Inclusion of Contact Friction for Particle-Based Simulation of Sediment Transport Over Mobile Bed

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1 Introduction

The particle based approach, including the particle resolving method, such as CFD-DEM, e.g. Drake and Calantoni (2001), Schmeeckle (2014), and the Particle-In-Cell (PIC) method, e.g. Patankar and Joseph (2001); Finn, M. Li, and Apte (2016); Y. Li et al. (2014), has become important tool for simulation of sediment transport in recent years. The latter is advantageous in the required computing resources when large amount of particles are involved and hence is more suitable for simulation of sediment transport over mobile bed. However, unlike that in CFD-DEM, special treatment is needed in the PIC method in order to prevent overlap and over-packing of sediment particles in a computational cell. In particular, Patankar and Joseph (2001) used a repulsive force plus damping force (collision) on particles to prevent overlapping. Based on the tangential repulsive force, Zhou et al. (1999) identified the significance of particle's rolling resistance by sliding torque. The essence of these two models, however, is dissipating some of total kinetic energy between particles by correcting the post-velocities to match the restitution coefficient. The disadvantage of the former is that the repulsive interaction caused by the rigid collision of particles cannot be accurately captured due to the sundry damping coefficients, e.g. Navarro and Souza Braun (2013); while the latter leads to misalignment due to the shortage of the torque carried the particles before collision. Most models so far ignore the contact friction force between particles that hinders relative movement but often is essential to maintain particles in static position, especially in the seabed where the contact forces between particles are the largest. An new friction force is proposed to simulate the particle interactions, similar to the collision used in previous studies, so that the kinetic energy driving particles motion can be effectively dissipated and over-packing can be minimised under either static or dynamic stages of the particle motion.

2 Methodology

The friction effect is considered to take place once the contact occurs between two adjacent particles in order to effectively prevent the violent and multi-frequency collisions between them. It will be effective till the two particles are separated and loose contact from each other due to collision repulse or other mechanisms. It is assumed that the magnitude of the friction force is related to the contact area between the particles, as well as the relative motion velocity. The influence of shape is ignored for simplicity reasons. Once the friction process takes effect, the two contacting particles' speed will reduced accordingly and subsequently, the collision can be considered.

In the present study, based on the three aspects of particles' motion, e.g. collision, rolling resistance and the new contact friction effect, the motion of sandy particles within the seabed and the region higher above the bed can be represented properly in both energetic flow motion or in static environment. Tests were performed to simulate settling a sphere assembly and the repose angle falling particles in the hopper, the importance of contact friction in dense grain flow is verified. To validate the model's performance for mobile bed with the new contact friction effect, tests were also conducted for sediment suspension and transport under sheet flow conditions.

3 Results and discussion

3.1 Settling of a sphere assembly

In total 25 identical mobile spheres were arranged in a pattern above the aligned motionless particles bed as shown in the top figure of Figure 1. The diameter of particles is 10mm, and the shifting gap between two neighbor rows is 5mm. This modelling was devised to test the settling capacity of the three different models when they are used to track a system involving from dynamic phase to static phase. Once the assembly collapses, particles are driven by gravity to enter the dynamic state, and then reach a static state through the dominant actions of collision damping, rolling resistance and contact friction with adjacent particles in three different models, respectively. In Model A, only inter-particle collision is considered, and the damping coefficient in tangential colliding direction η was 0.3. In Model B, both collision and rolling frictions are taken into account with the rolling resistance coefficient for rotational energy dissipation η_r was set as 0.8. In Model C, the collision and the new contact friction force are considered. The corresponding friction coefficient η_c was set as 0.8. The time step used for all of these simulation was $1e^{-5}$ s.

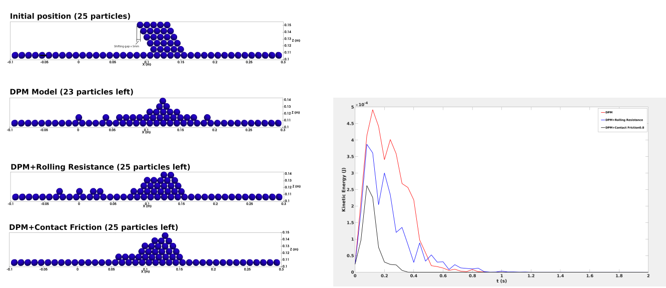

Figure 1: Sphere assembly diagram from initial position to static state (a) and comparison of kinetic energy (b) for three models.

Figure 1 (a) shows the equilibrium pattern of positions for the three different scenarios. It can be seen that without specific friction, the two left upper particles will be lost in the domain and the rest of spheres are dispersed to both left and right directions. A reasonable pile formed either rolling resistance or contact friction was used, which indicates that blocking effect from both models are significant to settling assembly.

However, the fundamental differences in the two models are shown in Figure 1 (b), in which the total kinetic energy within the pile of particles are computed over the time. Before the kinetic energy reaches maximum, Model

A and Model B increase with nearly same grow trend, while Model C shows a lightly weaker growth. This phenomenon indicates the first two did not account the inter-particle interaction from the beginning of contact rather than corrected post processes, which may results in over-estimate the particle's motion. Meanwhile, the rolling resistance did not perform noticeably well at a small relative velocity system since it excessively relies on the collision interaction. However, Model C dissipated energy from the beginning of contact, and easily settle particles down. This result shows the fact that in practice the slow spheres are easier to settle in first, and such result is critical in computational dense particle systems.

3.2 Repose angle

It is known that a repose angle generated around structures is important for scour or erosion phenomenon. Tests were conducted to test whether a realistic surface profile and an angle of repose can be reproduced from random arrangement particles. In these test, particles from upper hopper were released to fall into a lower hopper to form a pile with repose angle. Different from the previous similar simulations, the present test contains a random arrangement of particles with the particle size is non-uniform (d_{50}=0.5mm, σ=0.2mm) and the ground is a flat rough bed. This is presented here to demonstrate that the effect of the proposed model on particles occurs randomly with the particle motion itself and is not affected by particle arrangement.

Figure 2 show that repose angles of 14.73°, 24.22° and 32.02° were generated for the three aforementioned models with same coefficients, respectively. The computed particle positions are clearly been affected by the presence of inter-particle frictions in both model B and model C. However, compared with the typical value of angle of repose for dry sand, e.g. Al-Hashemi and Al-Amoudi (2018); Tomlinson and Boorman (2001), ranging from 30° to 35°, the angle formed by model B is obviously under-predicted. The reason is that the rotational energy is partly dissipated by the rolling resistance that is generated by the sliding collision only. The rest part of the rotational energy contained within particles are ignored. For model C, the stability of the pile is clearly improved as a direct result of the newly proposed contact friction, and the overall shape of the pile is closer to a typical triangle form as observed in experiment.

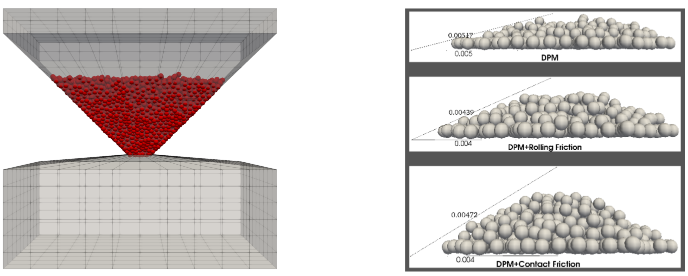

Figure 2: The initial particle positions (a) and comparison of three models with repose angles (b).

3.3 Sediment transport under sheet flow over mobile bed

The two tests above demonstrate the contribution of contact friction to the particle packing phenomena, but the motion of surrounding fluid is absent. To test the effect of contact friction on the sediment transport process under dynamic fluid flows, simulations were conducted for large wave driven near bed oscillatory sheet flow of O'Donoghue and Wright (2004). The presence of contact friction between particles on the formation of a stable sand bed and its adverse effect on the hydrodynamic properties will be verified. Among the series experiments, the 6 second sinusoidal wave driven transport of fine sand, LS612, was used for the model test. This experiment not only contains complex flow reversal at middle of wave period, but also provides extreme conditions of water flow, which the maximum corresponding wave orbital velocity reaches up to 1.2m/s in both forward and reverse. A sand bed with a depth of 15mm is designed for simulation model and the medium particle size d_{50} is 0.13mm as same as experiment.

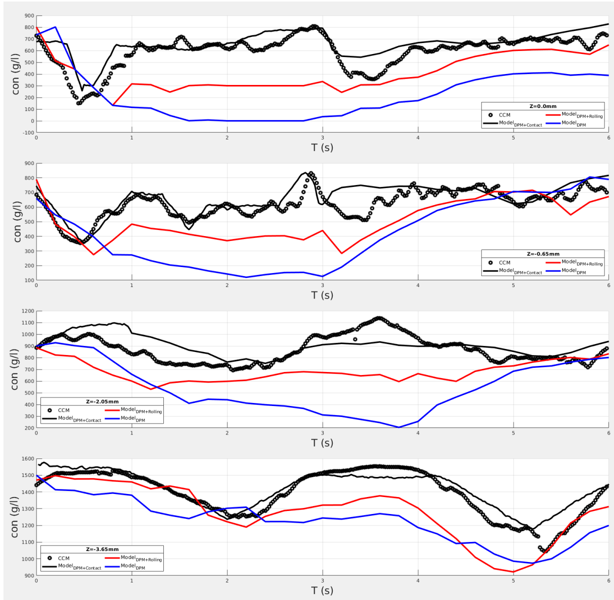

Figure 3: Comparison of computed and measured concentration at various elevations for LS612 test.

The computed time series of concentration at four different elevations are shown in Figure 3 for the three different approaches, in comparison with the laboratory measurements. The computed concentrations of Model A (blue) and Model B (red) are lower than the experimental observations throughout the wave cycle. The main reason for this phenomenon is that the particles carry too much energy transferred by the fluid to dissipate, resulting in intense motion in suspended state. The neglect on the dissipation of energy due to mutual contact between microscopic particles causes that particles are easily swept away by the fluid, resulting in a non-stable bed in macroscopic view. The macroscopic changes changes the particle motion mechanism in turn. As shown in the figure, the increase in particle concentration after 3s is no longer due to the interaction of the fluid, but due to the reduction on the velocity of reverse flow by the downstream accumulation, which observed in the modelling. It should be pointed out that the existence of rolling resistance in Model B improves the feasibility of the model and also provides an effective basis for adding contact friction.

Compared with previous models, although certain phase differences can be found, the overall agreement is considered to be good in Model C. The onset of particle motion was observed in the first second in Figure 3. The accelerated fluid increases shear on the surface of the sand bed and causes the particles to move. The loose surface provides space for the underlying particles to move, so the second graph is slightly delayed than the first graph as the initial concentration decreases. The subsequent increase in concentration is due to the infestation on the loose sand bed by the fluid, which drives the particles to sink. After that, the particles are swept by the strong flow velocity in the x-direction uniformly until the flow reversal is generated with nearly zero velocity. Gravity-dominated particle motion caused the increase in particle concentration around 3s. After that, the effect of reverse flow on the concentration of particles is similar to 0s, but the intensity is relatively weak. Possibly the particles also carry a little forward motion, or a dampening effect on the flow rate due to a slight accumulation on the downstream. These important undulating displays were captured, which is in good agreement with the findings in experiments O'Donoghue and Wright (2004). At z=-2.05mm, the concentration of particles has larger phase difference with experiment because particles are in the transition range from moderately dense to highly dense, which is more complicated to find out the mechanism of motion of particles. But the fluctuation pattern of concentration is consistent with the experiment. For the research of this phase, more precise verification will be revealed in subsequent studies. At z=-3.65mm, the results obtained from the simulation are extremely consistent with the experimental results.

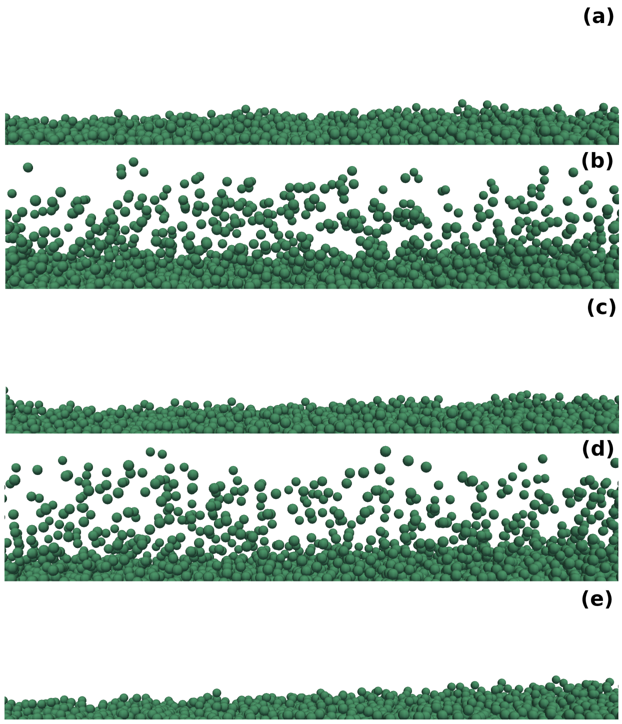

Figure 4: Bed evaluation against time.

Figure 5 shows (a) initial state, (b) forward maximum flow rate, (c) reverse flow, (d) reverse maximum flow rate, and (e) final state, respectively. Particles were swept up in slices, and at lower flow rates, gravity dominated particle settling, which is consistent with the the observations by O'Donoghue and Wright (2004). Due to the existence of contact friction, the consistence of the initial and final bed patterns shows the stability of bed. Compared with Model A and Model B, forward-reverse symmetrical bed migration pattern demonstrates that the interaction between microscopic particles plays an important role both in the fluid hydrodynamics and the evolution of the sand bed.

4 Conclusion

A new inter-particle contact friction interaction model has been developed to predict sediment transport. This model reveals the mechanism of energy transfer between particles by analyzing the kinetic energy in the computing domain of settling simulation. In addition, the performance of this model for dense particle flow is also verified by both static fluid state and dynamic state simulations. Contact friction is proposed by considering the relative motion of microscopic particles, and the simulation results show its rationality. This model plays an important role in the energy dissipation of dense particles, which is key factor in dense particle flow. Further research on the friction coefficient and time scale factor will be presented in the further paper.

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