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Numerical simulation of the emergency brake process in granular material transportation using DEM: Effect of the liquid bridge

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Abstract

A numerical simulation of the emergency brake process in granular material transportation was carried out using the Discrete Element Method (DEM). The interaction laws between the particles were based on the contact mechanics in which the normal force was calculated by the Hertz contact law and the incremental tangential force was evaluated by the Mindlin-Deresiewicz theory. Moreover, the liquid bridge force was considered in the wet particle simulation and the effect was especially discussed. Two strategies including the spatial segmentation and reconstruction of orthogonal grids were introduced to analyze the interaction force on the truck during the braking and backfilling processes. It is found that the particles concentrated in front of the truck in the brake process with a slope forming on the upper surface of the agglomerating particles. The liquid bridge force can significantly influence on the particle and force distribution trends. When the liquid bridge force was considered, the particles moved more slowly, the slope was gentler and the force on both the bottom and front wall of the truck was higher. The findings in this study reveal that the liquid bridge force plays an important role on the instantaneous distribution of the particles and pressure on the truck walls and thus cannot be ignored in the simulation.

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Keyword : Emergency brake; granular material transportation; DEM; liquid bridge.

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1. Introduction

Granular material transportation is very common in the industrial production process [1,2,3]. However, it is very difficult to grasp the macroscopic behaviour and the micro mechanism of the particles due to its stochastic nature. Especially, when an emergency situation or other traffic safety problems appear during the transportation of a high loading truck, the driver should stop the truck immediately to reduce the incidence of traffic accidents, the problem will be more complex. In the emergency brake process, the vehicle will still move forward because of the inertial effect. The distance of sliding and the interaction between the particles or between the particles and truck wall are very important for the safety of the truck and goods (such as the integrity of the fragile things). The complex motion of the particles brings much more difficulties for the researchers, experimental study could be used to study this phenomenon, but the cost and the experimental safety are the problems that cannot be ignored. In recent years, numerical simulation has been the third method and came to wide attention after the experimental and theoretical research. The Discrete Element Method (DEM) as a non-continuous medium mechanics method was widely used in investigation of particle material [4,5,6,7]. The DEM focuses on the movement law of the particle system and thus has great advantages in the particle study than other continue-based methods [4,5,6,7]. Moreover, the development of computer technology provides a powerful support for the computation of the DEM[8].

Some DEM researches were reported to study the granular material transportation. Hong [9] studied the interaction force on the truck wall from granular goods when the truck was impacted, he also proposed the general formulae of the dynamics and liquid approximation theory. Yang et al. [10] used DEM to simulate the motion of the particles in the truck and the interaction force between particles and walls during the brake process in which the pressure force chain at different time and total force on the forward wall were presented. Zuo et al. [11,12] simulated an assembly of the spherical particles within a truck box in motion under sudden braking, the effects of the dynamic force with different braking speeds were discussed. He [13] selected the gondola train and tank car as the studying object and provided a theory model to compute the effect of the granular goods on the wall. Li et al. [14] used DEM to simulate the C80B gondola train and study the static lateral pressure on a gondola train with different granule materials. The distribution law of the lateral pressure changing with the wall height was given when the internal and external friction angles changed. Hossein and Michael [15,16] studied the change of the contact forces between the contact particles (agricultural products) during the fresh product transportation using DEM, they analysed the effect of the contact force on the products and provided a guidance for the product transportation.

All the afore-mentioned investigations provide a good guide for the transportation of materials, but the force distribution on the bottom in varies region at different braking time are still unclear. Moreover, the backfill of the particles in truck box is also an important factor but not reported. In this paper, the instantaneous distribution of the particles and pressure on the truck walls during emergency brake process was numerically studied using DEM in which the normal force and the tangential force were calculated based on the theories of Hertz and Mindlin-Decesiesicz, respectively. The study of Zhang et al. [17,18] showed that the numerical results based on those two theories have a better agreement with the actual situation than using an artificial linear stiffness. Moreover, since the particulate materials are always exposed to the open air during the transportation, therefore, certain liquid may exist in particle system. When a quantity of liquid is introduced between two spherical bodies, a stable bridge is formed which produces a resultant attractive force between the two bodies [19].The liquid bridge force between the particles has significant effects on the motion of particles [20]. In this study, the results with and without liquid bridge models were compared, and the effect of the liquid bridge force on the particle movement and interaction force distribution on the wall were also discussed.

2. DEM modeling of the interaction between particles

2.1. Governing equations

The basic idea of the discrete element method is using the Newton's second law of motion, and then tracking the trajectory of each particle, which can be simply described as follows:

$$\begin{cases} m\ddot{U} + Cm\dot{U} = F(\mathrm{U},\dot{U},\Delta \mathrm{t}) + \mathrm{mg} \\ I\ddot{\varphi} + CI\dot{\varphi} = M(\varphi,\dot{\varphi},\Delta \mathrm{t}) \end{cases}, \tag{1}$$

where $m, U, \dot{U}, \ddot{U}$ are the mass, displacement, velocity and acceleration of particle respectively, $\varphi, \dot{\varphi}, \ddot{\varphi}$ are the angular position, angular velocity and angular acceleration . C is a constant which is related to damping. F and M are the contact force and torque respectively generated by the direct collisions between particles or particles and walls.

2.2. Contact models

In this study, the normal force-displacement relationship is based on the Hertz theory. A small overlap α between the contact pairs on the normal direction is allowed. Under the condition of two balls with radii R_i, Young's modulus E_i, shear modulus G_i and Poisson's ratios v_i (i=1,2). The normal force-displacement relationship is given by

$$N = \frac{4}{3} E^* (R^*)^{1/2} \alpha^{3/2} \tag{2}$$

where $\frac{1}{R^*} \equiv \frac{1}{R_1} + \frac{1}{R_2}$ and $\frac{1}{E^*} \equiv \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}$ are the equivalent radius and Young's modulus. When the overlap between two contact balls reaches $\Delta\alpha$, ΔN denotes the normal force increment

$$\Delta N = 2aE^* \Delta\alpha \tag{3}$$

The Mindlin-Deresiewicz theory is adopted to describe the relationship of the incremental tangential force and the incremental tangential displacement which is depended on the loading history

$$\Delta T = 8aG^* \theta_k \Delta\delta + (-1)^k \mu (1-\theta_k) \Delta N \tag{4}$$

where $G^* \equiv \frac{2-v_1}{G_1} + \frac{2-v_2}{G_2}$ and $a = \sqrt{\alpha R^*}$ denote the equivalent shear modulus and the radius of the contact area, $\Delta\delta$ denotes incremental tangential displacement and the value of k and θ_k changes with loading history.

2.3. Liquid bridge force of wet particles

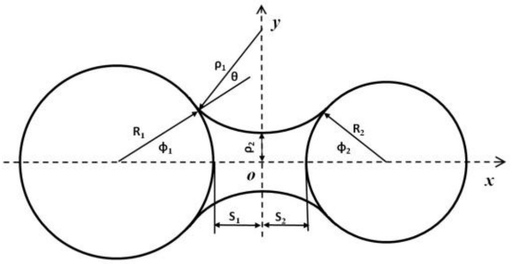


Fig.1. Geometry of the liquid bridge between two unequal sized spheres.

Fig.1 shows the geometry of the liquid bridge between two unequal sized spheres. For a liquid bridge between particles are introduced, we choose the origin of the coordinate system at the neck of the bridge, where the sphere radii are denoted as R_1 and R_2 , from geometric considerations, the two principal radii are $\rho_1 = (S_i + R_i(1-\cos\phi_i)) / \cos(\phi_i + \theta)$ and $\rho_2 = R_i \sin\phi_i - \rho_1[1-\sin(\phi_i + \theta)]$,where $i = 1,2$, S_1 and S_2 are the distance from sphere i to the neck of the bridge, θ is the solid-liquid contact angle and ϕ_i is the half-filling angle of sphere i, so the static liquid bridge force can be given by

$$F_s = 2\pi\rho_2\gamma_{lv} + \pi\rho_2^2\gamma_{lv}\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right) \tag{5}$$

For a dynamic liquid bridge between two spheres, a continuous deformation of the liquid bridge takes place due to the relative movement of the spheres and hence the strength of the bridge depends not only on the shapedependent meniscus force of the bridge but also on the rate-dependent viscous resistance of the fluid. The normal viscous force simple solution between two spheres can be described as $F_v = 6\pi\eta(\mathrm{R}^*)^2 \mathrm{v}_n / S$, where η denotes liquid viscosity, $R^* = (R_1 + R_2) / (R_1 * R_2)$, v_n denotes normal relative velocity and S denotes separation distance.

When the separation distance between sphere and wall is very small, the analytical solution of the tangential viscous force can be described as $T_{tw} = 6\pi\eta R v_{tw}\left(\frac{8}{15}\ln\frac{R}{S} + 0.9588\right)$, where S denotes separation distance between sphere and wall, v_{tw} denotes tangential relative velocity between sphere and wall, R is the radius of sphere. Similarly, if the wall above mentioned is also a sphere, the tangential viscous force between two spheres can be described as above mentioned , and then replace R with R^* , where S denotes separation distance between spheres, v_{tb} denotes tangential relative velocity between spheres, R^* is the effective radius of pairs.

3. Numerical results and discussions

3.1. Initial preparation of the particle bed

As stated by Zuo et al. [11, 12, 21], the particle size has little effect on the dynamic force distribution on the truck, therefore, a mono-disperse system of particles are adopted. Meanwhile, Xu et al. [11, 12, 21] pointed out that the physical material of the particles has insignificant effect on the behavior of granular system. Therefore, we follow the parameters given by Zuo [11,12],the relevant parameters used in the simulation in this study are listed in Table 1.

Table 1. Properties of the particle and wall.

Parameter	Value
Number of particles	6000
Diameter (particle)	0.115m
Density (particle)	1,200kg/m^3
Density (wall)	7,800 kg/m^3
Young's modulus (particle)	70MPa
Young's modulus (wall)	70GPa
Poisson's ratio(particle)	0.25
Poisson's ratio(wall)	0.30
Fraction(particle)	0.35
Fraction(wall to particle)	0.35

The main content in this section is to simulate the instantaneous distribution of the particles and pressure on the truck walls during braking and back-filling process. Here, a truck with the length is 4.0m, the width is 2.0m and the height is 1.8m is considered. Initially, the particles are random generated in the computational domain and then fall down under the effect of the gravitational force, the surface of accumulated particles is substantially parallel to the truck bottom. This time is assumed to be the initial state. In Section 3.2, numerical simulations are carried out without considering the liquid bridge force. Then, the results of dry and wet particles are compared in Section 3.3 with the effect of the liquid bridge force discussed.

3.2. Dry particles

Firstly, the bottom floor of the truck is divided into 20 regions and thus the width of each sub-region is 0.2m. Under the condition of contact between balls and walls, the line segment from hilum to contact point in the wall will vertical the body, and thus in the every subdomain we can circulate all the contact pairs to compute the force between them.

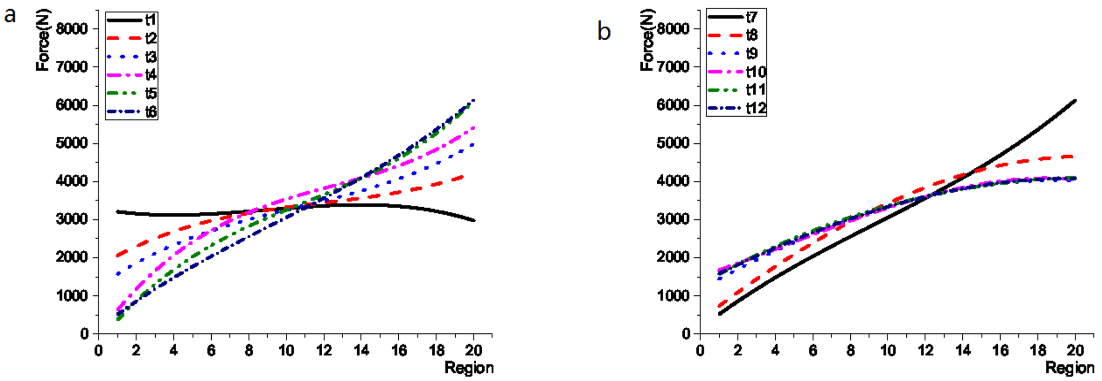
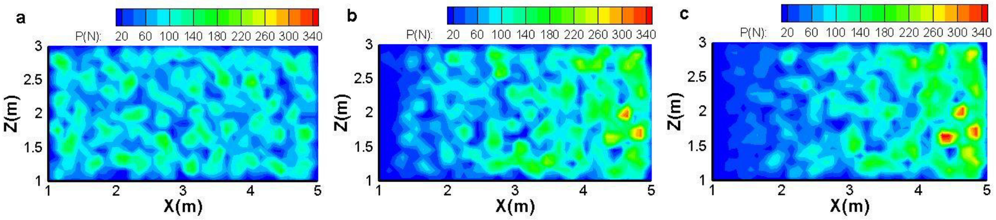


Fig.2. The force distribution on the bottom wall (a): braking process; (b): backfilling process at different time.

t1=0.0s, t2=0.15s, t3=0.46s, t4=0.76s, t5=1.37s, t6=1.83s; t7=1.83s, t8=1.98s, t9=2.29s, t10=2.59s, t11=3.20s, t12=3.66s.

Fig.2 shows the force distribution on the bottom at different time, at the initial state, all the particles distribute almost uniformly in the truck box and thus the pressure on the truck bottom also presents a flat profile. When the braking takes place, the particles especially at the upper half of the truck accumulate in the front of the truck box. This leads to a change of the pressure on the truck bottom that the pressure on the end regions is lower than that on the front regions. This difference increases during the whole braking process. As shown in Fig.2(b), when the brake process finishes (black line), a particle backfill takes place due to the losing of breaking acceleration, the particles tend to step back for a while. However, because of the existence of friction force, the shape of the particle will not be the same as the initial state with a gentle slope left.

For a more detailed analysis of the force acting on the bottom wall, the whole bottom domain is divided by orthogonal grid meshes, and then we shadow the particles contacting with the inside wall to the mesh, the projection should belong to one grid or more, the force of the particles acting on the wall is regarded as the average distribution of the mapping mesh. In this process, if more than one particle mapping into the same grid, the force expressing to this grid will be added up. The bottom wall is divided into 60×40 rectangular meshes with the size of the element is $0.1 \times 0.1 m^2$. Several typical moments are selected and shown in Fig.3, Braking process: t1=0.0s, t2=0.76s, t3=1.83s; Backfilling process: t4=1.83s, t5=2.59s, t6=3.66s. From Fig.3 (a), (b) and (c), it is found that, at the initial moment, the pressure distribution at the bottom of the truck is almost uniform. With the advance of the simulation process, the pressure in front of the platform floor gradually increasing. The maximum pressure is seen happening in the bottom axis and close to the region of the front compartment (from 4.35m to 4.85m). The Fig.3 (d), (e) and (f) show that, starting from the particle flow backfilling, the pressure on the right side of platform floor decreases gradually, and as the center of gravity of the particles moves to the left side, the pressure on this side is gradually increasing.



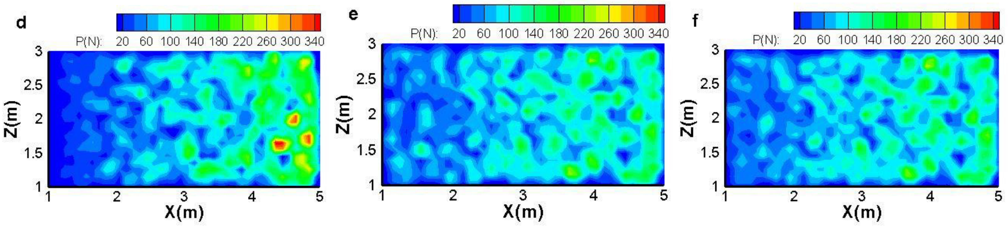


Fig.3. The force distribution on the bottom wall (a) (b) (c): braking process; (d) (e) (f): backfilling process.

3.3. Wet particles: Effect of the liquid bridge force

In this section, a specific volume of liquid is assigned into all the particle-particle gaps where the liquid bridges are able to form. In the process of calculation, the binding force of liquid bridge is calculated after the calculation of contact force. The simulation parameters which come from the survey of Lian [19,22] for this work are shown by table 2.

Table 2. Parameters related with liquid bridge.

Parameter	Value
The liquid volume percentage	0.1
Surface tension of liquid bridge	0.025N/m
Solid-liquid contact angle	0°
Viscosity	0.01Pas

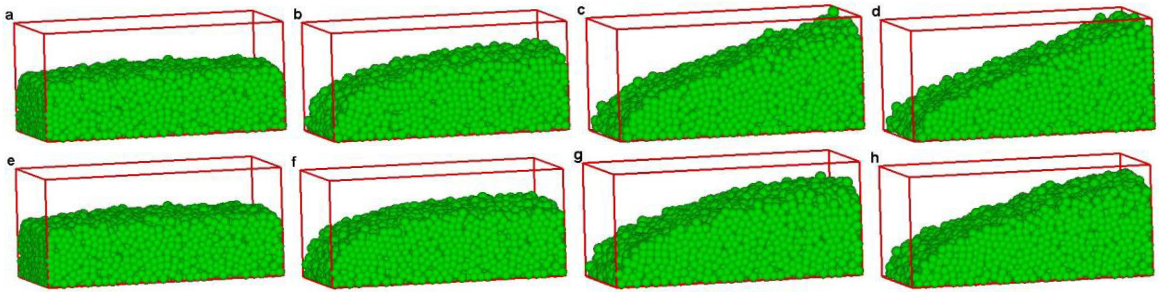


Fig.4. (a), (b), (c) and (d):without liquid bridge; (e), (f), (g) and (h):with liquid bridge.

Fig.4 shows the accumulation status of four moment with and without liquid bridge, t1=0.15s, t2=0.76s, t3=1.37s, t4=1.83s. The effect of the liquid bridge force is not difficult to be seen. Obviously, when the liquid bridge force is considered, the piling height is lower and the slope is gentler, it shows that liquid bridge force block the movement of particles in this process.

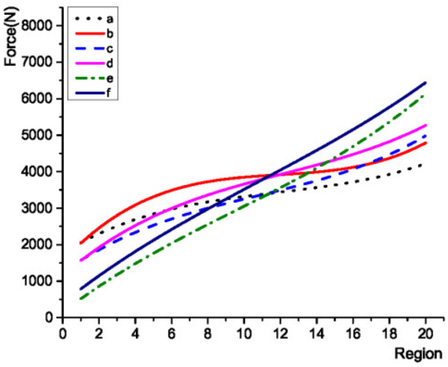


Fig.5. The force acting on the bottom wall.

a and b:t1=0.15s; c and d: t2=0.46s; e and f: t3=1.83s

Fig.5 shows the force acting on the bottom wall in varies regions at different time with and without liquid bridge. Solid line represents the force with liquid bridge while the dotted line represents that without liquid bridge. From the picture, we can find that the tendencies of the two situations are similar, but under the condition of liquid bridge the interaction force is larger than that without liquid bridge. This is because the particle packing is looser without the liquid bridge. Moreover, the liquid bridge force can prevent the particle movement in this process, therefore, the instantaneous normal pressure on the truck bottom is larger.

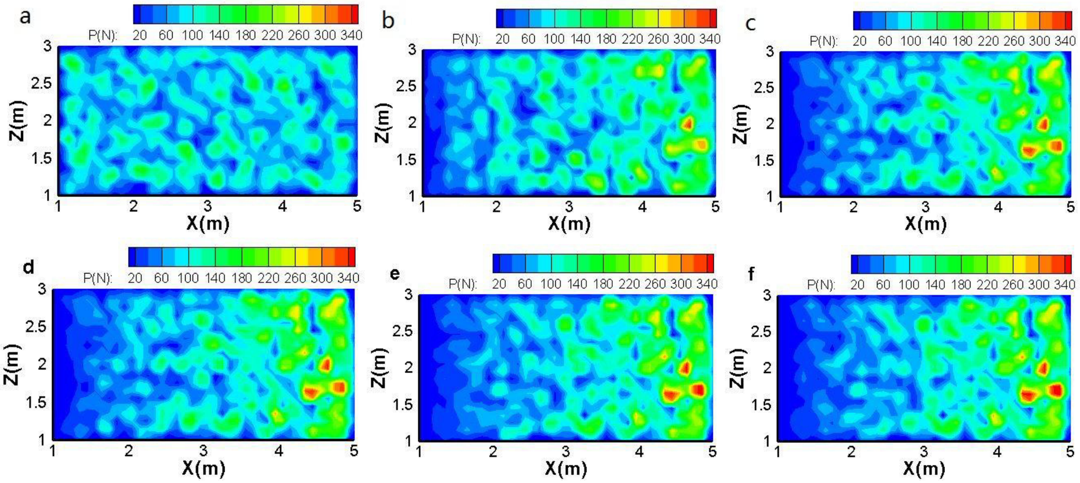


Fig.6. The force distribution on bottom wall with liquid bridge:(a)(b)(c) braking process;(d)(e)(f) backfilling process..

Fig.6 shows the force distribution on bottom wall with liquid bridge at braking and backfilling processes. It is shown that the tendencies of the two cases are similar, the force acting on the front regions is greater than the end regions, this trend is becoming more and more serious during braking process. The trend becomes relaxed during the backfilling process, but this change is very slow due to the effect of liquid bridge. A perfect consistency is played between Fig.3 and Fig.6.

4. Conclusions

In this paper, the DEM simulations have been conducted to study the emergency brake process in granular material transportation. The liquid bridge force was introduced to the study and the effect of the liquid bridge on the instantaneous distribution of the particles and pressure was discussed. According to the results analysis, the main conclusions can be made as follows:

1. Braking start and backfilling start moment the roll velocity of particles is relatively larger than the other moment.
2. The motion of the particle is affected by the viscous due to the existence of liquid bridge. The liquid bridge force can significantly influence on the particle and force distribution trends and thus cannot be ignored in the simulation.
3. When the liquid bridge force was considered, the particles move more slowly, the slope is gentler and the force on the bottom wall of the truck is higher.
4. Much greater accuracy and efficiency in computation to simulate the mechanical behavior of wet particle motion may be obtained by using the above models.

Acknowledgements

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