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FLOW PATTERN FOR MULTI-SIZE SILOS

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ABSTRACT: Silo container is a very important storage structure for coal, sand and other granular materials. Nonhomogeneous granular flow is sometimes found in ore discharging in mining engineering, but so far there are only limited studies to this topic, particularly for double opening silo. In views of that, it is necessary to figure out the details about the flow pattern behavior. In the present paper, four physical models are designed to investigate the flow patterns for silos discharge behavior with double openings. The opening spacing, height ratio, sand properties and automatic separated manners are considered in these laboratory tests. Meanwhile, two-dimensional discrete element method is used to reproduce the flow behavior as well as to evaluate the dynamic wall stresses distribution on the silo hopper from bottom to top. It is found that the flow pattern is very sensitive to the spacing between openings under close opening silos. For the wide opening silos, the discharge efficiency would change nearly 30%. The arch effect in the dead zone and ore recovery are significantly influenced by the height /spacing ratio. The results from discrete element analysis can match well with the experimental study if suitable micro-parameters are used in the analysis.

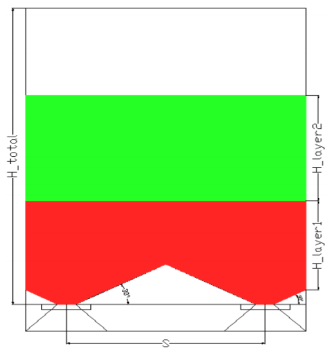
Keywords: Silos; Flow Pattern; Discharging; Laboratory Tests; Discrete Element

1. INTRODUCTION

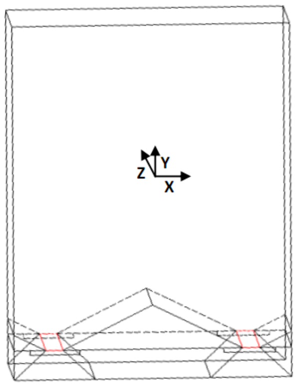
Many engineers still use the classical Janssen formula [1] to analyze the stress distribution on the wall of silo, where only homogeneous material is considered and the end effect is ignored. The limitations of this formula come from the assumption of uniform flow required in the classical continuum mechanism for analyzing discontinuous problem. Cheng et al. [2] discovered that columniform channel flow can be observed when two layers of materials with different sizes are introduced into short silos, where maximum stress can be found at the top of dead region. Cheng et al. [3] had found that the double opening silo can increase the recovery of the bottom material. The material deposition from the nature is complicated, as the columniform channel and funnel flow are required to be considered for granular discharge flow. In this paper, four physical models are designed to carry out 16 groups of tests with double openings for the silos. The effect of opening distance, height/spacing ratio and layering are investigated for the flow pattern, arching effect and ore recovery. The discrete element method [4]-[7] is also used for comparing the analysis and monitoring the stress field for the whole processing.

2. EXPERIMENTAL TESTS

Four different double-opening silos are designed, where the opening spacing and height ratio are varied. The schematic diagram is shown in Fig. 1, where *S* means the opening distance, *H_layer* is the height of each soil layer, and *H_total* is the height of each silo. The heights of the two shorter silos (silo A and silo B) are 650mm, and it is 1000mm for silos C and D. The laneway in the physical model is 30mm wide with an angle of 30 degree to the horizontal direction. The laneway can be removed to induce the initial sand drawing. The surrounding sides of the silos were made of transparent PVC sheet with scale lines for easy monitoring and capturing discharge process. The flow pattern of this test is also recorded by a high speed camera. In this experimental study, red sand and green sand, which were deposited and compacted in layers, were used for visualizing the flow behavior. The particle size distributions of the sands are nearly uniform. Cheng and co-workers [2] have used these two sands for comparing the single and double opening effects in flow patterns, where the opening distance is close and the height ratio is small.



(a) 2D Vertical View



(b) 3D Geometric Model

Fig. 1 2D and 3D double-opening schematic.

The number and types of layers are limited in this study. In this paper, multiple experiments have been carried out to capture the sensitivity of the above three factors for granular flowing pattern and ore recovery. Detailed information about these tests can be seen in Table 1, where the height of each layer is associated with layer orders. For silo model A, the reverse deposition manner may directly influence the flow pattern. In test 1, the coarse red sand is placed at the bottom layer, where the global flow is basically a uniform discharge. In test 2, the fine green sand laid at the bottom will induce two twin funnel flows, and a steady dead zone with sharp geometry at the interface between the two layers were found during the flow. The speed of the red sand (coarser sand) is much greater than the fine sand, and the green dead zone will support the upper layer to generate two fast flow side zones. Red sand will firstly deposit in the deposition tank. The flow pattern of these two tests can be seen in Fig. 2.

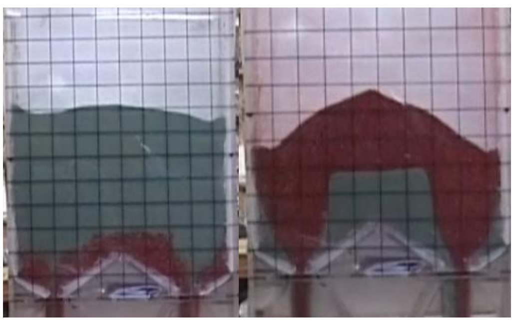


Fig. 2 The flow patterns in test 1(left) and 2.

The discharge time in Table 1 can be influenced by the material property at each layer, which has been found by *Cheng et al.* [2]. In these experimental tests, it can be found that the opening spacing can significantly affect the discharge efficiency. The difference in the discharge time for reversing the layerings in the close opening silo A and C are not obvious.

Table 1 Detail information of experimental tests (T means the time required for complete discharge)

Groups	Layer	Num	*S (mm)*	*H_layer (mm)*	T (s)
Silo A	Red Green	1	155	155 155	5.8
	Green Red	2			5.9
Silo B	Red Green	3	240	240 240	10
	Green Red	4			14.2
Silo C	Red Green	5	140	140 280	6.8
	Green Red	6			7.2
	Red Green	7		140 420	9.5
	Green Red	8			9.7
	Red Green	9		140 560	9.8
	Green Red	10			10.1
Silo D	Red Green	11	270	270 270	10.8
	Green Red	12			13.2
	Red Green	13		270 405	11.1
	Green Red	14			14.6
	Red Green	15		270 *540*	12.6
	Green Red	16			16

However, for the wide opening silo B and D, the variations are nearly 30% which can directly influence the discharge behavior. This may be induced by the couple effect of the geometry and the material properties. The frictional coefficient of fine green sand is larger than the coarse red sand, and this may impact the flow ability. Meanwhile, higher height can accelerate the whole flow velocity to increase the discharge efficiency. The dead zones at the bottom layer can be found in each test for silo C and silo D, especially at a larger height value. The dead zones are unstable in higher top layer, which will gradually decrease in the global processing behavior. This interesting phenomenon can be seen in Fig 3. In this figure, since the opening spacing is close, the depression cone will also appear in the bottom layer. Ore recovery will be better when the height ratio is higher, where the height of bottom layer is coincident with the opening spacing. In this paper, the authors choose test 5 and test 9 for comparison which is shown in Fig 4. These foundings can be of importance for non-homogeneous ore mineral discharge behavior.

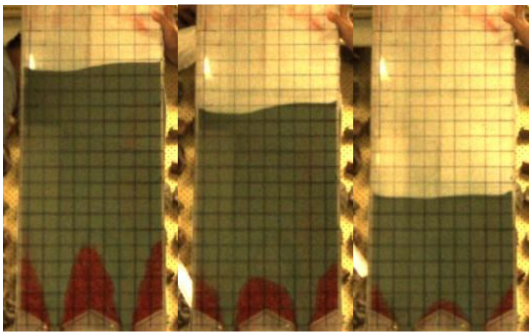


Fig. 3 The variation of dead zone in bottom layer.

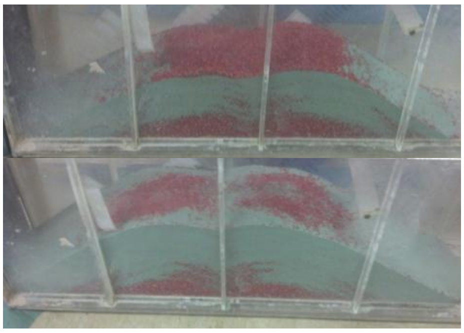


Fig. 4 The deposition veiw of test 5(top) and 9.

3. NUMERICAL COMPARISON

Two dimensional program PFC2D [4] using rigid "Disk" with soft contact is used for the present study. The governing principle in the modeling includes three models: 1) contact model; 2) bonding model; 3) slip model. For cohessionless materials such as sand in the present study, the bonding model can be ignored. The authors have chosen the linear elastic model and Coulomb slip model in the present study which is also adopted in many previous studies [2]-[7]. The micro parameters of linear contact model include the normal and shear stiffnesses and the internal frictional coefficient. Furthermore, the velocity vectors of each "Disk" consist of two plane translational components and a rotational component. The skeleton of the linear contact model in this paper is given in Fig 4. Meanwhile, the mechanical governing equations of the bond/slip model are given by:

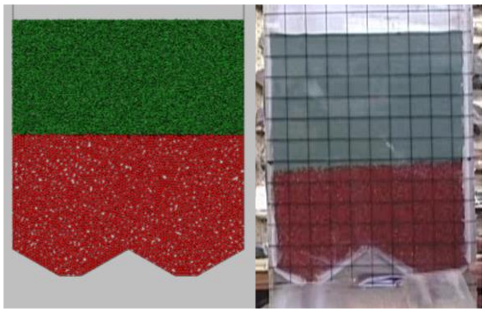
$$\begin{cases} F_i^n = K_n U_n \\ \Delta F_i^s = -k_s \Delta U_s \\ F_i^s \le \mu F_i^n \end{cases} \tag{1}$$

Where *Kn* and *ks* denote the normal and shear stiffness coefficients, ΔUn is the normal overlap, ΔUs is the incremental tangential displacement, μ is the inter-frictional coefficient.

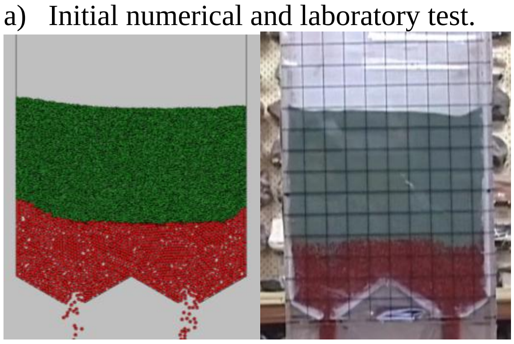
The calibration of the input micro parameters has been discussed by many researchers [2], [7]. The physical and micro parameters of the material used in numerical modeling are given in Table 2. Particles are generated by the deposition method, which can generate a similar initial stress filed as the experimental specimen initial condition. The dimensions in the numerical model are the same as the physical model. The vertical and horizontal stresses can be monitored at every step in the computing procedure, which can qualitatively analyze the stress distribution on the boundary. The stress field on the boundary is another important index for optimizing the design of the silo and ore discharge.

Table 2 Physical and micro parameters

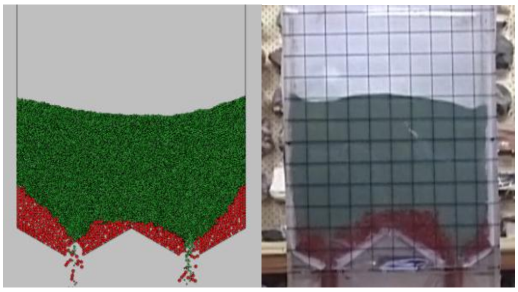
Sand	Size (mm)	φ	Density (kg/m^3)	*Kn* (N/m)	*ks* (N/m)
Red	2-2.2	27	1415	4e6	4e6
Green	0.15-0.60	31	1379	1e6	1e6



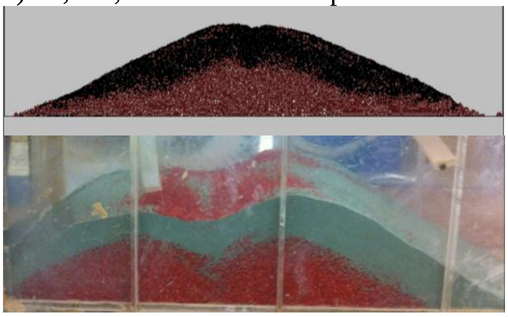
a) Initial numerical and laboratory test.



b) 400,000 numerical steps



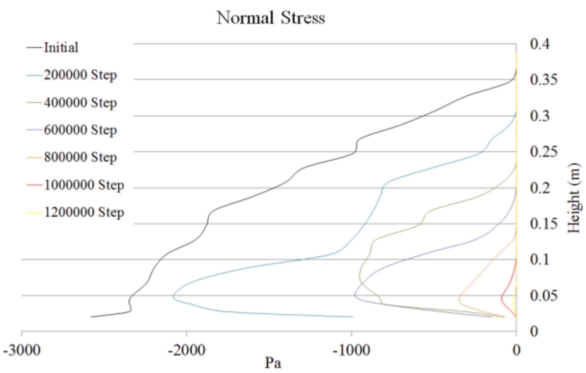
c) 1,000,000 numerical steps



d) 5,500,000 numerical steps

Fig. 5 Numerical and experimental comparion.

In this paper, the authors choose test 1 to carry out a numerical simulation. It was observed that the sand is drawn uniformly beginning, but it gradually becomes twin short funnel channel. The flow patterns of test 1 at different numerical time steps are shown in Fig.5, which is simultaneously compared with experimental test from the high speed cameral. These results can totally match well with the trend of the laboratory results.



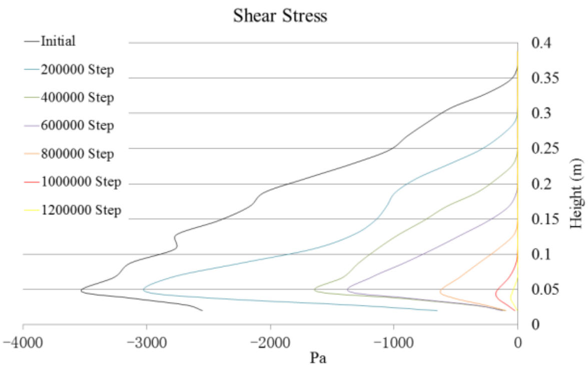
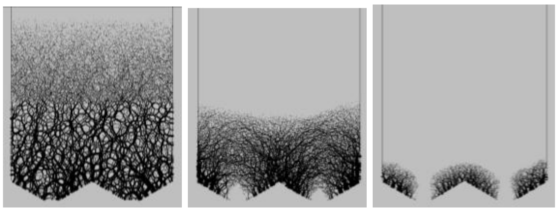


Fig. 6 Normal and shear stresses on the side wall.

The monitored normal and shear stress data can be easily analyzed to capture the qualitative trend of boundary circumstance, which is shown in Fig.6. The normal stresses in the initial stage are fluctuating dramatically and stress concentration is found at the corner of the side and bottom plates. This is induced by the instantaneous opening behavior and geometry effect. Normal stress drops very significantly in the initial stage, meanwhile, the peak stress location has also changed, which is induced by the short funnel flow pattern after 100 million numerical steps in Fig.5. Accompanied the whereabouts of red coarse sand, the normal stress variation and stress concentration location gradually change steadily. The flow pattern can't lead to a sharply variation for the shear stress, as the short funnel would just produce extra lateral compression for the dead zone in boundaries, where the dynamic force is on the horizontal direction. The discrete element simulations just give some qualitative assessments for stress or other physical quantities. The flow pattern behaviors can similar be reproduced by discrete element method, which can give some visualization not possible from the model test even in the internal of each layer.



(a) Initial stage (b) 1,000,000 steps (c) 2,600,000 steps

Fig. 7 Contact force distribution of test 1.

In Fig.7, from the contact force of test 1, different contact force chains within these two sand layers can be noticed. Red sand which owns larger size generates much stronger force chains concentrated at the silo bottom and is shown in Fig. 7 (a), and its gravity transfers to the four hopper walls forming strong connections between sands and walls. On the other hand, Green sand creates much weaker force chains on the silo top, which represent more intense and sufficient contact and friction inside this layer. It can also be noted from the sequence of contact force diagram that the interaction of particles becomes stronger during the discharging process.

The circular shaped arch of distribution zone can be noticed above the caving arch near the silo openings in Fig. 7 (b). The falling velocity of sands is large within the distribution zone, while the sand draws slowly outside the arch. In the beginning of the silo flow, particles from the two sides travel the same distance with those flow at the middle, which explains why the mass flow is formed during discharging. As sands are continuously drawn out, less contact force induces smaller stress on the silos hopper walls. Hence, the distribution zone start developing upward, so funnel flow may possibly be formed at the later stage till the end of flow.

4. CONCLUSIONS & RECOMMENDATIONS

The present study in this paper has focused on nonhomogeneous granular flow behavior from both macroscopic and microscopic view points, and has revealed some interesting phenomenon for a silo flow problem with granular material. The results from the present study are particular useful for mining engineering in ore discharging.

Four sets of silos are investigated in this research. It is found that the opening spacing can significantly influence the discharge efficiency. The flow pattern and efficiency can also be influenced by the soil layerings. For close opening silos, the flow pattern is slightly changed while the efficiency of flow is not sensitive to the layerings. However, for the wide opening silos, the discharge efficiency can change by nearly 30%. Larger height ratio is also beneficial for ore recover. Depression cone can be seen in the close opening silos. Meanwhile, the dead zone in the bottom layer is unstable for relative higher top layer.

Numerical analysis can match well with the flow pattern and give some qualitative results. The porosity of the dead zone in funnel flow is larger than the mass flow. The size of opening affects the contact force in the middle of the silo, which leads to the formation of a depression cone. The nature of the internal force network is of great importance in the understanding of various properties of granular assemblies.

A good agreement between the laboratory and numerical results can be observed if suitable microproperties are used in the analysis. It is recommended that for the further study, more in-depth numerical study needs to be carried out to capture the fundamental behavior for these interesting experimental results. Three dimensional simulations are also suggested.

5. ACKNOWLEDGEMENTS

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