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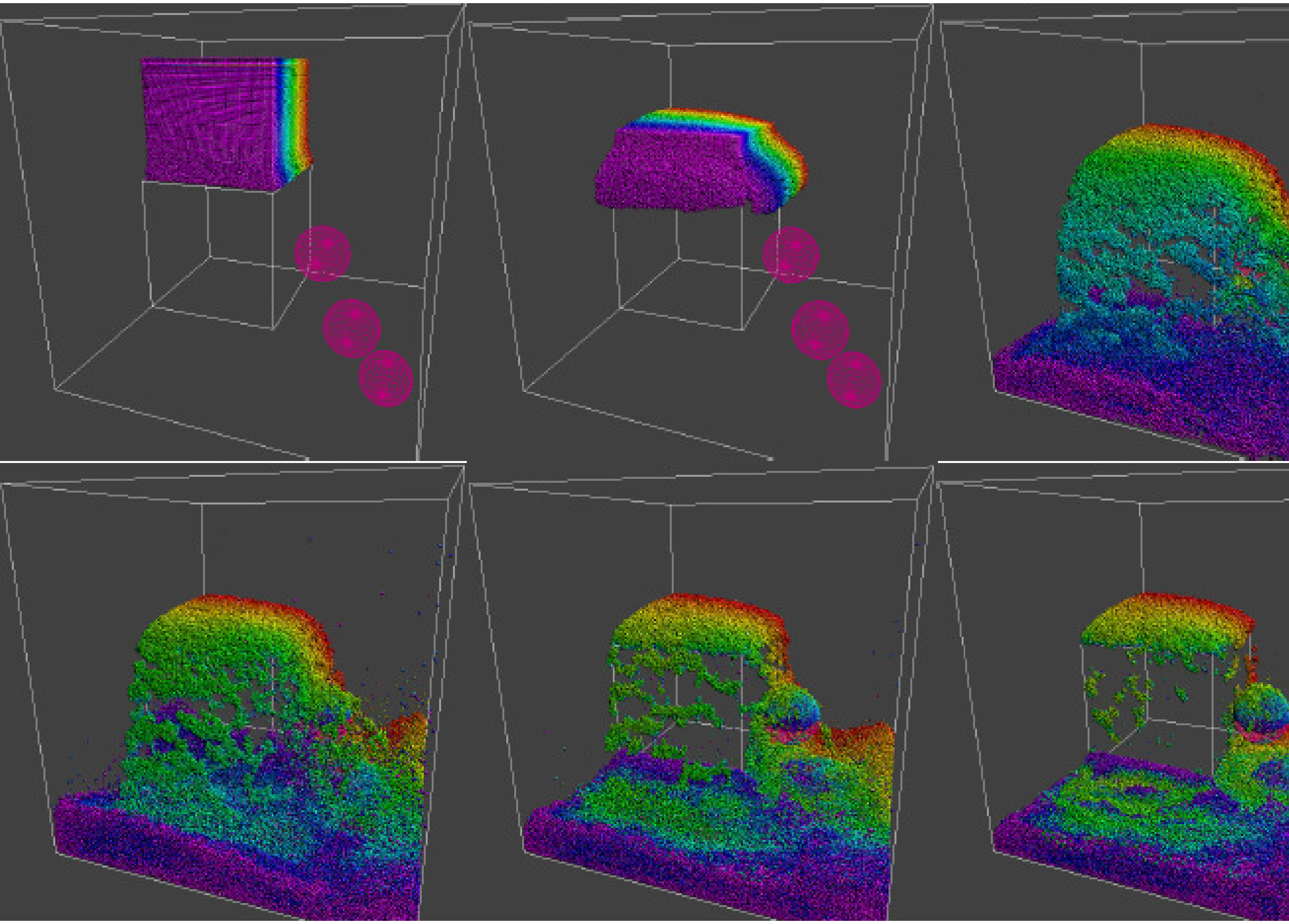

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THE IMPACT OF GRANULAR FLOW ON A WATER RESERVOIR – A COUPLED CFD-DEM STUDY

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This paper presents a micromechanical study on the impacting behavior of debris flow or rock avalanche falling into a water reservoir from an inclined slope, based on a coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) approach. To account for the interaction between the particles and the fluid during the impacting, three interaction forces are considered in the coupling between CFD and DEM, namely, the buoyancy force, the drag force and the virtual mass force. Numerical simulations indicate the presence of water in the reservoir can generally help to reduce the overall velocity of the granular flow and its direct impact on the check dam behind the reservoir, and minimizes the intense collisions and bouncing among particles observed in the dry case. A rather distinctive energy dissipation mechanism is found for a granular flow in the presence of water as compared to a dry granular flow. While inter-particle/particle-wall frictions and collisions dominate energy dissipation in the dry case, the granular flow in the wet case first transfers the majority of its kinetic energy to the water body which induces surging waves oscillating between the check dam and the slope surface for a rather sustained period before it dissipates out all energy and eventually settles down. The Savage number shows the water presence changes the granular flow pattern from a collision-dominant one to a contact shearing stress dominant one after the flow passes by the slope toe.

INTRODUCTION

Hazardous granular flows such as rock avalanches, landslides and debris/mud flows may cause devastating losses of both human lives and properties. A recent tragic example happened in Zhouqu City of China in August 2010 when the city was demolished by a catastrophic debris flow which killed 1765 people, injured another 2000 and destroyed over 5500 houses. Frequently, water is involved in the occurrence of debris flow or avalanche. A large number of landslides or debris flows reported around the world every year have indeed been triggered by sustained rainfalls and a good proportion of them run into downhill reservoirs. The consequence of a massive high-speed granular flow impacting on a water reservoir may be equally, if not more, devastating than the flow itself may cause. Overtopping or even breakage of water/check dams relating to the reservoir could cause severe damage to a wider region than debris flow alone. The famous Vajont dam tragedy happended in Italy in 1963 was exactly such an accident caused by a gigantic landslide falling into the reservoir (see, Wikipedia – Vajont dam). A deeper understanding towards the impacting behavior of a granular flow on a water reservoir in such an event is urgently needed. The progress in this regard, however, has long been constrained by the unavailability of effective analytical tools to simulate and analyze the complicated interactions between fluid and particles in such a process. The prominent issue lies in that the granular system may become highly discrete and discontinuous in the impacting process, while the fluid system remains largely continuous. Conventional purely continuum-based or discrete-based approach cannot adequately handle the situations in this case. In this paper, we employ a coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) to tackle this issue. The CFD-DEM method typically solves the locally averaged Navier-Stokes equation for the fluid flow by CFD which is continuum based, and the Newton's equation for the motions of the particle system by DEM which is discrete based. The coupling between DEM and CFD computations is furnished by exchanging fluid-particle interaction forces. The coupled CFD-DEM method is hence a coupled continuum-discrete method indeed. In comparison with other options such as the Lattice-Blotzman-DEM coupling method and the Direct Numerical Simulation-DEM coupling methods, the CFD-DEM approach proves to be computational more efficient and numerically more convenient to handle for practical applications.[1-3] Detailed formulation and solution procedure of the coupled CFD-DEM approach have been described in Zhao and Shan [3-5]. In particular, Zhao and Shan [3-4] showed that the consideration of buoyancy force, and drag force may offer reasonable predictions for general geomechanics problems, such as particle settling, 1D consolidation and sandpiling in water. When the unsteady flow behavior is significant, other unsteady forces such as virtual mass force, Basset force and lift forces may become important. [2] Following Zhao and Shan [5], in addition to the buoyancy force and the drag force, a third unsteady flow force, the virtual mass force, is also considered. The virtual mass force is an interaction force to account for the extra virtual inertia caused by the deflection of surrounding fluid of a particle accelerating/decelerating in a fluid, which is considered to be important in simulating the impacting behavior of granular flow on a water reservoir.

MODEL SETUP AND SIMULATION CONTROL

To simulate the impacting behavior of granular flow falling into a water reservoir, this paper considers an idealized model setup illustrated in Fig 1. A packing of 15,000 monozied granular particles is first generated behind a valve wall over the slope surface, and is then set free to run down on gravity over the slope surface into a water reservoir at the slope foot. The adopted geometries of the inclined slope, the water reservoir and the check dam are presented in Fig 1 where a side view of a three-dimensional model with an out-of-plane width 1.5 m is shown. Once the granular packing is set free to go, a channelized flow will be observed. Two infinitely high side walls are used to confine the channel granular flow. The side walls, the slope surface and the ground surface of the reservoir as well as the check dam surface are idealized as elastic walls. The adopted model parameters are as follows: the particle density = 2700 kg/m^3; particle diameter = 70 mm. A Hertzian contact model is used where the inter-particle friction coefficient = 0.7; inter-particle contact Young's modulus = 70 GPa; particle-wall contact Young's modulus = 700 GPa; Poisson's ratio = 0.3; restitution coefficient = 0.7. In addition to the case shown in Figure 1, a purely dry case for the reservoir has also been simulated for comparison. For convenience, we hereafter call the dry reservoir case as "dry" case and the water reservoir case as "wet" case. Starting from releasing the granular assembly from the valve, a total of 10-second real time of flowing and mixing process has been simulated. Small time steps have been used in both the DEM and CFD computations. As such, adequate accuracy can be achieved by stepping 2000 DEM calculations after one step CFD computation. While the CFD and DEM computations are carried out on parallel, the total computing time for each simulation, on a 4-core Intel CPU (3.2 GHz) desktop computer, is around 3 days.

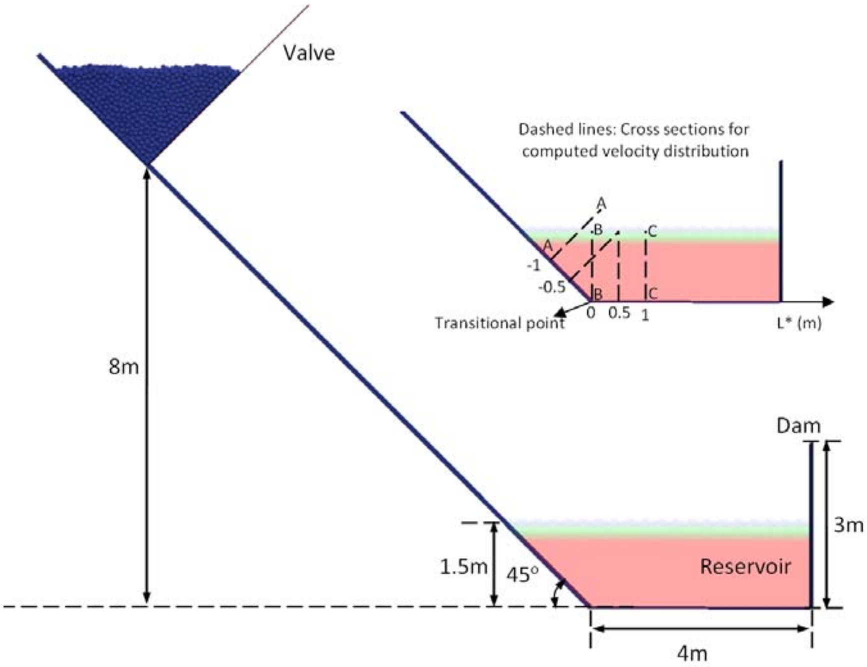


Fig 1. Side view of the numerical model setup of the granular packing flowing down to a water reservoir from an inclined slope

SIMULATIONS AND DISCUSSION

Fig 2 presents a side view of the development of granular flow at different time instants. As can be seen, in the dry case, the kinetics of the granular flow changes dramatically when the granular flow reaches the transitional zone of the slope with the reservoir ground at around t = 2.0 s. At the same time instant, the forefront of the granular flow in the dry case already hits the check dam and bounces back. In all cases, all particles settle down on the ground in front of the dam at t = 5.0 s. In the wet case, the presence of water apparently drags down the flow velocity of the granular system when it hits the water. The flow of the granular system also depicts a thicker vertical profile moving on the reservoir ground than in the dry case. The final stable deposit is relatively levelled in the wet case in contrast with an inclined one in the dry case. Meanwhile, due to significant energy transfer from the particle system to the fluid system, a surging fluid flow field is developed. The maximum fluid velocity occurs at the proximity of the forefront of the granular system. The surging wave is so intense at around t = 5.0 s that it climbs the slope surface up to as high as 3.5 m over the ground, which is more than double of the original hydrostatic height of the water reservoir (1.5 m). The oscillated wave can carry some particles from deposit top. The oscillation can sustain for a long time before it settles down.

Fig 3a presents the evolution of kinetic energy of both the particle system and the fluid system (E_k^p = particle kinetic energy; ΔE_p^f = fluid potential energy change; E_k^f = fluid kinetic energy). Notably, the kinetic energy of the particle system evolves in a similar manner in both dry and wet cases. It increases steadily with the release of the valve and reaches a peak at around t = 2 s, and then gradually decreases to almost zero after t = 4 s. The presence of water causes a slightly smaller kinetic energy for the particle system than in the dry case. While seemingly similar in evolving trend, the dry and wet cases involve indeed different underlying mechanisms on energy dissipation. In the dry case, a great portion of the energy is dissipated through inter-particle/particle-wall frictions and collisions. In the wet case, the majority of the particle system energy is first transferred to the water system to raise the potential energy of latter. Due to unbalanced distribution of potential in the horizontal direction of the reservoir, surging waves are subsequently caused which will periodically change the kinetic energy of the water system. The energy will be gradually dissipated out with the oscillation of water. During this process, the particle system plays a minimal role, which is evidenced by the almost vanishing kinetic energy of the particle system after $t = 4$ s. From the evolution of energy dissipation of the whole system in Fig 3a (denoted by lines of E_d). From around $t = 1.6$ s, the initial mixing of water with particles leads to a slightly faster dissipation of energy of the system in the wet case than in the dry case, which is indicated by the diverging dashed line of the wet case from the solid line for the dry case from above. However, this process is rather brief when the two lines cross over at $t = 1.9$ s. After $t = 1.9$ s, the energy dissipation line of the dry case stays above that of the wet case, indicating a faster dissipation process in the dry case. This is a stage where the two energy dissipation mechanisms mentioned above come into effect. The total energy dissipation in the dry case approaches to a steady value when the particle system settles down, while the non-smooth curve of energy dissipation for the wet case reflects the fluctuation of the water wave in the reservoir which needs long time to dissipate out the energy.

Fig 3b shows the evolution of the impacting forces exerted by the granular system and the oscillating water (F_n^p / F_s^p = the total normal/shear force of the particle system; F_n^f = the total excess normal force exerted by the excess fluid pressure). Evidently, both the normal and the shear forces applied by the particle system to the dam surface are considerably reduced in the presence of water as compared to the dry case. In the wet case, the surging wave in the reservoir applies to fluctuating excess normal fluid pressure to the dam surface, the magnitude of which is much greater than the nearly constant normal pressure applied by the particles after $t = 4$ s. In the case of a water dam, especially a concrete arch dam which is sensitive to tension, this kind of pressure change pattern may be potentially harmful to the dam body. Meanwhile, the large positive normal excess water pressure, if aggregated by the particle normal force and the initial hydrostatic water force, may greatly exceed the particle normal force in the dry cases, which could potentially cause dam breakage or overtopping with high surging wave.

The Savage number (Savage [6]) is an indicator of the relative significance of the contact shearing and the collision (inertial effect) in granular flow, which is defined by $N_{sav} = \dot{\gamma}^2 d^2 \big/ \left(gH \tan\varphi \right)$, where d is the particle diameter, H is the thickness of the granular flow, φ is the inter-particle sliding friction angle. $\dot{\gamma}$ is the shear rate of granular flow (Savage, 1984). $N_{sav} < 0.1$ means that contact shearing stress is dominant over the solid inertial stress by collision, and the collisions are dominant if $N_{sav} \geq 0.1$. Fig 4 plots the change of Savage number at different cross sections shown in Fig 1. Notably, the Savage number increases when the chosen location is moving towards the slope toe, and reaches a peak at the toe, and then gradually decreases when the flow moves farther from the toe. After the flow passes the toe and moves on the reservoir ground, the Savage number can dramatically reduce to less than 0.1 in the wet case, whereas it remains larger than 0.1 in the dry case. This implies the granular flow can be largely characterized by a collision-dominant flow in the dry case. The same is true for the wet case until the flow travels to the toe, after which it gradually evolves to a contact-shearing dominant one. The presence of water can totally change the granular flow pattern.

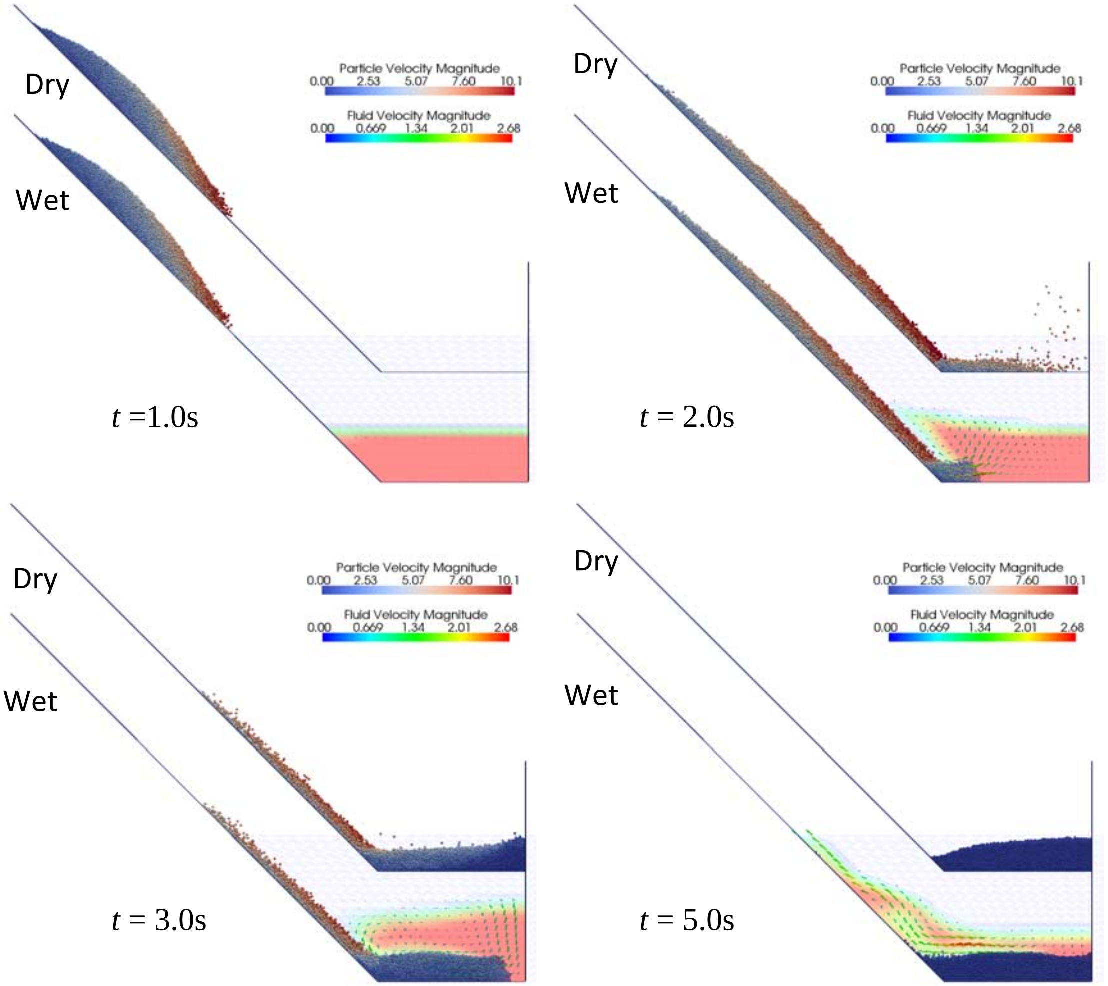
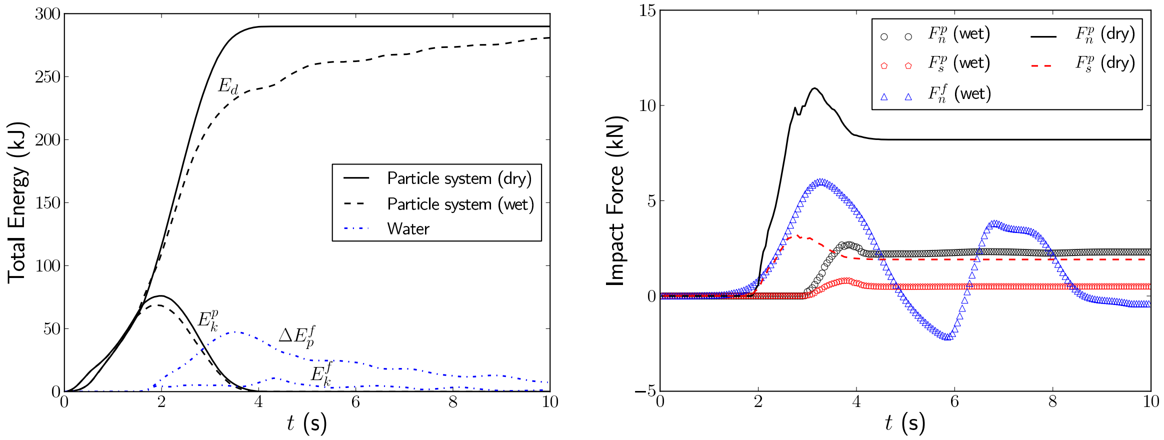


Fig 2. Simulated process of granular flow falling down and impacting on the water reservoir



(a) (b)

Fig 3. (a) Energy evolution in the process of granular flow; (b) Evolution of impact forces on the check dam.

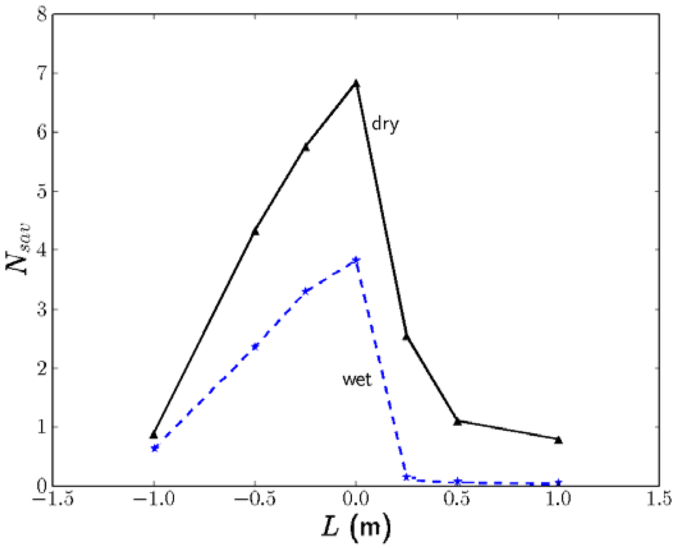


Fig 4. Variation of Savage number along the travelling direction around the slope toe (L = 0 m)

CONCLUSIONS

A coupled CFD-DEM approach was employed to investigate the impacting of granular flow on a hill foot water reservoir. The presence of water in the reservoir can generally help to reduce the overall velocity of the granular flow and its direct impact on the check dam behind the reservoir, and minimizes the collisions and bouncing among particles observed in the dry case. In the dry case, inter-particle/particle-wall frictions and collisions dominate energy dissipation, while in the wet case the granular flow transfers the its kinetic energy to the water body and the system then dissipates energy through the surging waves formed in the reservoir. The Savage number shows the water presence changes the granular flow pattern from a collision-dominant one to a contact shearing stress dominant one after passing by the slope toe.

ACKNOWLEDGEMENT

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