Sensitivity analysis in the modelling of debris flow with coupled CFD-DEM

Ali OSAIRAN[1], Bastien CHEVALIER[1], Rime CHEHADE[1]
1 Université Clermont Auvergne, CNRS, Clermont Auvergne INP, Institut Pascal, F-63000 Clermont-Ferrand, France

ABSTRACT
Due to socio-economic development and climate change, geological disasters such as landslides and floods are expected to increase. In mountainous areas, these geohazards are often caused by heavy storms. Natural disasters such as debris flows (DF) and rockfalls usually occur within natural terrain areas. Since urbanization in many cities, hills have always been incorporated into residential areas. Therefore, debris flow poses a risk to infrastructure and human life increasing the need to predict debris flow impacts for vulnerability and risk assessment. Our general approach proposes debris flow modeling that can derive its impact on the structure where previous model is used to simulate the interaction of debris with structures. The objective of our current work is to perform a parametric study to analyze the effects of REV porosity, ground-particle fi fluid density on debris flow characteristics consequently affecting the impact force on the structure.
Keywords: Debris flow, impact force, vulnerability

I. INTRODUCTION

The challenge of evaluating the impact of debris flow on structures is due to debris flow diversity and complexity, and different types of structures and their exposure. Many experimental studies have focused on the quantification of pressure induced in structures: field measurements, outdoor channel experiments, small and miniaturized experiments. However, these approaches are not economical and are difficult to repeat. Numerical modeling helps overcome the shortcomings of experimental measurements by allowing advanced analysis of the parameters that characterize DF. A granular fluid model is proposed to estimate the effect of lahar on a pillar, based on the Distinct Element Method using PFC3D and individual CFD calculation results by Telemac 3D (Chehade et al. 2021).

II. MODEL

The model is intermediate between purely granular and purely fluid where a one-way coupling exists. The effect of the fluid phase on particles was only considered by calculating the buoyancy and drag forces acting on the particles. The model of the fluid is first calibrated without presence of pillar. Buoyancy generates an upward force on the particle and is calculated according to the following formula:

$$Fb = -\rho v g z \quad (1)$$

where ρ is the fluid density, $\mathbf{v}$ is the particle volume, g is the gravitational acceleration and z is the unit vector. Drag is a force acting by a fluid to the particles resulting from the difference of velocity between them.

$$Fd = \frac{1}{2} C\rho \frac{\pi d^2}{4} \|Vf - Vb\|(Vf - Vb)n^{-\xi+1} \quad (2)$$

where ρ is the density of the fluid, d is the particle diameter, V_f and V_b are the velocities of the fluid and the particle respectively. C is the drag coefficient and is written by:

$$C = \frac{24}{Rep}(1 + 0.15Rep^{0.681}) + \frac{0.407}{1+\frac{8710}{Rep}} \quad (3)$$

Rep is the particle Reynold's number and is expressed in terms of the kinematic viscosity η_f of the fluid

$$Rep = \frac{\|Vf - Vb\|}{\eta f} \quad (4)$$

As proposed in Zhao et al. (2014), a correction factor depending on the solid fraction n in the flow to consider the influence of the particle concentration and the contacts between particles, where:

$$\xi = 3.7 - 0.65exp\left[\frac{-(1.5 - logRep)^2}{2}\right] \quad (5)$$

A channel is supplied with particles through a chamber containing a representative elementary volume (REV). Particles move towards the channel entrance where a pillar exists with a fixed velocity equal to the velocity of the fluid phase (3 m/s), then are released once they enter the channel. The characteristics of the simulated DF is given in Figure 2. The channel slope is 2% and is surrounded by walls. The pillar is 8m heigh, divided into 20 zones, 0.4 m heigh and perfectly fixed to the ground.

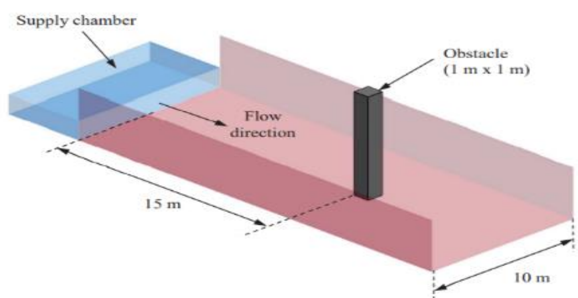

Figure 1: Artificial channel (Chehade et al.2021)

Property calibration	
Density of particles (kg/m³)	2500
Fluid density (kg/m³)	1100
Dynamic viscosity (Pa.s)	0.048
Friction particle-particle	0.4
Friction particle-wall	0.0
Rolling resistance	0.2

DFs characteristics obtained	
Solid concentration (%)	55
Apparent density (kg/m³)	1867
Flow rate (m³/s)	40

Figure 2: Debris flow characteristics (Chehade et al.2021)

The results of the proposed numerical model having a flow height 1.5 m and a velocity of 3 m/s were verified with other empirical formulas based on experimental approaches. The comparison shows good agreement with variation of Froude number, the ratio of inertial to gravitational forces.

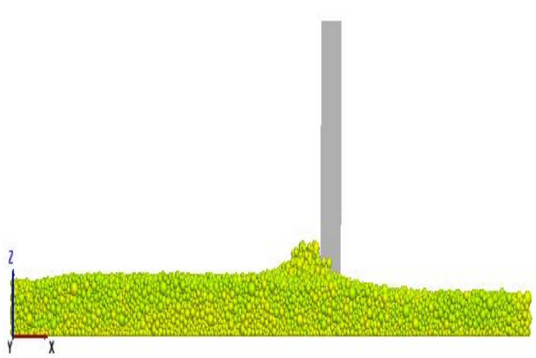

Figure 3: Flow of particles against pillar

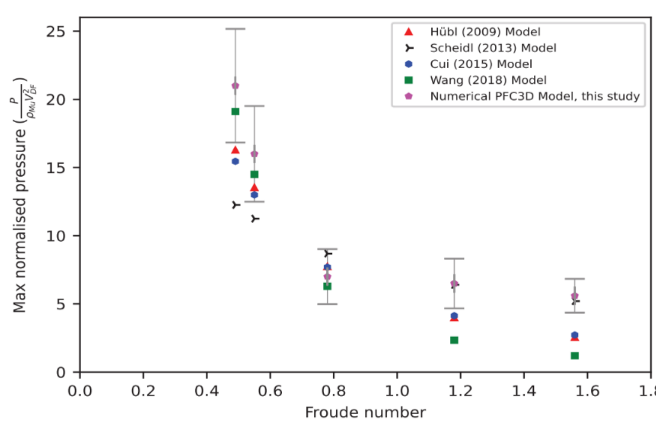

Figure 4: Comparison of numerical model with empirical models (Chehade et al. 2021)

III. SENSITIVITY ANALYSIS OF DEBRIS FLOW CHARACTERISTICS

It is desired to study the effect of REV porosity, friction between walls and particles, and fluid density on the flow characteristics, hence on the average impact force. The dynamic force at each zone was calculated numerically and assumed to impact the center of each zone. The static force at each zone was calculated according to this formula:

$$\boldsymbol{F}static = \boldsymbol{\rho g}[Z - z(i)] \quad \textbf{(6)}$$

$\boldsymbol{\rho}$ is the fluid density, g is the gravity, Z is the accumulation height or particles around pillar, and zi is the height of the center of each zone of the pillar. Then, then the average dynamic and average static force at each zone were added to calculate the average total force on the pillar and its position of impact.

$$\boldsymbol{Faverage} = \sum_{i=1}^{20}[\boldsymbol{F}(\boldsymbol{i}+\mathbf{1}) + \boldsymbol{F}(\boldsymbol{i})] * (\frac{\mathbf{0.4}}{\mathbf{2}}) \quad \textbf{(7)}$$

$$\boldsymbol{Position} = \frac{\sum_{i=1}^{20} \boldsymbol{F}(i) * \boldsymbol{z}(i)}{\sum_{i=1}^{20} \boldsymbol{F}(i)} \quad \textbf{(8)}$$

A. REV Porosity

The results are shown in the following table.

Table 1: Analysis of sensitivity to REV porosity

Porosity (REV)	Velocity (m/s)	Flow Height (m)	Z (m)	Static Force (kN)	Dynamic Force (kN)	Total Force (kN)	Position (m)
0.45	2.13	1.95	2.59	31.70	58.00	89.70	0.86
0.50	2.12	1.78	2.30	26.33	49.01	75.34	0.80
0.55	2.12	1.61	2.17	21.00	40.02	61.02	0.77

Here, it is interesting to notice that varying the REV porosity also has a hidden effect on the impact pressures since it significantly affects the flow height. With an increase of REV porosity, we notice a decrease in the flow height and hence less impact pressures on the structure.

B. Ground-Particle Friction

In general, the friction force applied during any motion will have an effect on the response of the overall system. It is also desired to study the effect of the friction with the bottom of the channel to mimic the interaction of debris particles with the terrain. Therefore, several values of ground-particle friction were taken into account and the results are provided in the following table.

Table 2: Analysis of sensitivity to ground-particle friction

Friction	Velocity (m/s)	Flow Height (m)	Z (m)	Static Force (kN)	Dynamic Force (kN)	Total Force (kN)	Position (m)
0	3.2	1.27	2.30	26.33	49.01	75.34	0.80
0.1	2.82	1.40	2.45	27.51	54.81	82.32	0.86
0.2	2.6	1.50	2.41	23.84	57.40	83.96	0.87
0.5	2.12	1.78	2.41	26.56	45.26	71.82	0.85

Table 2 shows that with the increase of ground-particle friction, we have a decrease in the velocity of the flow and increase its flow height. By analyzing the results, we deduce that there is no specific trend due to the effect of particle-ground friction on the impact forces.

C. Fluid Density

In the model understudy, the effect of fluid on particles is taken into consideration by the action of buoyancy and drag. These two forces are in function of fluid density according to equations 1 and 2. Therefore, a sensitivity analysis of the fluid density parameter is performed to analyze its effect on the flow characteristics.

Table 3: Analysis of sensitivity to fluid density

F.Density (REV)	Velocity (m/s)	Flow Height (m)	Z (m)	Static Force (kN)	Dynamic Force (kN)	Total Force (kN)	Position (m)
1100	2.12	1.80	2.41	26.33	49.01	75.34	0.80
1200	2.19	1.75	2.41	28.48	50.45	78.94	0.83
1300	2.25	1.70	2.33	29.15	48.85	78.00	0.85

Table 3 indicates that the increase of fluid density affects the flow characteristics. We can notice a slight increase in the flow velocity and a decrease in the flow height. There is no significant variation in dynamic forces, whereas static forces increase with fluid density.

IV. CONCLUSION

Using the Distinct Element Method, a numerical model was developed of debris flow based on explicit modeling of particles that takes into account the effects of fluids. Its role is to calculate the impact forces of the debris on a pillar. It was shown that the REV porosity, fluid density, and wall-particle friction affect the flow characteristics and impact forces. For the future work, it is interesting to study the effect of other parameters like canal slope and boundary conditions of the structure.

REFERENCES

Bugnion L, McArdell BW, Bartelt P, Wendeler C (2012) Measurements of hillslope debris flow impact pressure on pillars. Landslides 9(2):179-187. https://doi.org/10.1007/s10346-011-0294-4

Matthias Jakob, Steven Lambert (2009). Climate change effects on landslides along the southwest coast of British Columbia. Geomorphology, Volume 107, Issues 3-4, Pages 275-284. https://doi.org/10.1016/j.geomorph.2008.12.009

Rime Chehade, Bastien Chevalier, Fabian Dedecker, Pierre Breul, Jean-Claude Thouret (2021). Discrete modelling of debris flows for evaluating impacts on structures. Bulletin of Engineering Geology and the Environment, Springer Verlag, 2021, 80 (8), pp.6629. https://doi.org/10.1007/s10064-021-02310-6

Scheidl, C., Chiari, M., Kaitna, R., Müllegger, M., Krawtschuk, A., Zimmermann, T., Proske, D., (2013). Analysing Debris-Flow Impact Models, Based on a Small Scale Modelling Approach. Surv. Geophys. 34, 121–140. https://doi.org/10.1007/s10712-012-9199-6 Wesley Ashwood and Oldrich Hungr (2016). Estimating total resisting force in flexible barrier impacted by a granular avalanche using physical and numerical modeling. Canadian Geotechnical Journal, Volume 53. https://doi.org/10.1139/cgj-2015-0481