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Discrete Element Study of Dissipative Behavior of Ice Particles

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Abstract. Dissipative behavior of ice particles is investigated by the discrete element method (DEM). The DEM presents numerical technique elaborated to describe motion of contacting particles. Limiting the size of spherical particles to a moderate millimeter scale, the noncohesive elastic-dissipative model is applied here for description of particle contact. Internal dissipation is characterized by experimentally obtained quantity, the coefficient of restitution (COR). Particular focus of this study is evaluation of velocity-dependence of the COR. Series of numerical experiments were performed considering packing on the horizontal plane. The essential difference between the elaborated velocity-dependent and traditional fixed-value COR approaches is illustrated by numerical results.

INTRODUCTION

The dissipative behavior of ice particles is considered by Discrete Element Method (DEM). The DEM suggested by Cundal and Strack [1] presents numerical technique elaborated to describe Newtonian motion of contacting particles. Rigidity and dissipative properties of the interparticle contact plays a dominant role in predicting the behavior of an individual particle and the multiparticle systems. Evaluation of energy dissipation and its contribution to macroscopic parameters are still not fully discovered.

Due to the complex nature of dissipative mechanisms [2], the theoretical basis of it has not been developed for practical purposes. The simplified spring-dashpot structure was applied for mechanical characterization of the normal contact, while different expressions that were difficult to compare were proposed for evaluation of description of the dashpot constant.

The common feature of existing models is that the energy dissipated during the contact of the particle of the particle with its neighbors may be evaluated by the dimensionless parameter, the coefficient of restitution (COR) varying between 0 and 1. This coefficient is an experimentally obtained parameter defined as a ratio between the rebound and impact velocities. It depends on the geometry and physical properties of the bodies in contact. Experimental results illustrate, however, that the COR is an impact velocity dependent characteristic of contact. described by the experimentally confirmed COR-velocity profile.

Generally, experiments are performed for a limited range of velocities; therefore, they are not suitable to reflect entire motion of particle until the rest separate fragments. In light of recent achievements, the COR-velocity profiles presented by Higa et al. [5] and Eidevåg et al. [6] and describing the ice particle that impacts the ice wall in the broad range of velocities belong to mostly informative developments. The analytical COR profiles suggested by Higa et al. [5] will be applied for simulation of multiparticle system.

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MATHEMATICAL MODEL

The mathematical DEM model describes the motion of separate particles. The balance of linear momentum at an arbitrary time instant *t* is used to obtain the equations of motion. The equation of 3D translational motion of a particle *p* having mass m_p may be written in a vector form as follows.

$$m_p = \frac{\mathrm{d}^2 x_p(t)}{\mathrm{d}t^2} = F_p(t). \quad (1)$$

Here, F_p is the resultant vector of static forces due to contact with neighbors and external forces occurring due to the action of the external environment. Rotational motion is described in the same manner.

Reformulating Eq. (1) for each of particle, the governing DEM mathematical model is presented by a set ordinary differential equations simultaneously reflecting boundary conditions. This model completely defines global vectors of positions of the particles centers $x_p(t)$, its velocity $v_p(t) = \mathrm{d}x_p(t)/\mathrm{d}t$ and acceleration $a_p(t) = \mathrm{d}^2 x_p(t)/\mathrm{d}t^2$.

The nature of particle interaction is reflected via interparticle forces. The contact is separated into normal and tangential components. The DEM methodology applied here deals with noncohesive dissipative contacts. The normal repulsive contact between particle *p* and its neighbour *nb* is modelled using a nonlinear spring-dashpot model. Contact deformation in the normal direction is characterized by inter-particle displacement $h(t)= |x_{nb} - x_p| - 2R$. This time-dependent quantity is interpreted as particle overlap.

For better understanding, equation (1) of translation motion is rewritten in local coordinates. The motion of particle in normal direction during contact may be described as:

$$m_{eff} \frac{\mathrm{d}^2 h(t)}{\mathrm{d}t^2} + C_{eff}\big(h(t)\big) \frac{dh(t)}{dt} + K_{eff} h^{3/2}(t) = F_{gr}. \quad (2)$$

Here, the presence of the gravity load F_{gr} is assumed. Effective constants, mass m_{eff}, damping constant C_{eff} and elasticity constant K_{eff}, reflect proprieties of both of two contacting partners. The first term describes inertia force, the second term presents dissipative force, and the third term describes the elastic force.

The most complicated issue is proper evaluation of the state-dependent damping parameter *C.* Rearrangement of phenomenological expression of this parameter using dimensional analysis [7], [8] enables it to be presented by a unified expression in terms of nondimensional and dimensional multipliers, *c* and C_{dim}, respectively. It was observed that for most phenomenological models, the damping parameter *is* proportional to inter-particle displacement $C \sim h^{\beta}$. Here, the specified values of the power factor β indicate a particular damping model. It was later discovered (see [8]) that dimensional component C_{dim} is expressed in terms of the effective parameters, mass m_{eff}, stiffness K_{eff} and the impact velocity v_0 as $C_{dim} = (m_{eff})^{\beta_m(\beta)} (K_{eff})^{\beta_K(\beta)} (v_0)^{\beta_v(\beta)}$, where the power factors $\beta_m(\beta)$, $\beta_K(\beta)$ and $\beta_v(\beta)$ are defined as linear functions of *β*. The non-dimensional factor c is the COR dependent constant. The final expression of the damping constant presents a combination of three factors c, C_{dim} and h^{β}. The widely used Tsuji model is characterized by a displacement exponent *β*=1/4. As a consequence, $\beta_m = 1/2$, $\beta_K = 1/2$ and $\beta_v = 0$, and the damping constant may be expressed as follows:

$$C_{Tsuji}(t) = c_{Tsuji}(e) \cdot (m)^{1/2} \cdot (K)^{1/2} \cdot h(t)^{1/4} \quad (3)$$

The latest result indicates that for the fixed value of the COR, $e = const$, the change of dissipative properties in time is predefined by variation of interparticle displacement *h*(*t*) and is independent on impact velocity v_0. Thus, the experimentally observed dependence of the COR on impact velocity may be indirectly evaluated via variation of the COR $e(t) = e\big(v_0(t)\big)$. To account this relationship modification of the DEM code is required.

PACKING PROBLEM AND BASIC DATA

Conventionally, packing is a stable static structure formed as a result of nonstationary motion and fixed at a specified time instant. Static packing in the main cases of DEM simulations is regarded as the initial position of particles prepared for future actions. More definitely, the position and velocity of an arbitrary particle are the initial conditions for numerical solving of equations of motion.

Packing formation is simulated by gravitational settling particles on the horizontal plane. The composition of N = 135,000 mono-sized spherical ice particles with radius R = 0.015 m was considered. The cloud of particles was initially formed by placing particles into nodes of the 3D rectangular grid with a small random shift. The cloud was distributed over a squared area at a height of 0.14 m. Each particle is subjected to the gravity load and the small random velocity. The ice particle is characterized by the density ρ = 917 kg/m^3, the modulus of elasticity E = 8.98 GPa and the

Poisson's ratio $\nu = 0.31$. The damping properties are defined by a set of fixed values of the coefficient of restitution $e_1 = 0.9$, $e_2 = 0.7$, $e_3 = 0.5$, $e_4 = 0.3$ and the variable impact velocity-dependent COR. The relationship considered with the maximal COR value $e_{max} = 0.89$ is described by the curve developed by Higa *et al* [5] . This COR profile is shown in Figure 1a.

NUMERICAL RESULTS

A series of tests of nonfrictional and frictional particles with different values of COR was performed to evaluate dissipative effects. Non-frictional particles interact exclusively by normal contacts, and the energy is dissipated via a normal damping mechanism. For frictional materials, dissipation of energy is not limited to normal damping but is also contributed by the tangential friction. The gravitational settling process started at zero time instant and was continued within a time interval of 0.5 s.

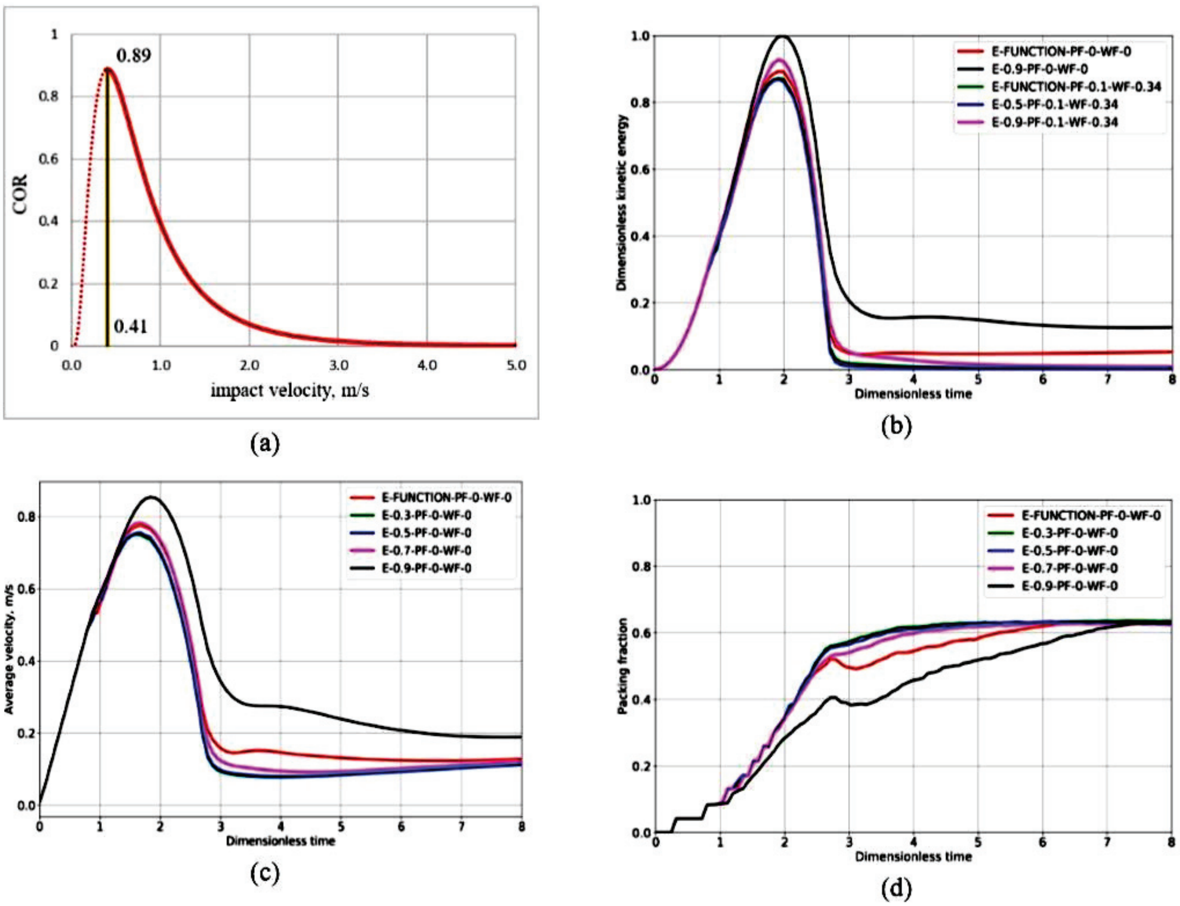

FIGURE 1. The input COR profile (a) and basic numerical results – time histories for different coefficients of restitution: kinetic energy (b), averaged velocity of particles (c) and packing density (d).

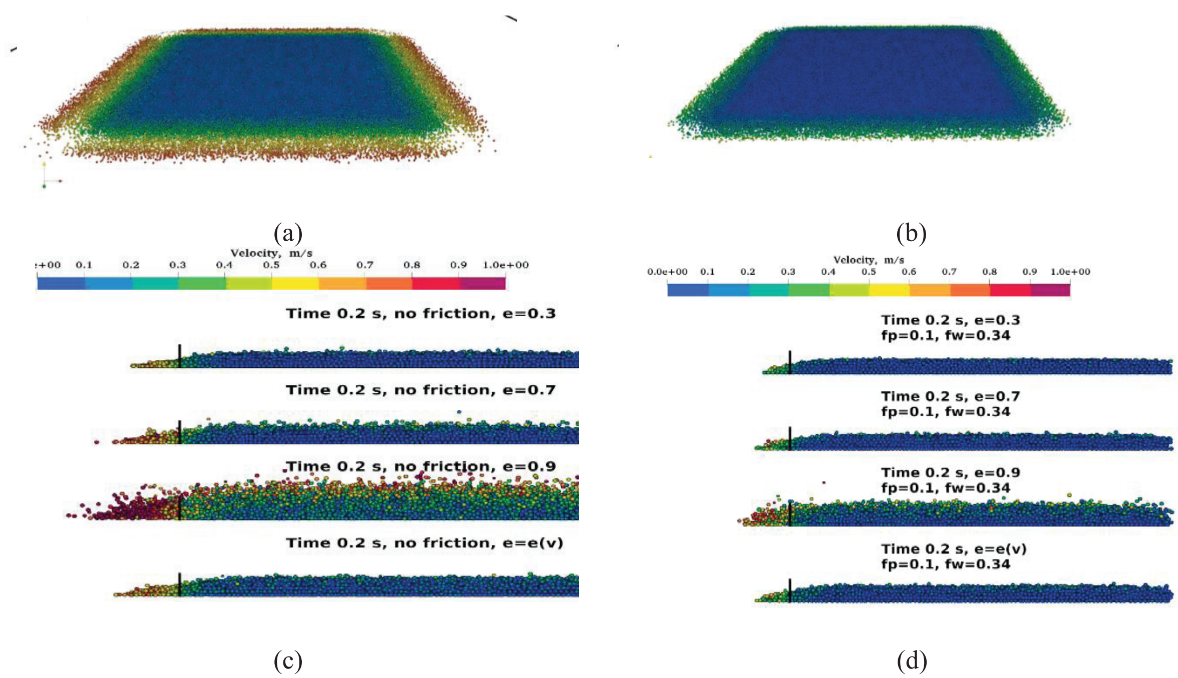

FIGURE 2. Illustration of the final settling of particles (a-b), and profile in the central section after 0.2 s for different values of the coefficients of restitution (c-d); for the frictionless particles (a-c) and the frictional particle (b-d)

The numerical results, such as kinetic energy, averaged velocity of particles and packing fraction obtained for frictionless particles in terms of the time histories, are presented in Figures 1b, 1c and 1d, respectively.

The main results visualized by VisLT [9] are presented in Figure 2. The views of the final state of the packing in a form of the bed are illustrated on subfigures 2a and 2b for frictionless and frictional particles, respectively. The locations of particles in the central section after 0.2 s for different cases of COR are shown in subfigures 2c and 2d.

CONCLUSIONS

Simulation of the packing of particles illustrated essential differences between fixed values and variable COR. The fixed values COR yielded large scattering of kinetic energy. Contributions of velocity dependence of the COR are observed after rebound of contacting particles. The biggest differences were observed in the dilute packing fraction region. It is also noted that free falling is characterized by relatively low impact velocities below 1.0 m/s. Dissipative damping is reduced by tangential friction.

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