Powder Technology 191 (2009) 315–326

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Contact time of an incident particle hitting a 2D bed of particles

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ARTICLE INFO

Article history:
Received 30 October 2007
Received in revised form 4 August 2008
Accepted 28 October 2008
Available online 8 November 2008

Keywords:
Granular matter
Force propagation
Contact time

ABSTRACT

Removal of particles from fouling layers due to an incident particle impact is affected by the fluid fluctuations in industrial applications if the contact time is larger than the fluctuations time scales. The contact time is an important parameter when analysing the influence of the fluid structure interaction on a fouling process. The contact time for a particle hitting a bed of particles is defined as the time it takes for the incident particle to bounce off the bed. The contact time for a particle hitting a bed of particles arranged in a rectangular and a hexagonal array is measured experimentally and calculated numerically based on the discrete element method. The incident particle and the bed particles are of the same size and material. It is found that the contact time is proportional to the number of bed layers in case of a rectangular bed array and independent of the number of bed layers in case of a hexagonal bed of particles. The contact time is inversely proportional to the impact speed. The rebound speed of the incident particle is independent of the number of bed layers in case of a hexagonal arrangement of particles and is exponentially dependent on the number of bed layers in case of a rectangular arrangement. A hexagonal bed of particles acts as a massive particle due to its large co-ordination number compared to a rectangular bed of particles. The force propagation speed in granular matter could be calculated by plotting the path of the force as a function of the contact time and finding the gradient of this graph.

1. Introduction

Problems concerning the impact of particulate aggregation, that is, a collection of many particles such as granular material and powder, have become increasingly important in mechanical engineering, material engineering and physics. Particulate fouling of heat exchangers is one of the major problems related to particulate aggregation. Particulate fouling is defined as the accumulation of particles on a heat transfer surface that forms an insulating powdery layer, which reduces the rate of heat transfer and can lead to operation failure as has been reported by many researchers, e.g. in waste incinerators by van Beek et al. [1], in a coal-fired power plant by Bryers [2] and in biomass gasifiers by Abd-Elhady et al. [3]. Removal of fouling layers by externally injected particles becomes an important issue of study especially in power generation applications. Particle–particle collision is now fairly understood [4], but the mechanics of collision involving more than two particles has not yet been fully revealed [5–7]. A summary of engineering approaches to model granular flows and the behavior of granular matters could be found in [8,9]. The contact time for a particle hitting a bed of particles is calculated from the time the incident particle reaches the bed till it bounces off the bed. The removal of particles from fouling layers due to an incident particle impact can be affected by the fluid fluctuations in industrial applications if the contact time is larger than the fluctuations time scales [10]. The contact time becomes an important parameter when analysing the influence of the fluid structure interaction on a fouling process.

Granular aggregates like sand, grains, rubble, ore and others, although customarily treated in mechanics as continuous materials [11,12], exhibit essentially discontinuous or discrete behaviour when subjected to static or dynamic stress or strain [13–15]. Dynamic wave propagation in granular media differs considerably from classical wave propagation in continuum mechanics because of the peculiar structure of granular materials as has been found by Rossmanith and Shukla [13]. Shukla and Damania [16] found that the dynamic load transfer in granular material occurs essentially through contact mechanisms between each grain and the character of the force propagation depends on the ratio of the elastic properties of the granules, the filler material and on the geometric structure. Shukla and Zhu [17] who investigated the wave propagation in a disc arrangement subjected to the impact of an explosion reported that the force propagation phenomena through granular matter depends on the pulse duration of impact, diameter of discs and its arrangement. Thornton and Randall [18] and Tanaka et al. [19] have

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doi:10.1016/j.powtec.2008.10.024

investigated the dynamic behavior of a two-dimensional particulate aggregate subjected to a projectile through experiments and discrete element method (DEM) simulations. The DEM pioneered by Cundall and Strack [20] has been widely used in mechanical engineering as one of the most direct and simplest methods for granular matter simulation [21,22]. Tanaka et al. [19] found that the contact force exerted by the direct impact of the incident particle is transmitted gradually from the top row of particles to the base plate at a propagation speed of 300 m/s, and the contact force in each particle increases from zero to a peak value and then gradually decreases to zero. Tanaka et al. [19] found also from the DEM simulations that the contact force at the base plate has two peaks at a short lateral distance from the point just under the impact point, which is not in a good agreement with the result of Clément et al. [23], who measured the pressure distribution at the bottom of a granular layer in response to a local perturbation. The discrepancy between the simulations of Tanaka et al. [19] and the measurements of Clément et al. [23,24], is due to the spring-dashpot model [25] used for modelling the contact forces between colliding particles. The disadvantage of the spring-dashpot model is that the resulting coefficient of restitution is constant [25], independent of the colliding particles velocities, which is not the case as found by many researchers, e.g. Gorham and Kharaz [26] and Wu et al. [27].

Sadd et al. [28] performed numerical simulations to assign the force propagation speed in granular matter using the DEM, and used an empirical model for the contact forces between colliding particles. The empirical constants used in the model are material and geometry dependent, which adds to the complexity of modeling, and the constants were determined based on photoelastic experiments [29]. Sadd et al. [28] found that the force propagation speed is slower in a granular medium than in a homogeneous solid of the same material, and the accuracy of simulation depend on the calculation of the inter-particle forces. The DEM could be extended to the simulation of wave propagation and the scattering behavior of particulate aggregation struck by a projectile by taking into account the contact forces between particles based on the concept of contact mechanics [30]. In the present paper the contact time for a particle hitting a bed of particles arranged in a rectangular and a hexagonal array is measured experimentally and calculated numerically based on the discrete element method. The force propagation speed is calculated from the contact time and the results are compared to theory. The rectangular and the hexagonal arrangement of particles are chosen as a preliminary step towards the understanding of the dynamic properties of randomly arranged particulate aggregation, which is commonly found in practical granular materials. The numerical method adopted, the numerical code used, the numerical simulations performed and the numerical results obtained are given in the next chapter. The experimental setup used to verify the numerical results, experiments performed and experimental results are presented in Section 3. Discussion of results and conclusions are given in Sections 4 and 5, respectively.

2. Numerical simulations

2.1. Numerical method and the numerical code

The numerical method adopted is the discrete element method (DEM), which is based on Newton's second law of motion. For the translational motion of a spherically symmetrical particle, Newton's second law has the form

$$\vec{F} = m\,\ddot{\vec{r}}, \tag{1}$$

where $\vec{F}$ is the sum of the forces exerted on the particle by other particles and by gravity. $\ddot{\vec{r}}$ is the acceleration vector of the particle and m its mass. Integrating Eq. (1) over a time step Δt yields the velocity of the particle

$$\dot{\vec{r}} = \dot{\vec{r}}_o + \frac{\vec{F}}{m}\Delta t, \tag{2}$$

where $\dot{\vec{r}}_o$ and $\dot{\vec{r}}$ are the initial and final velocities of the particle due to the applied force F. Δt is the integration time step. Integrating once more results in the particle's displacement

$$\vec{r} = \vec{r}_o + \dot{\vec{r}}_o\Delta t + \frac{\vec{F}}{m}\Delta t^2, \tag{3}$$

where $\vec{r}_o$ and $\vec{r}$ are the initial and final positions of the particle. The numerical integration method used is Euler's explicit scheme because of its stability at large integration time steps [31]. Detailed information of the movement of every particle is obtained by integrating Eq. (1) for every particle in the simulation domain step by step from some initial state until the final simulation time is reached. The motion of the individual particles is further processed to provide the macroscopic physical properties over the entire simulation domain. To solve Eq. (1), the force on the left hand side of the equation needs to be known. The interacting forces between colliding particles is calculated based on the concept of contact mechanics [30], which relates the contact force to the relative approach of particles. The interacting laws used in the numerical model are described in detail in [4,32], and a brief description of the force models used are given in Appendix A. In all the simulations, the colliding particles had no rotational speeds at the beginning of collision, and the rotational speed ω of a particle due to an impact is a function of the tangential torque T acting on the particle and its mass moment of inertia I, and it is governed by

$$T = I\dot{\omega}. \tag{4}$$

I is equal to mR^2 in case of a spherical particle, where m and R are the mass and radius of the particle, respectively. The tangential torque is a function of the tangential force acting on the particle which is governed by,

$$T = F_t d_p/2 = \mu(F_n + F_{adh})d_p/2, \tag{5}$$

where μ is the coefficient of static friction, F_n is normal contact force due to the overlapping of the interacting particle, F_{adh} is the adhesion

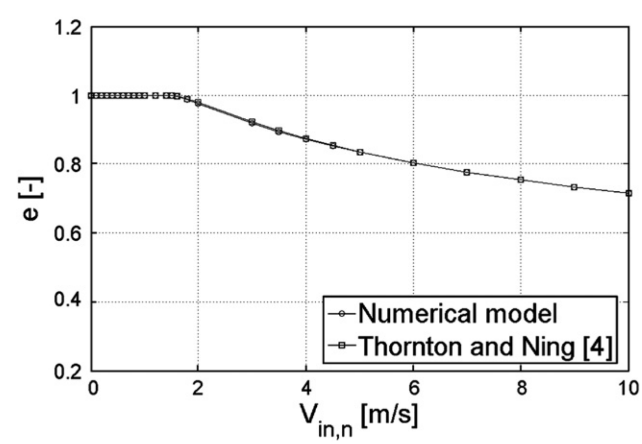

Fig. 1. Coefficient of normal restitution, e, for a steel particle hitting normally a steel plate as a function of the impact speed, $V_{in,n}$. The coefficient of restitution is calculated using the numerical code presented in Section 2.1 and the analytical model of Thornton and Ning [4]. The diameter of the incident particle is 20.64 mm.