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The mechanism of vibrations-aided gravitational flow with overhanging style in hopper

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ABSTRACT

Arching, blocking, and sticking might be frequently encountered in hopper. Studies are carried out in order to solve these problems in Luoyang Bauxite Mine, China. The results of similarity model tests show that factors affecting flowability of particles are mainly friction and cohesion, when the moisture content changes from 8.2% to 10.8%, the influence of friction and cohesion on the flowability of particles becomes increasingly unfavorable, particles are easier to stay in the corners. In addition, the discharge effect is also affected by friction coefficient of the inner wall. In the numerical simulation, vibration is imposed by means of two blue balls fixed in the corners, where the flowability of particles is proved to be the worst. Results indicate that, no matter whether vibration is added or not, the total numbers of discharged particles and contacts change linearly with time steps, the contact forces between particles and walls are generally greater than that between particles. Compared with gravity discharge, the average velocities of the particles are obviously increased with the help of vibrations, especially in the corners of the hopper. The contact forces between particles as well as between particles and walls are optimized, that is, larger fluctuations of the contact forces are exhibited periodically, mainly because the contacts are greatly damaged by vibrations, therefore, the possibility of arching is limited effectively. The results of the studies reflect the mechanism of vibrations-aided gravitational flow and provide a theoretical basis for the design of a new vibrator. In combination with flow characteristics of particles, influencing factors of particle flow and theory of granular mechanics, a new flow-aiding vibrator with overhanging style in hopper is designed. In field tests, it has been proved to be a safe and effective device for solving problems of arching, blocking and sticking.

1. Introduction

The storage and transportation of particle substances might be greatly influenced by the problems of arching, blocking, and sticking. Therefore, the flowability of particles has become a hot topic in the field of powder engineering. At present, the methods of studying the problems include theory, experiment and numerical simulation.

In theoretical research, membrane theory was applied by A.J. Sadowski et al. [1] in the analysis of eccentric flow. A constitutive model with microstructure evolution proposed by Jin Sun et al. [2,3] was adopted in the theoretical predictions of granular flow in a conical hopper. These results are conducive to the understanding of the law of the particle flow in hopper.

The discharge characteristics of particles were demonstrated by laboratory tests [4,5], the discharge efficiency of particles was used in the design of new hopper [5–7], and the reliability of the relevant theoretical formulations was verified by Jasmina Khanam et al. [8]. The monitoring technology was utilized to study the variation of dynamic pressure in typical area of funnel wall by setting up monitoring equipment [9], based on the monitoring data, the service life of the hopper was prolonged through the design optimization [10]. Furthermore, the improvement of the flowability of particles was also studied by adding some additives in tests [4].

Numerical simulation can be adopted to study some important factors which are not convenient to achieve with conventional method, such as effects of physical and mechanical parameters on particle mobility, dynamic monitoring of pressure in hopper, influence of structural parameters of hopper on the flowability of particles. Furthermore, the structural design optimization of hopper was facilitated by numerical simulation [11–13], and the efficiency of design was improved [14]. Numerical simulation was also used for correction of theoretical formulations related to particle flow [15]. The combination of numerical simulation and experiment helped to ensure the accuracy of the results [16].

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The results quoted above reveal the laws of particle flow and the factors influencing the mobility of particles. However, it is difficult to fundamentally improve the flowability of particles only by structure optimization of the hopper, therefore, the proper method for assisting flow is also the focus of engineering researchers. Vibration has been studied in many fields [17–20], it is also a common method of assisting the flow of particles. For example, the friction coefficient of silo wall was effectively reduced by vibrations [21], in addition, it promoted the discharge efficiency of particles in a narrow hopper [22–23].

Due to too much powder in Luoyang Bauxite Mine, China, although many methods have been adopted to improve the flowability of particles during the past several decades, such as air gun, bottom vibration device, manual treatment and mechanical claw, it is still difficult to fundamentally solve the problems of arching, blocking and sticking in hopper. Take the bottom vibration device as an example, however, the flowability of particles at the bottom of the hopper can be improved effectively, the flowability of particles in the upper part of the hopper is difficult to increase, therefore, its effect of flow aids is very limited.

Similarity model tests and numerical simulations are employed to study the problems in Luoyang Bauxite Mine, vibration is taken into account in numerical simulations, results show the main influencing factors of particle flow and the laws of change of parameter values. In combination with flow characteristics of particles, influencing factors of particle flow and theory of granular mechanics, a new flow-aiding vibrator with overhanging style in hopper is designed, finally, the new vibrator is tested in the field.

2. Similarity model tests

According to the principles of similitude, the model is made in proportion. Main factors affecting the discharge of ore particles are listed as follows: geometry size l, pressure acting on ore particles F, normal stress σ, shear stress τ, cohesion c, internal friction angle φ, external friction angle φ_w, density of ore particles ρ, mass m, velocity of ore particles v, acceleration a, displacement s and time t. Their similarity constants are Cl、CF、C_σ、C_τ、Cc、C_φ、C_w、C_ρ、Cm、Cv、Ca、Cs and Ct, respectively. The corresponding similarity indicators are shown as follows:

$$\left.\begin{aligned} &\frac{C_\sigma}{C_\rho C_l}=1,\frac{C_v}{C_t}=1,\frac{C_v^2}{C_l}=1,\frac{C_\tau}{C_\sigma}=1,\\ &\frac{C_c}{C_\sigma}=1,C_\varphi=1,C_\alpha=1 \end{aligned}\right\} \tag{1}$$

The geometric similarity ratio is 1/12, that is, $C_l=12$. other constants should meet the following requirements:

$$\left.\begin{aligned} &C_\sigma=C_\tau=C_c=12C_\rho\\ &C_v=C_t=\sqrt{12}\\ &C_\varphi=1 \end{aligned}\right\} \tag{2}$$

The similarity relation is difficult to be fully satisfied, however, similarity model tests can be applied to the study of related problems, if certain parameters are similar, such as geometry size, internal friction angle, boundary conditions and initial conditions, etc.

Plexiglass is used to make the model of hopper, which geometric similarity ratio is 1:12. Particle samples are collected from three different storage sites of bauxite ores in Luoyang Bauxite Mine. Plastic films are used to prevent water loss during transport. Laboratory tests show that the moisture contents of the samples are 8.2%, 9.5% and 10.8%, respectively. The maximum diameter of ore particles in Luoyang Bauxite Mine is about 300 mm, considering the similarity ratio, ore particles of less than 30 mm in diameter are used for the similarity model tests, and can be separated from the samples by passing through a 30-mm-mesh sieve.

It is commonly known that moisture has a strong influence on the flow of granular materials [24], so that, the effect of moisture content on the flowability of bauxite particles will be firstly studied in similarity model tests. Taking into account the actual situation, similarity model tests will be carried out after 24 h, when the model of hopper is filled with ore particles. Test results show that ore particles with a moisture content of 8% are relatively easy to be discharged from the hopper, if the moisture content reaches 9.5% or 10.8%, the particles become more difficult to be discharged, this is mainly due to the formation of arches, which is a consequence of the presence of capillary bridges. Tang and He et al. [25] investigated the flow behaviors of particles, results showed that the liquid bridge force had a strong influence on the flow behaviors of the particles.

Therefore, a small diameter steel rod is used to poke the particles at the bottom of the funnel, particles with a moisture content of 8% need to be poked about 3 times, as for moisture content of 9.5%, it takes on average about 5 times, when the moisture content reaches 10.8%, it takes about 7 times. In addition, a few particles are still left in the corners (water content: 9.5%), the discharge effects are shown in Fig. 1.

The results of the model tests show that there are some differences in the flowability of particle samples with different moisture content, the main reason is that the moisture content affects the friction and cohesion between particles as well as between particles and walls. The friction and cohesion can have a negative effect on the flowability of particles, cohesive forces acting on wet particles cause particulate aggregation and the adherence of devices [26]. The studies carried out by M. E. Me'dici et al. [24] showed that cohesion also has an important influence on the behavior of granular flows inside a hopper, the granular flows were divided into two regimes: jamming and no-jamming considering the effect of moisture content. As for the friction coefficient, Amin. MN et al. [27] determined the effect of moisture content on coefficient of friction of pulse grain, results are used to prevent friction losses in food processing. The similarity model tests have been enriched by the valuable previous works.

When the moisture content changes from 8.2% to 10.8%, the influence of friction and cohesion on the flowability of particles becomes increasingly unfavorable, therefore, the flowability of particles become worse in similarity model tests. Tang and He et al. [28] also studied the behaviors of wet particles in a riser, the translational axial velocities was reduced with increasing the liquid content of the wet particles. It was concluded that the fluidity of particles became worse when the water content increased over a certain range, the result was similar to that of the similarity model tests.

In addition, the discharge effect is also restricted by friction coefficient of inner wall. Take ore sample (water content: 8.2%) for example, it needs to be handled five or more times by the rod, after sandpaper is attached to the inner surface of the funnel. The result shows that ore particles become easier to be left in the corners, the problem of arching, blocking and sticking might be exacerbated by these detained particles in the long term. The simulation also shows a similar situation (Fig. 2(b)), where particles are divided into ten layers by different colors, as shown in Fig. 5. Therefore, it is necessary to improve the flowability of particles in the corners of hopper.

3. Arching and vibrations-assisted flow

3.1. Mechanism of arching

In granular media, force transmission depends on the contact of particles which are subjected to friction, cohesion and other forces during its movement in hopper. Under certain conditions, the balance arch can be formed, as shown in Fig. 3.

Where 1 represents the moving band, 2 represents arch, 3 represents orifice, 4 represents load acted on arch, 5 represents uniform load in the mobile belt before arching, 6 represents affected boundary of horizontal dynamic lateral pressure.

Velocity of particles in each layer has difference, forces are also not the same in different positions of the arch, the maximum force is on