures, the difference to debrisInterMixing appears in larger flow heights due to the particle disturbance of the smooth surface.

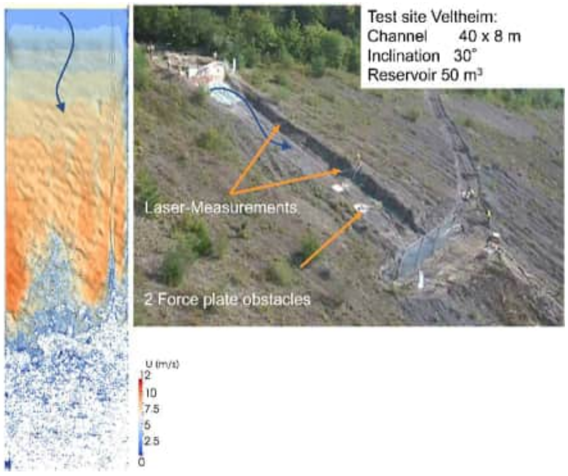

Fig. 7. Left: Top view of the material surface as it reaches the first laser (colour by surface velocity) from a CFD-DEM simulation with debrisInterMixingLP, right: field test site at Veltheim, Switzerland.

4 A 3D debris flow solver with Resolved CFD-DEM to cover all scales and compositions

However, the dominant part that large boulders play on debris flow front behaviour and pressure peaks rose some open questions considering the waterfall cascades at Fellbach torrent. Therefore, a first resolved CFDDEM coupling between debrisInterMixingLP and Yade, called DIMYade, was realised in 2022 in collaboration with the Berner Fachhochschule in Zollikofen, Switzerland, and the Staubli, Kurath & Partner AG in Zürich, Switzerland. Yet Another Discrete Element (YADE) is an extensible open-source framework for DEM-based discrete numerical modeling. Details of the applied contact laws can be found in [5]. Fig. 8 shows the comparison of measured and modeled flow front arrivals at the Veltheim test, including some blocks (black) of resolved-CFD-DEM using the clamp technique. The debrisInterMixing part was again calibrated to match the arrival time based on tau00. The Yade particles were modeled friction-less, as the coulomb friction is covered by debrisInterMixing. The particles had modulus of elasticity of 1e9 N/mm2 and a particle density of 2526 kg/m3. A possible application of the CFD-DEM at the Fellbach torrent with large boulders in the front could give insight about peak impact forces and expected bouncing heights of falling boulders.

Veltheim Test 17 (viskous-granular)	Laser 1	Laser 2	Forceplate
X_L (m)	14	26	30
Front arrival time experiment (s)	1.92	3.31	3.67
Front arrival time simulation (s)	2.0	3.2	3.57
Relative difference	4%	-3%	-3%

Fig. 8. Side view perspective of the resolved CFD-DEM simulation of debrisInterMixing coupled with Yade, DIMYade, and a table comparing simulation and experiment.

5 Conclusions

The single-calibration parameter strategy can be applied to model laboratory scale and large scale experiments, as long as pebbles and boulders are neglected. The general flow process can be well captured, even in extreme flow conditions like debris flows that pass waterfalls or side spills. The deposition pattern is in good agreement with the experiments. However, the presence of larger particles demands either a four-way coupled CFD-DEM approach as used in debrisInterMixingLP or the calibration of two model parameters in debrisInterMixing. The simulation of the flow front dynamics with large boulders demands a four-way coupling of particles with resolved CFD-DEM. We presented the debrisInterMixingLP extension named DIMYade, that allows to account for the physical processes that larger pebbles and boulders introduce to the flow. Such a detailed approach demands a lot of additional computational time and costs.

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