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Experimental research and numerical simulation based on granary effect

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Abstract: Based on Janssen model and discrete element model, experiment and numerical simulation are used to verify the granary effect of coal storage silo in power plant. In the experiment, the bottom pressure of two different particles in a variable-diameter cylinder is measured. The type of particles and the diameter of the cylinder are used as the research objects to explore the function relationship between the bottom pressure of the cylinder and the particle filling quality. In the experiment with soybeans as filling particles, the granary effect is more obvious, and the smaller the cylinder diameter is, the more obvious the granary effect is. At the same time, establish a mathematical model of particles, simulation of particle accumulation process, solve the force information of particles. Through numerical simulation, it is found that the data is more in line with the Janssen model, and the granary effect is more obvious.

Keywords: Granary effect; Coal storage silo; Numerical simulation; DEM.

1. Introduction

Generally speaking, the containers for storing particulate matter are generally cylindrical silos, conical silos and other silo structures. The types and sizes of silos are various: sugar cans containing several grams of sugar and coal silos storing tens of thousands of tons of coal [1]. However, in the actual construction and use of silos, we often see the dangerous accidents of silo wall cracking and even overall collapse [2]. Therefore, it is very important to study the pressure distribution in the silo and the internal stress distribution of particulate matter, which will be of great help to the design of the silo. In addition, it is of great significance to reduce the cracks often found in the side wall of the silo and the overall collapse accident of the silo [3,4].

This paper mainly studies a famous static mechanical property in granular matter physics: granary effect [5]. The granary effect means that the pressure on the bottom of the silo will not increase significantly when the height of the filled particles in the silo exceeds twice the diameter of the bottom of the silo, that is, when the filled particles in the silo accumulate to a certain height, the bottom pressure of the silo will approximately reach a saturated stable value and will not increase significantly with the increase of the height of the filled particles.

2. Discrete element method

Discrete element method is to discretize the target into a finite number of elements, analyze and solve each element according to the classical mechanical theory, so as to obtain the state of the whole system of the target [6]. This method is widely used in the study of particle physics [7]. According to the characteristics of particle movement in silo, a particle calculation model of free settlement and accumulation process is established based on discrete element method, which realizes the real-time update of micro information such as force, acceleration, velocity and displacement of particle.

The collision force between particles is:

$$\vec{F}_p = \sum_{j=0}^{k} (\vec{f}_{n,\ ij} + \vec{f}_{t,\ ij}) \tag{1}$$

In the formula: k is the number of particles colliding with particle j; $\vec{f}_{n,\ ij}$ is the normal force between particle i and particle j; $\vec{f}_{t,\ ij}$ is the tangential force between particle i and particle j.

The normal force on the particles is:

$$\vec{f}_{n,\ ij} = \vec{f}_{cn,\ ij} + \vec{f}_{dn,\ ij} \tag{2}$$

$$\vec{f}_{cn,\ ij} = -k_n * \Delta\vec{\delta}_n \tag{3}$$

$$\vec{f}_{dn,\ ij} = \eta_n * \vec{\mu}_n \tag{4}$$

In the formula: $\vec{f}_{cn,\ ij}$ represents the elastic force generated by the collision of two particles; k_n represents the elastic coefficient of particles in the normal direction; $\Delta\vec{\delta}_n$ represents the normal upward relative displacement of particle i and particle j after impact; $\vec{f}_{dn,\ ij}$ represents the viscous damping force of two particles in the normal direction; η_n represents the normal damping coefficient; $\vec{\mu}_n = \vec{\mu}_r * \vec{n}$ represents the relative velocity of a particle in the normal direction at the point of impact.

$$\Delta\vec{\delta}_n = (\vec{\mu}_r * \Delta t) * \vec{n} \tag{5}$$

In the formula: $\vec{\mu}_r$ represents the velocity vector of two particles; $\vec{n}$ represents the unit vector of particulate matter in the normal direction.

$$\vec{f}_{t,\ ij} = -(k_t * \Delta\vec{\delta}_t + \eta_t * \vec{\mu}_t) \tag{6}$$

In the formula: k_t represents the elastic coefficient of particulate matter in the tangential direction; η_t represents the damping coefficient of particulate matter in the tangential direction; $\Delta\vec{\delta}_t$ represents the relative displacement in the tangential direction when particle i and particle j collide; $\vec{\mu}_t$ is the relative velocity of two particles in the tangential direction at the impact point.

when $\left|\vec{f}_{t,\ ij}\right| \le \mu \left|\vec{f}_{n,\ ij}\right|$

$$\Delta \vec{f}_{t,\ ij} = \vec{f}_{ct,\ ij} + \vec{f}_{dt,\ ij} \tag{7}$$

when $\left|\vec{f}_{t,\ ij}\right| > \mu \left|\vec{f}_{n,\ ij}\right|$

$$\left|\vec{f}_{t,\ ij}\right| = \mu \left|\vec{f}_{n,\ ij}\right| \tag{8}$$

In the formula: μ is the sliding friction coefficient of particles.

According to Newton's second law, the motion equation of granular material is:

$$m_i \frac{\overrightarrow{du_i}}{dt} = \vec{F}_p + m_i g \quad (9)$$

In the formula: $\vec{F}_p$ is the resultant force of all collision forces on the particle; $m_i g$ is the gravity of the particle itself.

After a time step Δt, the velocity of particle j at t +Δt:

$$\vec{v}_j^{t+\Delta t} = \vec{v}_j^t + \vec{a}_i * \Delta t \quad (10)$$

The position of particle j at t + Δ t is:

$$\vec{x}_j^{t+\Delta t} = \vec{x}_j^t + \vec{v}_x * \Delta t \quad (11)$$

$$\vec{y}_j^{t+\Delta t} = \vec{y}_j^t + \vec{v}_y * \Delta t \quad (12)$$

$$\vec{z}_j^{t+\Delta t} = \vec{z}_j^t + \vec{v}_z * \Delta t \quad (13)$$

In the formula, $\vec{x}_j$ 、 $\vec{y}_j$ 、 $\vec{z}_j$ are the coordinates of particulate matter j in the rectangular coordinate system; $\vec{v}_x$ 、 $\vec{v}_y$ 、 $\vec{v}_z$ are the velocities of particulate matter j in the X, Y and Z directions in the rectangular coordinate system.

3. Experimental and numerical simulation methods

3.1. Experimental method

The experimental design is shown in Figure 1. Fix the rigid and non-deformable acrylic transparent round tube on the stainless-steel support, place the electronic balance horizontally under the cylinder, adjust the height of the cylinder to ensure that the cylinder and the electronic balance do not contact each other, so as to ensure that there is no interaction between them. At the same time, the size of the gap shall not be greater than the radius of the particles to avoid the leakage of particles from the gap. Put a smooth glass plate with a thickness not greater than the size of the gap into the gap [8].

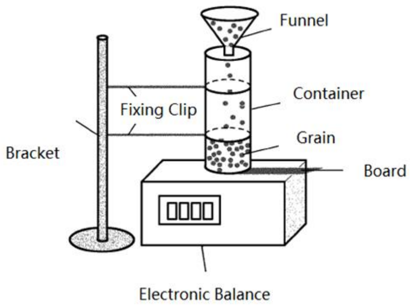

Figure 1. Flow chart of target tracking process

3.2. Numerical Simulation

The simulation object is shown in figure 2.

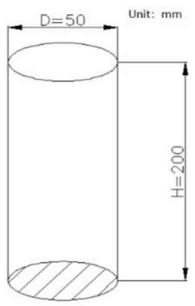

Figure 2. Simulation object

The discrete element method is used to simulate the settlement and accumulation process of particles in a three-dimensional cylindrical silo under the action of gravity. The relevant simulation parameters are set as shown in table 1.

Table 1. Simulation parameters and values

Simulation parameters	Analog parameter value
time step(s)	$1*10^{-5}$
Particle recovery coefficient	0.9
Particle friction coefficient μ	0.3
Particle density(kg/m^3)	2700
Young's modulus	$1.04*10^6$
Particle diameter(mm)	4

4. Results and discussion

4.1. Experimental results and discussion

The functional relationship between the apparent mass Ma of mung bean under four different cylinder diameters and the corresponding filling mass Mt is shown in figure 3. From the diagram, it can be seen that in the function curves of four different cylinder diameters, the apparent mass Ma of mung bean increases with the increase of the filling mass Mt, and finally tends to be saturated. The whole trend shows a nonlinear relationship, and the apparent mass Ma that finally reaches the saturation value is obviously smaller than the actual filling mass Mt. In addition, when the cylinder diameter is 50 mm, the granary effect of mung bean is the most obvious, and when the cylinder diameter is 65 mm, the granary effect of mung bean is the least obvious.

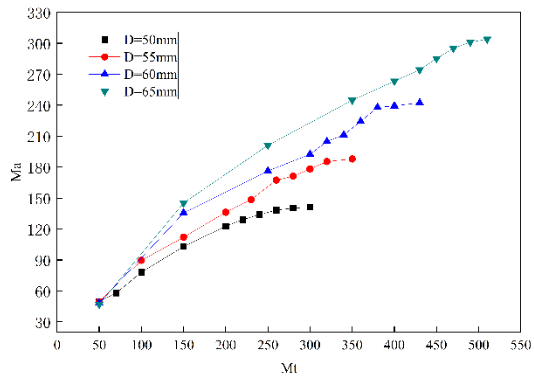

Figure 3. The relationship between Ma and Mt of mung bean under different diameters

The functional relationship between the apparent mass Ma of soybean and the corresponding filling mass Mt under four different cylinder diameters is shown in figure 4. From the diagram, it can be seen that in the function curves of four different cylinder diameters, the apparent mass Ma of soybean increases with the increase of the filling mass Mt, and finally tends to saturation. The whole trend shows a nonlinear relationship, and the apparent mass Ma that finally reaches the saturation value is obviously smaller than the actual filling mass Mt. In addition, when the cylinder diameter is 50 mm, the granary effect of soybean is the most obvious, and when the cylinder diameter is 65 mm, the granary effect of soybean is the least obvious.

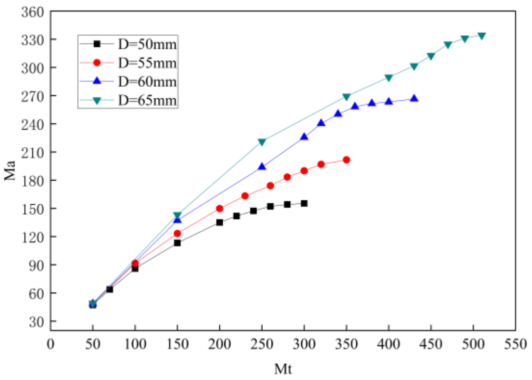

Figure 4. The relationship between Ma and Mt of soy bean under different diameters

4.2. Numerical simulation results and discussion

Figure 5 is the functional relationship between the apparent mass ma of soybeans and the corresponding filling mass Mt obtained by simulating the free settlement and accumulation of soybeans in a three-dimensional cylindrical silo with a barrel diameter of 50mm by using the discrete element method. The apparent mass Ma of the particulate matter increased with the increase of the filling mass Mt, and finally tended to be saturated. The whole trend showed a nonlinear relationship, and the apparent mass Ma that eventually reached the saturation value was significantly smaller than the actual filling mass Mt. In addition, compared with the experimental data, the granary effect is more obvious in the data reflected by the numerical simulation.

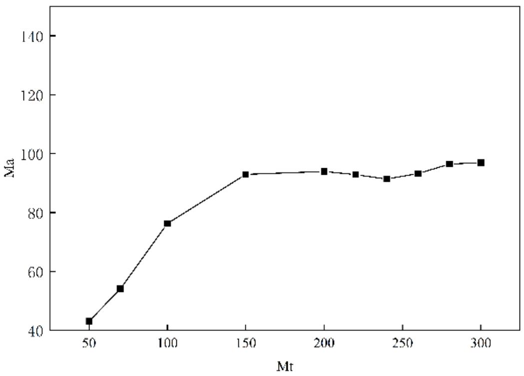

Figure 5. The relationship between Ma and Mt under numerical simulation

5. Conclusion

Based on the granary effect phenomenon and Jason model, this paper studies the functional relationship between the pressure at the bottom of the cylindrical silo and the actual filling quality of particulate matter from the macro scale and micro scale by using the methods of physical experimental research and numerical simulation, respectively, to verify the granary effect phenomenon and explore its causes. In the bottom pressure measurement experiment of three-dimensional cylindrical silo, by measuring the bottom pressure of soybean and mung bean in three-dimensional cylindrical silo with different diameters, taking the particle type and silo diameter as the research object, the functional relationship between the bottom pressure of silo and the actual filling quality of particles in silo is explored, which basically conforms to Jason model, And the phenomenon of granary effect appears. It is found that the granary effect is more obvious in the experiment with soybean as filling particles, and the smaller the silo diameter is, the more obvious the granary effect is. In the numerical simulation of discrete element method, a three-dimensional DEM particle motion mathematical model is established to simulate the free settlement and accumulation process of particulate matter in the three-dimensional cylindrical silo, analyze the stress of particulate matter in the cylindrical silo, verify the phenomenon of granary effect and explore the causes of granary effect in combination with physical experimental data and numerical simulation data. Through numerical simulation, it is found that the data reflected by numerical simulation is more in line with Jason model, and the phenomenon of granary effect is more obvious.

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