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ESTIMATION OF GRANULAR FLOW IMPACT FORCE ON RIGID WALL USING MATERIAL POINT METHOD

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Abstract. Landslides and avalanches cause loss of lives, as well as generate significant economic cost. Protection barriers help reduce the impact of such events. However, the design of the barriers requires the prediction of the landslide flow trajectory and the estimation of impact force. Material Point Method appears to have great potential for estimating those, since it can account for large displacement nature of sediment flows and their nonlinear behaviour. Therefore, it may be able to capture the complex interaction of landslides or avalanches with the ground and structures.

This study focuses on simulating granular flows with Generalized Interpolation Material Point Method. The calculations use a constitutive model inspired by the Bagnold theory of granular flow [1] to model sand landslide / avalanche experiment [2] with sand treated as a linear elasto-plastic material. Shown simulations aim was to replicate the experiment. In particular, the paper focuses on estimation of the impact force of sand flow on a fixed rigid wall. Such force estimation is a first step to validate the Generalized Interpolation Material Point Method for use as a tool for the design of barriers defending against landslides and avalanches.

1 INTRODUCTION

Natural or manmade phenomena may cause instabilities in slopes resulting in landslides and sediment flows. These flows may contain soil, debris and rock mixed together. The avalanches can reach high speed quickly after formation and carry significant amount of energy. Therefore, they can ravage areas and impose destructive forces onto anything on their way. The sediment flows and avalanches results in significant damages to infrastructures and economic losses every year while being also a threat to people living in the landslide prone areas. In order to reduce the threat of debris flows, protective actions are necessary. For example, protective barriers placed on the path of debris flows can stop the flows or at least decrease their speed and energy. Economical design of those protective barriers requires estimation of debris flow / avalanche impact force.

Researchers have used different approaches for estimating the impact force of debris flows. Empirical models were used alongside statistical analysis to identify problematic slopes [3]–[5]. Such an approach is certainly useful for general risk estimation. However, it is of limited help in design of the protection structures, as it cannot take details of each case into consideration. On the other hand, there are experimental data and tests which investigate the impact force of flows, e.g. [2], [6]–[8]. These tests are the most accurate and reliable approach, however, they can be very expensive, require significant time and, in many cases, simply not feasible as they cannot replicate full scale landslide. Therefore, numerical simulations may be the method, which could offer affordable assessment of the impact force of sediment flows. For example, Moriguchi et al. [2] performed numerical simulations within computational fluid dynamic framework, confined interpolation profile and Bingham constitutive model to simulate granular flow and estimated impact force of it on rigid obstacles [2]. On the other hand, Ceccato and Simonini [9] used Material Point Method (MPM) for modelling granular flows experiment in [2]. They used two different constitutive models (elastic-perfectly plastic and viscoplastic models) to describe granular materials.

This paper uses Generalized Interpolation Material Point to estimate normal impact force of sand flow on rigid barriers. The investigation focuses on replicating the dry Toyoura sand flow experiments [2].

2 GENERAL SPECIFICATIONS

2.1 Description of Laboratory Experiments

This paper presents modelling of small scale experiments on sand flow performed by Moriguchi et al. [2]. The described experiment involved placing 50 kg of dry Toyoura sand in a box on top of a flume with variable slope angles. After quick opening of the box, the sand flew on the flume surface, which was coated with the same sand used for the experiment. A load cell at the bottom of the flume measured the normal impact force on the obstacle. The opening mechanism is believed to be such that the sand box opening has no effect on the initial flow behaviour of the sand. Figure 1 shows a schematic illustration of the tests.

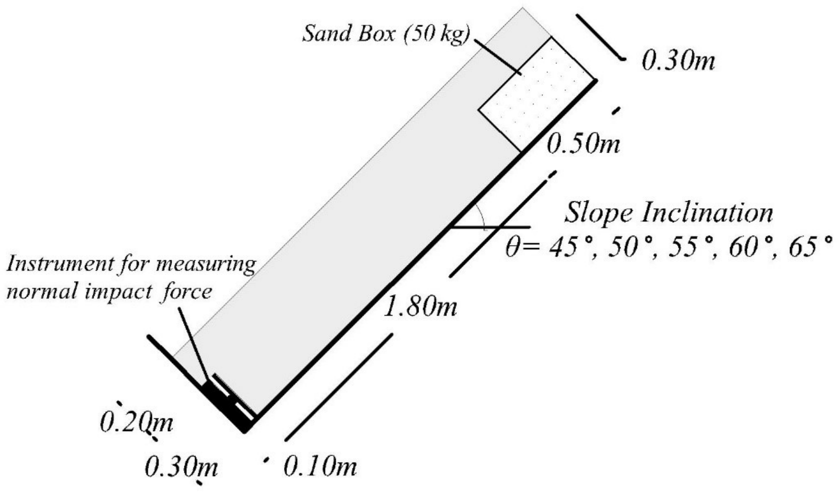


Figure 1- schematic illustration of the experiment tests (after [2])

2.2 Description of Numerical Models

The simulations shown used Generalized Interpolation Material Point (GIMP) method and investigated flow of Toyoura sand. Bardenhagen and Kober introduced GIMP in 2004 as an advancement to Material Point Method [10]. MPM is itself a development in particle cell method (PIC) tailored for solid mechanic by Sulsky et al. [11], [12]. Material Point Method simulations have the advantage of being free from mesh tangling common e.g. in the Finite Element Method and have no problem in modelling fluid-structure interaction [13] while using the continuum mechanics framework. In this research, GIMP method encoded in the software suite Uintah (http://uintah.utah.edu) was used.

The calculations approximated the laboratory experiments as plane strain problems with the flume in all models aligned to the horizontal axis and gravity varying instead of changing the flume inclination. In all the simulations, rigid wall was 0.3m high and 0.1m thick. The initial distance between the rigid wall and sand was 1.8m. Furthermore, a layer of the same sand, but fixed, approximated the surface coating. All the numerical model included an extra 0.3m domain in the left side of the rigid wall similar to simulations performed in [2]. This extra domain allowed for simulation of sand overtopping the wall. Figure 2 shows the schematics of numerical models used in this research. This figure also shows the temporary walls in the models. These walls blocked sand in the first 0.5s of simulation to replicate the initial stress in the soil and modelled the box in the experiments. The total simulation time was 2.5s, with the temporary walls deleted from all the models after the first 0.5s.

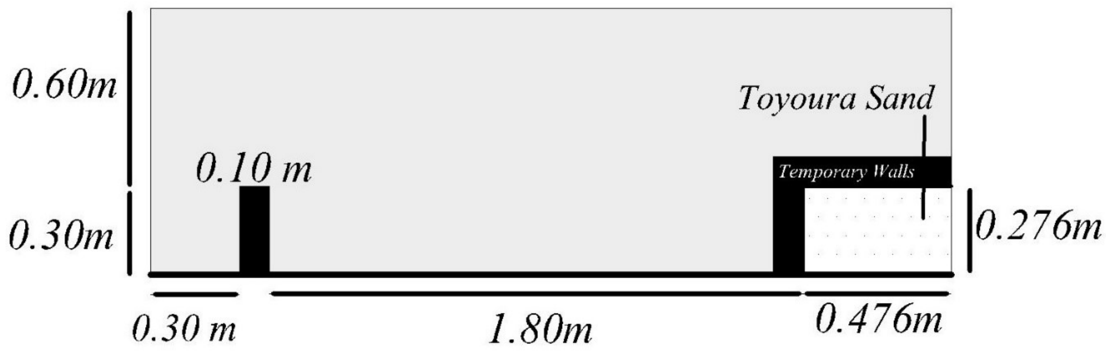


Figure 2- schematics illustration of numerical models

2.3 Constitutive Model

Numerical simulations used an elasto-plastic constitutive model based on the Mohr-Coulomb model enhanced with Bagnold scaling [1]. The sand was assumed to be a linear elastic material for stress states not on the yield surface. Equation 1 shows the formulation for 2 dimensional Coulomb friction criterion where τ is shear stress, σ is normal stress, $\tan\varphi$ is friction angle and c is cohesion [14]. Granular materials are cohesionless and c value is 0 in them.

$$\tau - \tan\varphi\,\sigma - c = 0 \qquad (1)$$

Experiments have shown that flow of granular material happens in parallel layers [1]. Bagnold used this observation to express a dependency between shear stress and rate of shearing. Internal stress also effects shear stress along each layer. Those led to Bagnold scaling relation shown in equation 2 where τ is the shear stress, σ is the normal stress, $\tan\varphi$ is the internal friction parameter and $\dot{\gamma}$ is the rate of simple shear.

$$\tau - \tan\varphi\,\sigma \propto \dot{\gamma}^2 \tag{2}$$

The equation above can be generalised and used to enhance the Mohr-Coulomb model. Comparison of equations 1 and 2 shows that during the flow of granular material non-zero strain rate leads to some shear resistance, which is mathematically same to the Mohr-Coulomb cohesion. Therefore, one can use a factor of shear rate squared ($\eta\,\dot{\gamma}^2$) instead of cohesion in the Mohr-Coulomb yield surface equation. Such model should be suitable for granular flow that is flow for materials in which cohesion for small strain rates would be zero. Equation 3 shows the obtained formulation of the modified Mohr-Coulomb yield surface,

$$F = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3)\sin\varphi - 2\,(\eta\,\dot{\gamma}^2)\cos\varphi = 0 \tag{3}$$

where σ_1 the maximum is principal stress, σ_3 is the minimum principal stress, φ is the friction angle, $\dot{\gamma}$ is the rate of simple shear and η is the calibration parameter. The difference between this formulation and the Mohr-Coulomb model is just the replacement of cohesion with the factor related to the shear strain rate squared.

The implemented yield surface and its rate dependent mechanism of flow has provided good predictions when solid fraction of granular flow is constant (i.e. uniform flow). On the other hand, this constitutive law does not have any way to account for the non-uniformity [14] in the flow. Therefore possible non-uniformity of the flow should be addressed differently.

3 NUMERICAL MODEL

3.1 Choosing Parameters of Constitutive Model

The model requires calibration of 2 elastic parameters and 3 parameters related to the yield surface and flow behaviour of the material. The elastic parameters used were the shear modulus and the Poisson ratio. The shear modulus of sand is high at very small strain and decreases when strains become larger [15]. In the calculations, as the sand is in the state of flow and very large shear strains are applied to it, a very low value of 20 kPa was used. Even though the chosen value of shear modulus is very low, the extensive set of data provided in [15] on shearing of sand suggests that it is not unrealistic. Elastic modulus in this range has been used in other researches investigating granular flows [9], [16].

Investigations on heap flows and rough inclined planes [14], [17], [18] revealed the existence of two regions in the granular flows. One region in lower parts where the ground surface prevents the grains from flowing freely and deform volumetrically. Another region is near the surface of the flow where nothing blocks the motion of grains. The constitutive model implemented in the simulations cannot address that difference. Therefore, the simulations approximated that constrain with soil layers which have different Poison ratio to account for the non-uniformity of the material during the flow. In all the models, 5 layers of sands with different Poisson ratio were considered at the initial state. Figure 3 shows Poisson ratio of each layer and their height in the beginning of simulations. Poisson ratio of the lowest layer was 0.495 (non-compressible) while the top layer had a Poisson ratio of 0.3 (a standard value for the Poisson ration for Toyoura sand).

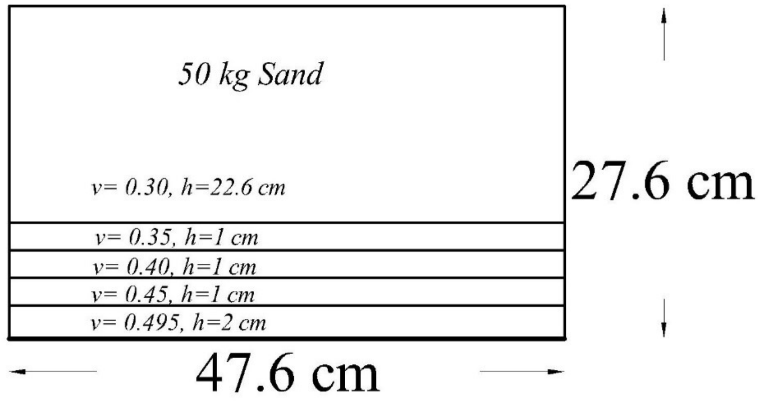


Figure 3- Poisson ratio of layers and their height (Not scaled)

The friction and dilation angles control the plastic behaviour of sand in the Mohr-Coulomb model. Laboratory tests on granular materials, including Toyoura sand, have shown that the friction angle at the critical state is independent from the initial void ratio and stress path. Furthermore, variations in the volumetric strain becomes zero when the critical state is reached [19]. The implemented constitutive model in this research is unable to model hardening / softening behaviour of soils. In addition, the initial void ratio of Toyoura sand in the experiment (0.917) is very close to the critical void ratios of Toyoura sand considering the possible range of pressure in the experiment. Therefore, we assumed that reaching the yield surface and the critical state happened simultaneously in the models. Consequently critical friction angle of Toyoura sand, which is 31° [20], and 0° dilation angle were used in all the simulations. Table 1 summarizes the parameters used in the simulations of the sand flow experiments.

Table 1- parameters in the numerical simulations

$\gamma\ (\frac{kg}{m^3})$	$G\ (kPa)$	υ	$\varphi\ (°)$	$\psi\ (°)$
1379	20	0.3 0.35 0.4 0.45 0.495	31	0

3.2 Calibration of Constitutive Model

Data available from the experiment on 45° inclination test was used in calibration of the extra parameter (η) in the constitutive model. That calibration parameter (η) was chosen such that the simulation gives very good estimation of the normal force as well as a similar flow profile to the one in the experiment. Figure 4 shows the calculated and experimental normal force on the wall in time. It is clear that the numerical model estimated the normal force very well with the parameter η chosen equal to $0.15\ (Pa.s)^2$. It also shows that the model with $\eta = 0.15\ \ (Pa.s)^2$ estimated arrival time of the flow to the end of flume quite well.

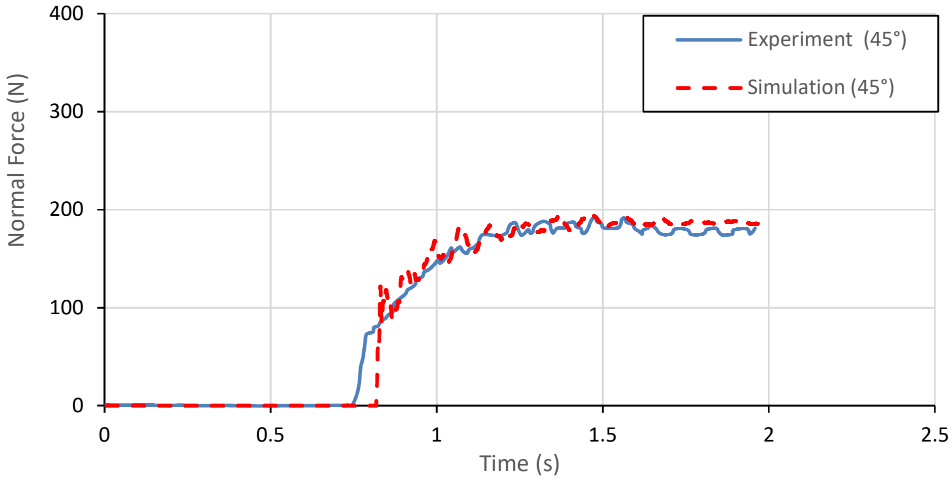


Figure 4- result of calibration

Furthermore, Figure 5 shows the simulated flow profile for the test with 45° and compares it with the experimental free surface of flowing sand (indicated by the black line). The simulated flow profile match the experiment free surface well especially in the later stages of the experiment.

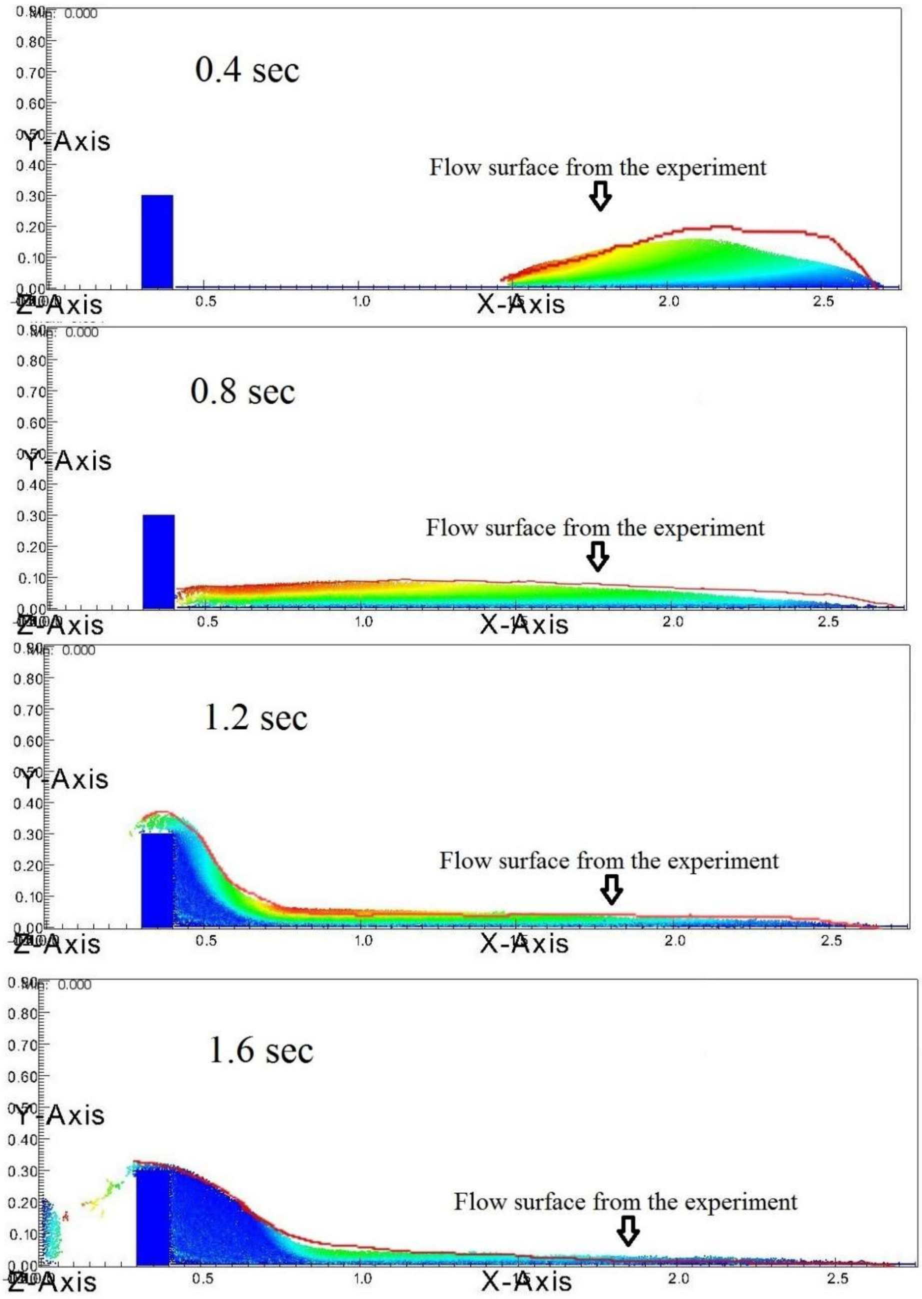
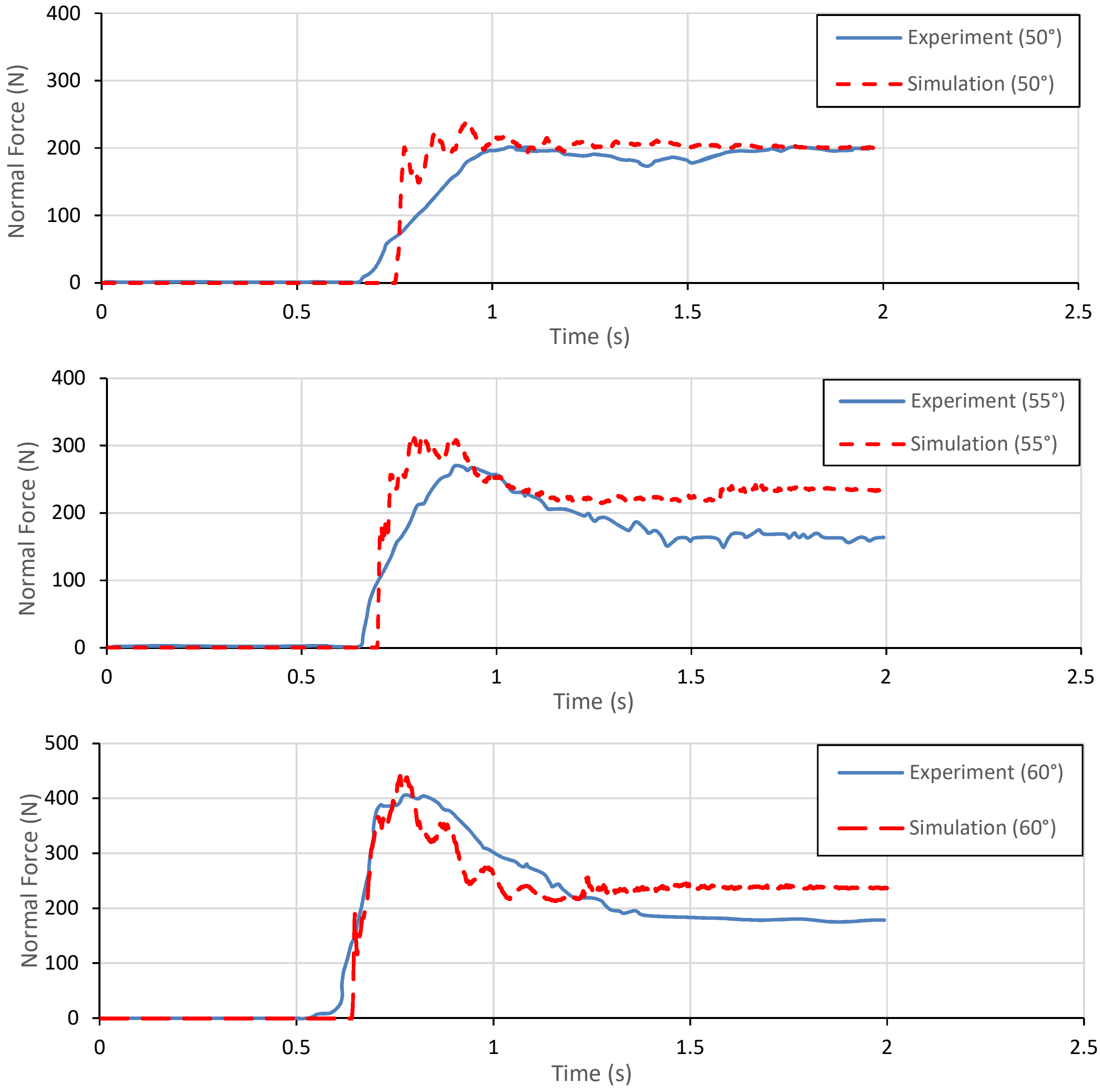


Figure 5- flow profile of numerical model with 45° inclination and 5 $(Pa.s)^2$

4 VALIDATION OF THE NUMERICAL MODEL

After calibration of the constitutive model, simulations modelled the experiments with 50°, 55°, 60° and 65° inclinations. All the simulations used 35064 particles, square computational grid of 5mm, same parameters of constitutive model as shown in Table 1 with the only variation being the inclination of slope. The numerical parameters were the same as in the simulation used for calibration, described in section 3.



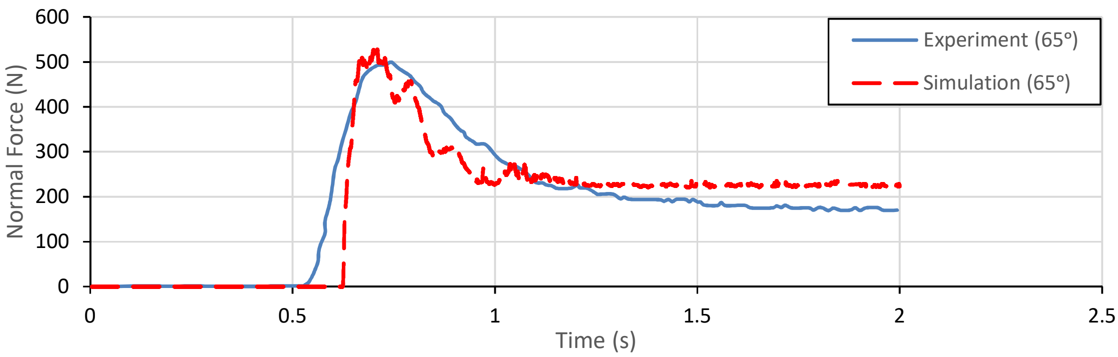


Figure 6- results of force estimations in experiments with 50°, 55°, 60° and 65° inclinations

Figure 6 shows that the numerical results replicate the soil flow experiments well. The arrival time of sand to the end of flume and the overall variations of normal force were predicted quite well especially for the 60° and 65° inclination experiments. Nevertheless, the simulations failed to estimate exactly the increase of normal force at the beginning of impact. That could be a result of the linear elasticity assumption or the constitutive model incapability of considering the softening / hardening behaviour. Also, the estimated normal force for all the experiments showed some oscillations which is one of the common problem in MPM based modelling. Nonetheless, the peak values of the force from the experiments have been recovered well. That is important, as the peak value is usually the critical one for the design of the impact barriers.

5 CONCLUSION

Granular landslides and avalanches are a consequence of slope instabilities and cause loss of lives and significant economic costs. This study used Generalized Interpolation Material Point method with a Mohr-Coulomb based constitutive model, extended with Bagnold scaling, to simulate experiments on sand flows. Results of the calculations are in a good agreement with those from the experiments. Simulations estimated arrival time of sand flows maximum impact and residual normal forces very well. The results of the study indicate capability and competence of GIMP for simulating sand flows and granular avalanches. They also show considerable improvement when compared to previous attempts for modelling these investigations ([2], [9]). However, the used constitutive model needs to be perfected, taking into account non-linearity in shear modulus with strain and more accurate modelling of volume change of the soil.

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