A DE numerical study upon particulate solids flow from model silos

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Introduction

The importance of avoiding flow disruptions and quality variations associated with funnel flow requires a mass flow rather than a funnel flow in silo design (Jenike, 1964; Drescher, 1992). Quite often, a silo designed to perform a mass flow turns into a funnel flow silo after a certain period of service, or later on when being used to store materials with changed flow properties. Some efforts have been expended in order to obtain mass flow in silos with a reasonably flat hopper; among which are to install a flow aid device such as inserts in a certain position in a silo (Johansen, 1982). A prediction to whether such inserts function or are suitable for a given application is therefore desirable.

However, one must admit that no perfect analytical methods have been developed to carry out such predictions because of complexity caused by a presence of inserts in silos (Nedderman, 1992; Drescher, 1991). Instead numerical approaches are usually adapted (mostly the Finite element (FE) method and the Decreased element(DE) mthod) to seek solutions or clues (Rotter at al., 1998; Karlsson et al., 1998; Ding et al., 2003; Eibl & Rombach, 1987; Haussler & Eibl, 1984; Eibl & Rombach, 1987; Cundall & Strack 1979 etc.). In the paper the Discrete Element (DE) models were created in an effort to investigate the flow mode of particulate solids discharged for a plane silo. Effects of a cone-in-cone insert on such flow modes were also addressed. The influence of the fluid filled voids of particulate solids on the flow mode was also attempted with modification to the DE model after considering the forces exerted on the particulate solids due to fluid bridge.

Object of the DE model and conditions

A two-dimensional model silo was considered in the present study. It consisted of a vertical bin section and an inclined hopper section. A cone-in-cone insert was fitted into the silo. The key dimensions for both silo and insert, and the configuration of the insert and silo were as shown as in Figure 1. A 2000 particulate solids as spheres of a 5 mm in diameter were filled into the silos. The solids have a density of a 2700 kg/m^3, and are pretty soft with an elastic Young's module of a 40000 Pa and a Poisson ratio of 0.3. The interaction between the particulate solids and solids against the surface of silo walls (/insert) was modelled as friction with a coefficient of 0.3.

Interaction of particulate solids considered in the model

In the model the particulate solids stored in a silo are treated as a set of discrete elements (Cundall and Strack, 1973), where interaction between the contacting elements could be determined through contacting forces. Such forces depend on the deformations of solids, and are usually resolved into the normal and tangential components (Johnson, 1994; Mindlin and Deresiewicz, 1953). The Newton’s equation of motion of a particle is given by:

$$\frac{d\vec{V}}{dt} = (\sum_{j=1}^{k_j} \vec{F}_{cj} + m\vec{g}) / m \tag{1}$$

The rotational motion of a particle caused by the contact force is governed by:

$$I \frac{d\vec{\omega}}{dt} = \sum_{j=1}^{k_j} \vec{r} \times \vec{F}_{cj} \tag{2}$$

Equations as given above can be solved numerically by a finite difference method. The trajectories and the transient forces of the individual solids can then be determined. As a result, particulate solids will undergo translational and rotational motion, and to be discharged from silos.

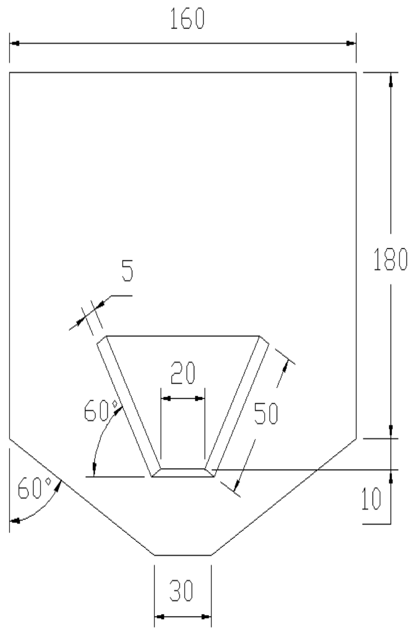


Figure 1. The key dimensions and a configuration of a silo, a cone-in-cone insert considered in the models

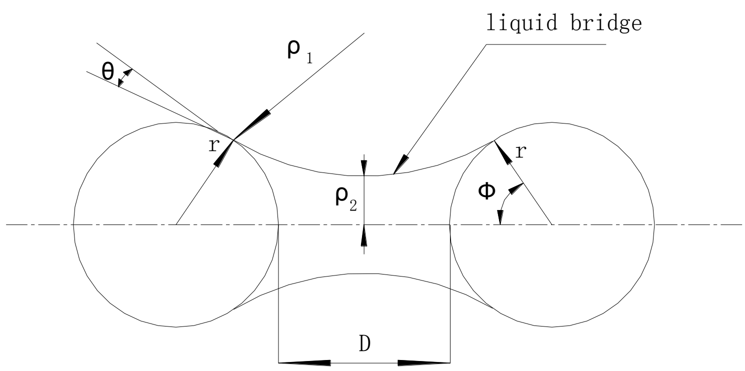


Figure 2 A pair of central moving spheres with interstitial Newtonian fluid.

When there exists interstitial fluid in the voids among the solids, liquid bridges would form in the gap between particles as illustrated in Figure 2, exerting adhesive force and viscous force up the particulate solids.

Fisher (1926) gave the adhesive force as follows:

$$F_{cap} = \pi\rho_2^2\Delta p + 2\pi\rho_2\sigma_s = 2\pi\rho_2\sigma_s(1+\frac{\Delta p}{2\sigma_s}\rho_2) = 2\pi\rho_2\sigma_s(1+\frac{\rho_2-\rho_1}{2\rho_1\rho_2}\rho_2) \tag{3}$$

$$= \pi\sigma_s\rho_2(1+\rho_2/\rho_1)$$

Where $\rho_1 = [r(1-\cos\phi)+D/2]/\cos(\phi+\theta)$ (4)

$$\rho_2 = r\sin\phi - [1-\sin(\phi+\theta)]\rho_1 \tag{5}$$

While the viscous forces were given by Adans and Perchard (1985) as:

$$F_{vn} = 6\pi\eta r^* V_n \frac{r^*}{D} \tag{6}$$

for the normal component, and

$$F_{vt} = (\frac{8}{15}\ln\frac{r^*}{D}+0.9588)6\pi\eta r^* V_t \tag{7}$$

for the tangential component, where $r^* = r/2$ for spheres of the same diameter.

Lian et al. (1994) showed that the distance of liquid bridge stability is proportional to the cube root of the volume of liquid bridge. This representation was used in the current study.

Incorporating a liquid bridge force into DE Model simulations, the program was further modified to investigate the effect of liquid bridge on the particulate solid flow mode during silo discharge.

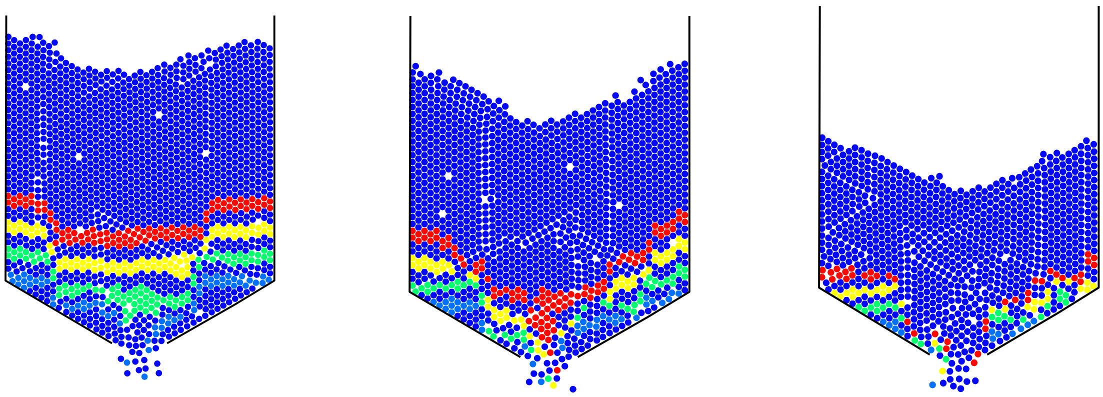
Effect of a cone-in-cone insert on flow mode during discharge

The flow modes of particulate solids discharged from silo were simulated. Thin layers of particles with colour were set at different levels as tracers to visualize the development of the flow patterns. The results are given in Figure 3.

As seen in Figure 3 (a) via the coloured particles, the particulate solids in the central zone started to drop, while those close to the walls sections remained intact at the beginning of discharge when no insert was inserted. With the discharging going on, those solids slid into the central moving zone and to be discharged. According to the shape of the coloured particles layer, it is obvious that the solids were discharged in a typical funnel flow mode.

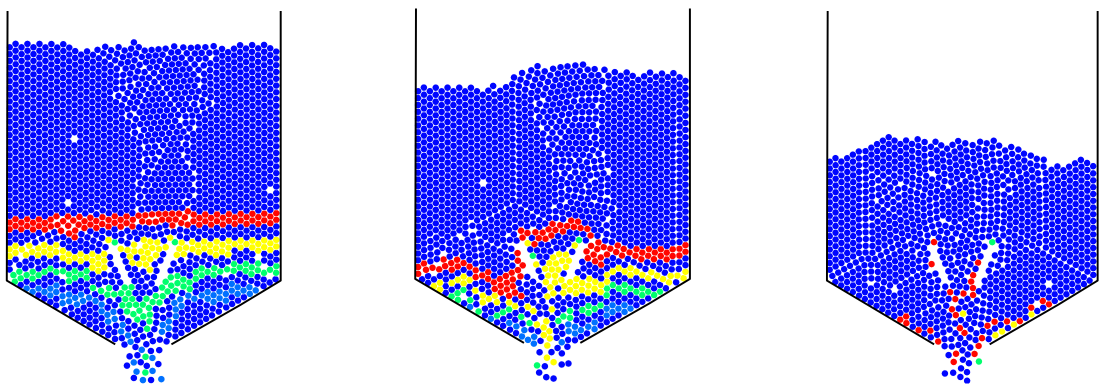
With a presence of a cone-in-cone insert in silos (see Figure 1), one can see in Figure 3 (b) that all solids in silos were in move; and were in fact discharged rather evenly at all crossed sections at the commencement of discharge. With the discharging going on, the solids above the insert were slowed down, and the evenness of discharge lost, but solids in the silo were still all in motion until totally discharged.

In brief, the funnel flow phenomenon is apparent from the motion of the coloured layers of particles when no inset was installed, whereas such funnel flow was turned into a mass flow in a presence of a cone-in-cone insert for the configuration as presented in Figure 1.



t=0.4 s t=1.3 s t=2.4 s

a.) without an insert



t=0.4 s t=1.3 s t=2.4 s

b.) with a cone-in-cone insert

Figure 3 Flow mode of particulate solids discharged from a silo

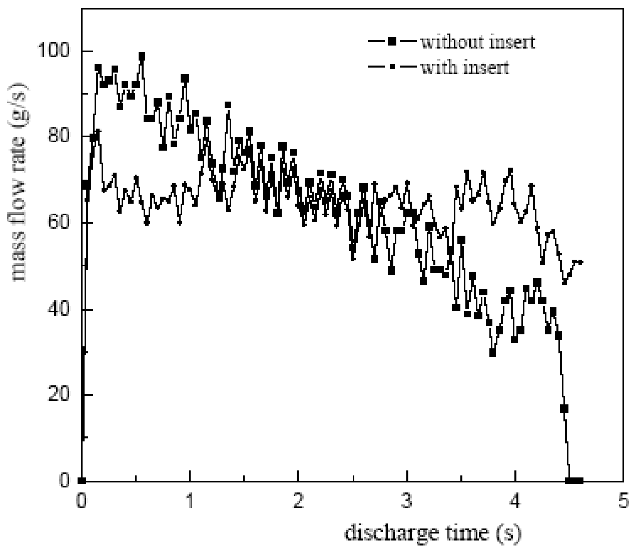
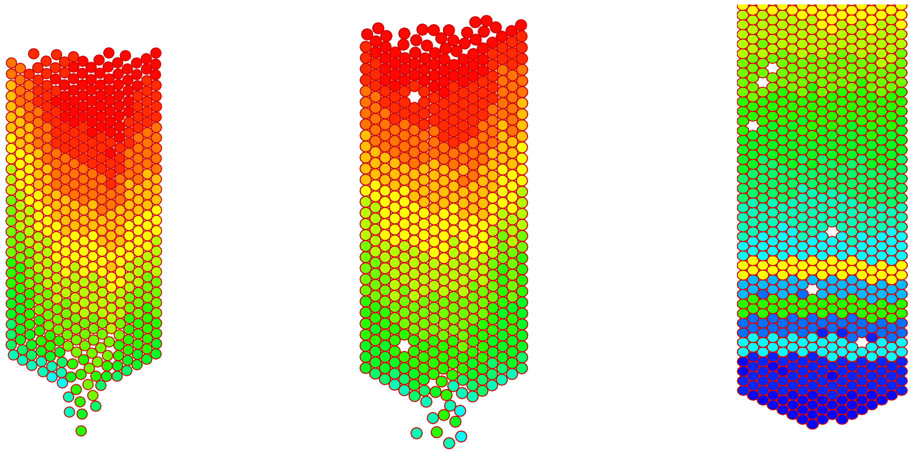


Figure 4 Development of discharging mass rate

The mass rate of discharging is respectively given in Figure 4 for the cases in a presence or an absence of the cone-in-cone insert. It is evident that the discharging rate fluctuated in both simulations. It could also be seen that an installation of a cone-in-cone insert decreases the fluctuations of the discharging rate, and become more stable.

Influence of water content to particles flow

Modification to the DE model was made in order to focus on investigation of the effect of interstitial fluid content on the discharge mode. In the modified model, the silo had an half angle of a 60 °, with a width of a18 mm for its bin section and an outlet of a 6 mm; A 1000 particles with a 1 mm in diameter were considered; the liquid surface tension was assumed to be 0.0725 N/m and viscosity of 0.001Pa s. The numerical results are shown in Figure 5. As seen in Figure 5, the water content has a distinctive affect on the flow of particulate solids in the silo. The discharge was uniform and steady from the silo when the water content is 0 (see Figure 5 (a)); the discharge took place, and the particles was discharged in agglomerate when the water content increased to 1%, Figure 5(b); however, an arch was developed at the outlet when the water content increased to 2%, Figure 5 (c), i.e., no discharge occurred.



(a) Water content＝0%　　(b) Water content＝1%　　（c）Water content＝2%

Figure 5 Influence of water contents on the mode of silo discharge

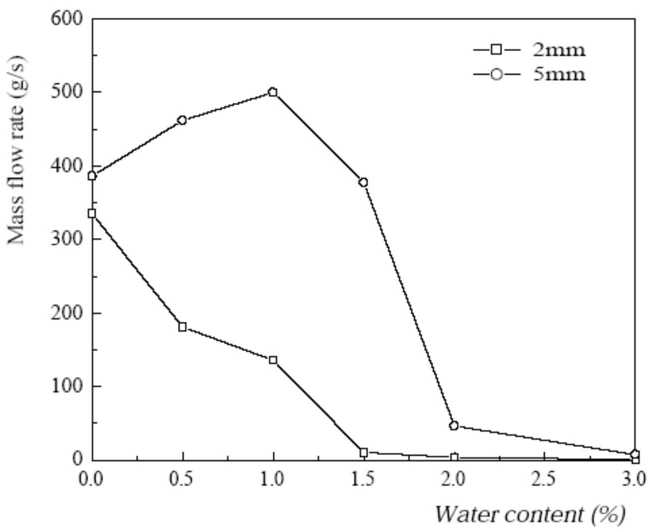


Figure 6 Effect of water contents on mass flow-rate

Efforts on the affect of the fluid content on the mass flow rate were also made. It was found that the mass flow rate decreased with the increase of the water content if particulate solids were small (2 mm in diameter); the affect of water content on the mass flow rate varied for particles of a 5mm in diameter. Typical results with such regards are given in Figure 6.

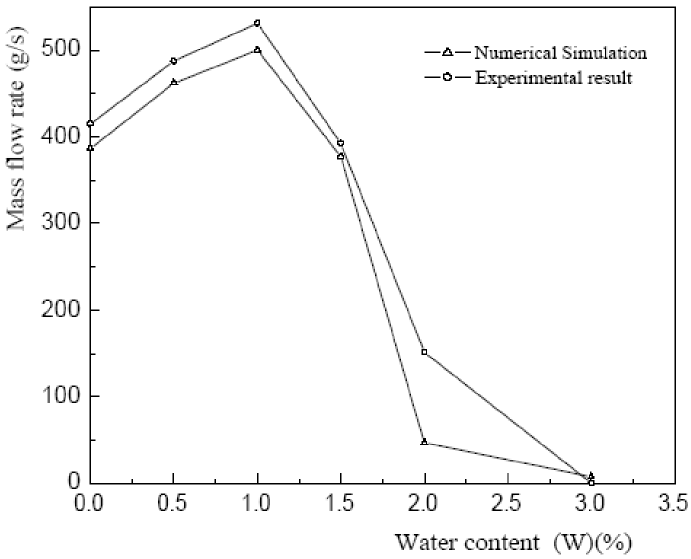


Figure 7 Comparison of calculated results and experimental data for mass flow-rate

Verification was conducted to demonstrate the influence of fluids content to the mass flow rate. It is shown in Figure 7 with the data obtained in experiments carried out with a silo in dimensions as used in the models; the particulate solids used were 5mm in diameter. One can see the good agreement between the predicted results and the experimental data.

Conclusions

The program developed with the discrete element method was used to predict the particulate solid discharge mode from silos. The prediction showed that the cone-in-cone insert can effectively change the particles flow mode from funnel flow to mass flow. It also showed that the interstitial fluid has a distinctive affect on the flow of particles; higher fluid content (with the value considered in the present study) might cause stoppage of silo discharge. The mass flow rate decreases with the increase of the fluid content for small particles. The existence of certain amount of fluid facilitate the discharge when the particle is relative large, but the mass flow rate of discharge would also decrease when the fluid exceeds a limitation.

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Nomenclatures

D	–	spherical surface distance, (m)
F_{cap}	–	the adhesive force, (N)
$\vec{F}_{cj}$	–	contact force acting on the particle, (N)
F_{vn}	–	normal component of the viscous force, (N)
F_{vt}	–	tangential component of the viscous force, (N)
$\vec{g}$	–	acceleration of gravity, (m/s^2)
I	–	moment of inertia, (kg m^2)
m	–	mass of particle, (kg)
Δp	–	capillary suction pressure, (Pa)
r	–	radius of particle, (m)
t	–	time, (s)
$\vec{V}$	–	translational velocity of particle, (m/s)
V_n	–	normal component of relative velocity, (m/s)
V_t	–	tangential component of relative velocity, (m/s)
$\vec{\omega}$	–	angular velocity of particle, (rad/s)
ρ_1	–	radii of curvature of liquid bridge surface, (m)
ρ_2	–	radii of neck of liquid bridge, (m)
φ	–	half-filling angle, (rad)
θ	–	contact angle, (rad)
σ_s	–	liquid surface tension, (N/m)
η	–	dynamic viscosity, (pa s)

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