STUDY ON THE EFFECT OF CURVED FUNNEL FOR SILO UNLOADING ON PARTICLE FLOW CHARACTERISTICS
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筒仓卸粮曲面漏斗对颗粒流动特性的影响研究

Mingxu WANG[1,2*)], Saiqiang LI[1)], Tao Gao[1)], Zhijie SONG[4)], Kunlun LIU[3)], Jianzhang WU[3)], Jiangfeng OUYANG[1)]
[1)]School of Mechanical & Electrical Engineering, Henan University of Technology, Zhengzhou 450001, China
[2)]Henan Key Laboratory of Grain and Oil Storage Facility & Safety, Henan University of Technology, Zhengzhou 450001, China
[3)]School of grain college, Henan University of Technology, Zhengzhou 450001, China
[4)]Jiaozuo Creation Heavy Industry Co.,Ltd., Jiaozuo 454000, China
Tel: 18623717728.; E-mail: wmx20032002@163.com
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ABSTRACT
In order to adapt to the needs of modern intelligent warehousing and reduce the unloading side pressure of grain silo, the influence of curved funnel on the unloading process is designed and analyzed, and this paper uses EDEM simulation software and Hertz Mindlin model for analysis. The results found that compared with the unloading characteristics of the conical funnel, the unloading side pressure is effectively improved; in the unloading process, with the increase of the shrinkage rate, the critical position of the flow transformation increases and the flow velocity of the particle group accelerates. However, the flow velocity of the particle group decreases when it reaches the critical position of 250 mm. Combined with the corresponding analysis, this paper uses the Froude number to quantitatively express the mobility of particles. As the shrinkage rate of the curved funnel and the unloading height increase, the Froude number also increases. This paper analyzes and calibrates the curved funnel for soybean unloading in silos, which will provide useful reference for avoiding arching and clogging during the unloading process of grain particles.

摘要
为适应现代化智能仓储的需求，减少粮食筒仓卸料侧面压力，设计并分析了曲面漏斗对卸料过程的影响，本文利用 EDEM 仿真软件，使用 Hertz-Mindlin 模型进行分析。结果发现，对比于锥形漏斗的卸料特性，有效改善卸料侧压力；卸载过程中，随着收缩率的增大，流形变换的临界位置增大，颗粒群的流动速度加快。然而，当达到临界位置 250mm 时，颗粒群的流速减慢。结合相应分析本文采用弗劳德数对颗粒的流动性进行了定量表述，随着曲面漏斗收缩率和卸料高度的增加，弗劳德数也在增大。本文对筒仓大豆卸料曲面漏斗的分析标定，将为解决粮食颗粒的卸料过程避免结拱和堵塞提供有益的参考。

INTRODUCTION
Silo as the main facility for grain storage, has many advantages, such as: it occupies a small area, it is easy to build, can be added to a variety of monitoring equipment, it is easy to use, it is conducive to the transfer of grain, and so on, therefore, worldwide it is more used for the storage of grain, sand and other bulk particles. In addition to bearing permanent load and variable load, the silo also bears the effect of grain storage on the silo during use (*Ayuga F. et al., 2001*). The effect of grain storage on silo is large, the action time is long, and it changes with time, which is the main factor affecting the safety of silo structure. The dynamic pressure of the silo will increase during the unloading process (*Zhao et al, 2013*), and overpressure phenomenon often occurs in the lower part of the silo.

Through a large number of studies by scholars, it is known that the conventional conical hopper silo will be clogged during unloading due to a number of factors such as the complexity of the bulk material, and even the silo wall is thus impacted, leading to the destruction of the silo. Pressure reducing tubes (*Wang et al, 2001; Yuan et al, 2020; Wang et al, 2023*) or fluid modifiers (*Qu et al, 2012*) are installed inside the silo to change the particle flow pattern, but in practice, the pressure reducing tubes are not easy to install and fix, and fluid modifiers can be damaged (*Qu et al, 2012*). One or both side chutes (*Yuan et al, 2019*) are installed on the side of the silo to change the particle flow pattern to reduce the side pressure, but the eccentric discharge is not well adapted. In this paper, the analysis of the law of influence of such a combined funnel on the unloading of a silo, when only one section of the unloading funnel is a curved funnel portion and the rest is still a conical funnel portion, is investigated.

Simulation of unloading from curved funnels with different degrees of curvature

Curved funnel model analysis

In order to study the influence of the bending degree of the curved funnel on the simulation of silo unloading, the height of 200 mm curved funnel is selected, and then the angle of the arc is used to represent the curvature of the surface, the arc angle of 20°~60° is selected for a total of five levels. After calculation, if the arc angle is greater than 60°, it will lead to the minimum discharge diameter change. Figure 1 shows the two-dimensional image of the curved funnel.

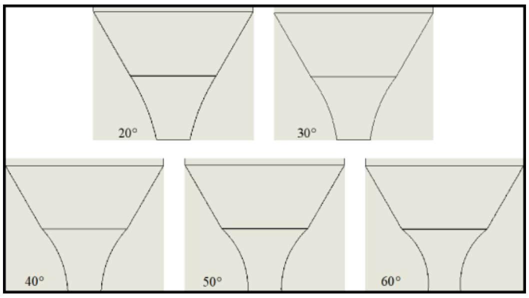


Fig. 1 - Curved funnels with different degrees of curvature

Shrinkage can be used to express the degree of curvature of the surface, which is expressed as the ratio of the difference between the area of the upper and lower two cross-sections and the ratio of the larger area of the two cross-sections in a unit distance of the longitudinal distribution of the discharge funnel; it is calculated by the formula shown below:

$$C = \frac{dS}{Sdy} = \frac{2\pi x dx}{\pi x^2 dy} = \frac{2}{y}\ln\left(\frac{2}{D_r}x\right) \tag{1}$$

where C is the shrinkage rate; S is the cross-sectional area; dS is the difference between the upper and lower cross-sectional areas; dy is the unit distance of the longitudinal distribution; and D_r is the outlet diameter of the funnel.

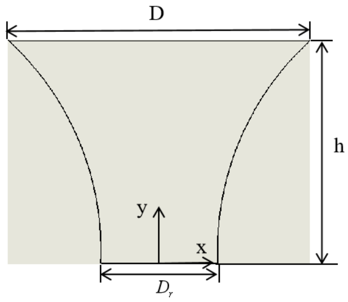


Fig. 2 - Schematic diagram of funnel cross-section

Figure 2 is the schematic diagram of the vertical section of the curved funnel. The shrinkage rate of the curved funnel with different arc angles can be calculated, as shown in Table 1:

Table 1

The shrinkage rate of five different funnels

Angle of a circle arc	Shrinkage rate/C
20°	0.089
30°	0.106
40°	0.125
50°	0.146
60°	0.171

The silo model was imported into EDEM software and unloading simulation was carried out, as shown in Figure 3 for the 3D model of the silo.

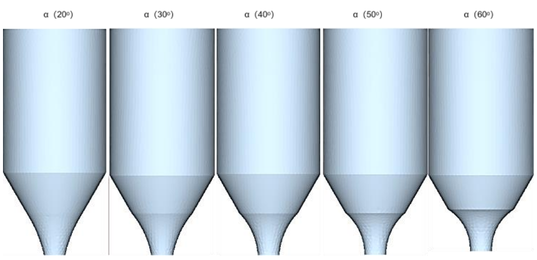


Fig. 3 - 3D model of the simulation test

The software uses the Hertz Mindlin model to calculate the indirect contact force of particles. The indirect contact force of particles includes normal force and tangential force, among which the calculation of normal force is based on Hertz theory. The calculation of tangential force is based on Mindlin's theory, which satisfies Coulomb's law of friction and accurately describes the interactions between particles. The particle model selected in this article is the four sphere particle model of soybean particles, and the corresponding three-dimensional model is shown in Figure 4.

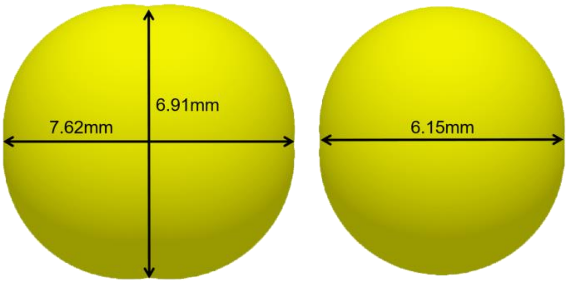


Fig. 4 - Three dimensional dimensions of soybean particles

The relevant physical attribute parameters and simulated attribute parameters are shown in the table:

Table 2

Physical parameters

Material	Parameter	Numerical value
Soybean	Poisson's ratio	0.23
	Young's modulus (MPa)	63
	Particle density (kg/m3)	1211
Silo	Poisson's ratio	0.5
	Young's modulus (MPa)	35
	Particle density (kg/m3)	1180

Table 3

Contact parameters

Material	Parameter	Numerical value
Particle - Particle	Coefficient of static friction	0.39
	Collision recovery coefficient	0.3
	Coefficient of dynamic friction	0.17
Particle - Silo	Coefficient of static friction	0.474
	Collision recovery coefficient	0.47
	Coefficient of dynamic friction	0.1

As can be seen in Figure 5 the average unloading rate of the conical hopper silo is 2.68 kg/s, while the unloading rate of the curved hopper silo accelerates with the increase of hopper shrinkage, and the growth slows down after the curved hopper arc angle of 40°.

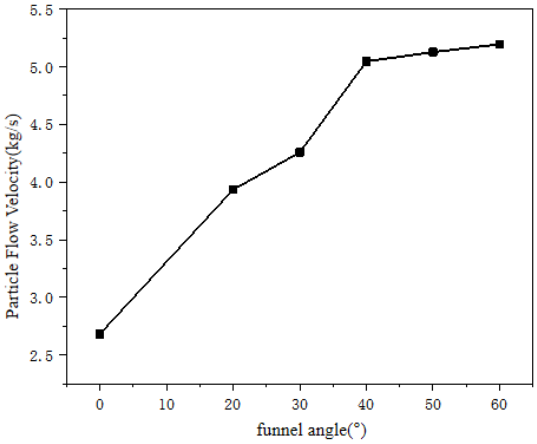


Fig. 5 - Comparison of discharge rate

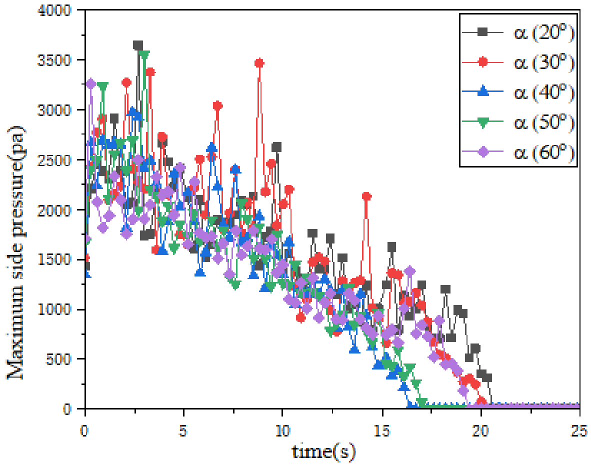


Fig. 6 - Maximum pressure of curved funnels with different shrinkage rates

From the analysis, it can be seen that the lateral pressure of the silo wall during unloading reaches the maximum value at the initial stage of unloading, and then shows an oscillating pattern of gradual decrease. It can be seen that the curved funnel plays the role of pressure reduction in the unloading process of the silo, and there is a difference in the degree of influence of different shrinkage of the curved funnel on the unloading of the silo. Among them, the unloading pressure of the simulation group with curved funnel shrinkage of 0.125 has the largest reduction, which reaches 27.1%.

Analysis of particle flow in curved funnel silos

In order to facilitate the observation of the changes in the particle flow form during the unloading process, the particle groups were stained hierarchically in the EDEM and divided into yellow and blue color, which was used to identify the particle flow form in the unloading. Figure 7 shows the comparison of the unloading particle flow patterns of the six simulation groups.

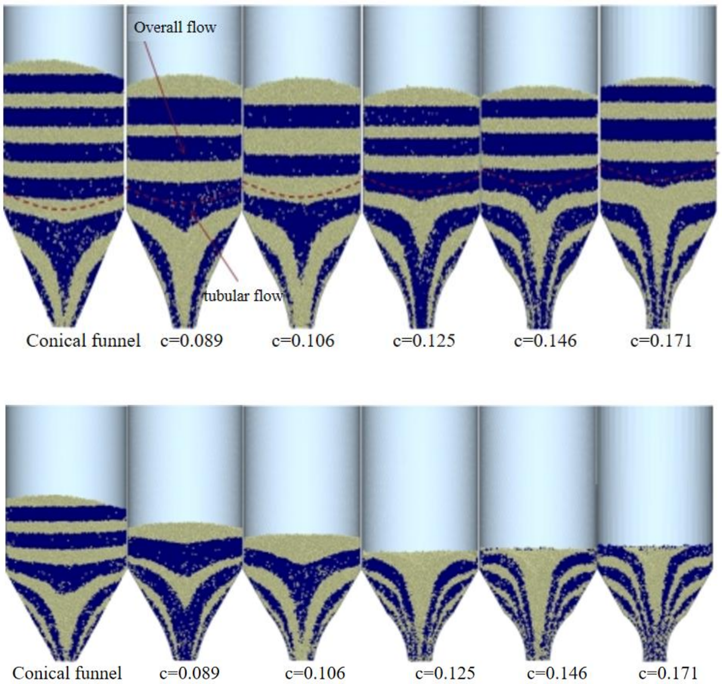


Fig. 7 - Flow pattern of particles from t=6s to t=15s

From the figure, it can be seen that when the shrinkage rate of the curved funnel is small, the critical position of the two forms of flow is low; as the shrinkage rate of the curved funnel increases, the critical position of the overall flow and the tubular flow increases, but the enhancement of the mobility of the particles slows down after the shrinkage rate increases to a certain extent.

Unloading flow rate analysis of curved funnel silos

A silo particle velocity cloud was created to analyze the change in velocity of the particles during unloading, as shown in Figure 8.

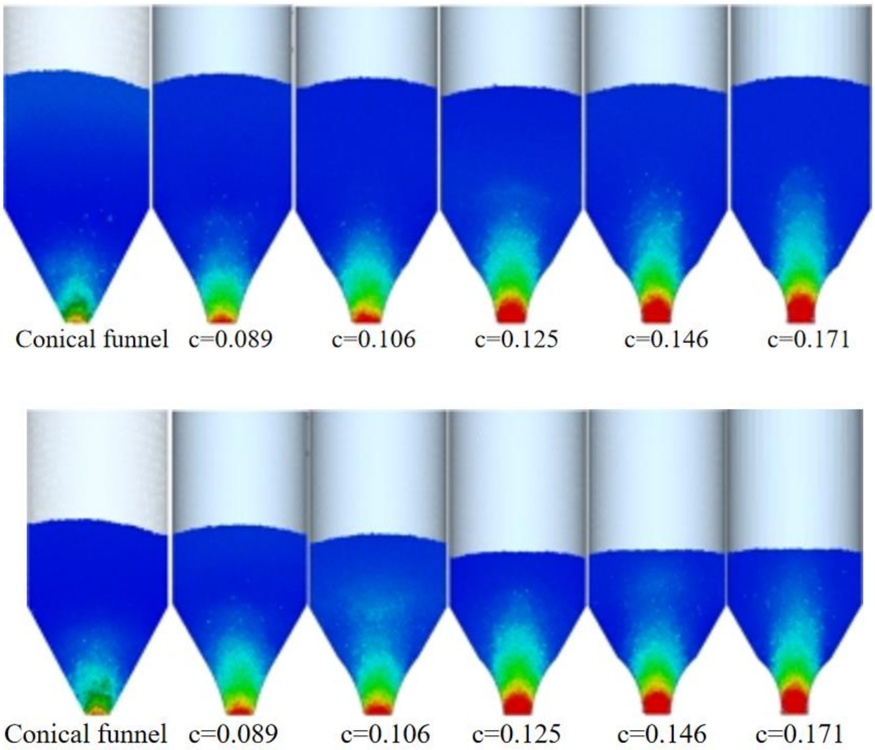


Fig. 8 Particle flow velocity cloud from t=6s to t=12s

The overall unloading process of the silo was investigated by laterally dividing the grid set into 11 regions, and the velocity of particles with different height in silo was collected along silo wall-center-silo wall, and the velocity of particles at each height was analyzed. It was ensured that each layer of the observation window was to contain multiple falling soybean particles, and each of the small grids created was a 20mm40mm rectangular observation window, as shown in Figure 9.

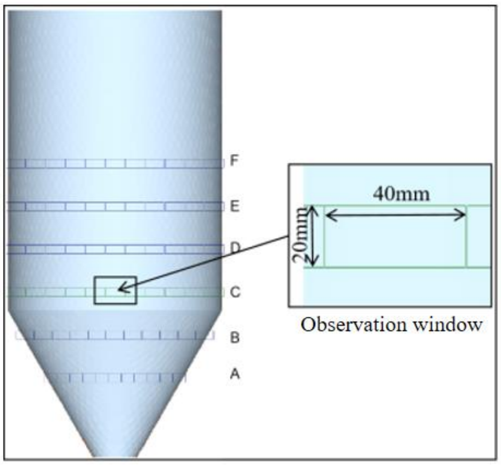
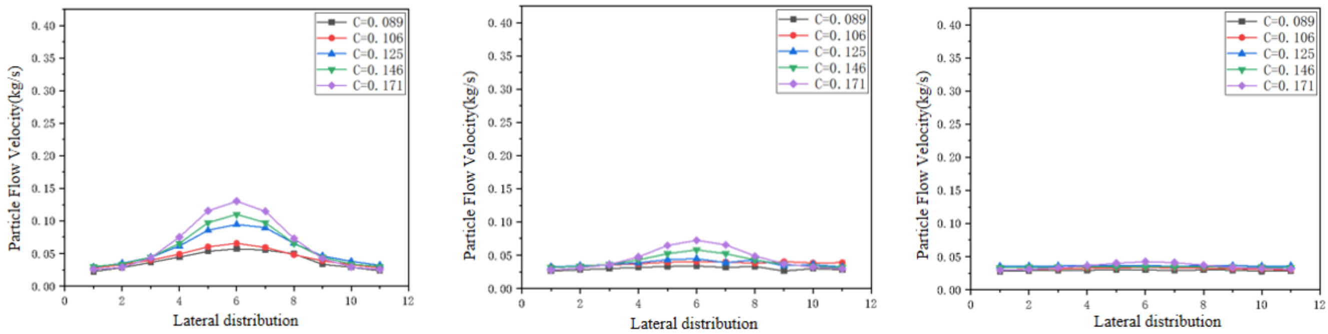


Fig. 9 - Particle flow rate observation window

The results in Figure 10 show that there are two stages in the variation of particle flow velocity with shrinkage: one in which the flow velocity of the particles is large and the difference in the flow velocity of the laterally distributed particles is obvious; and the other in which the flow velocity of the particles is small and the difference in the flow velocity of the laterally distributed particles is very small.



a) b) c)

Fig. 10 - Mean particle flow velocity within regions a to c

The particle flow velocity in the observation window at the center of the lateral distribution was analyzed. As Figure 11 shows the comparison of the flow velocity of the center particles unloaded from silos with different shrinkage rates, it can be seen that the flow velocity of the center particles becomes faster with increasing shrinkage rate, while the flow velocity of the center particles gradually slows down with decreasing depth of the silo.

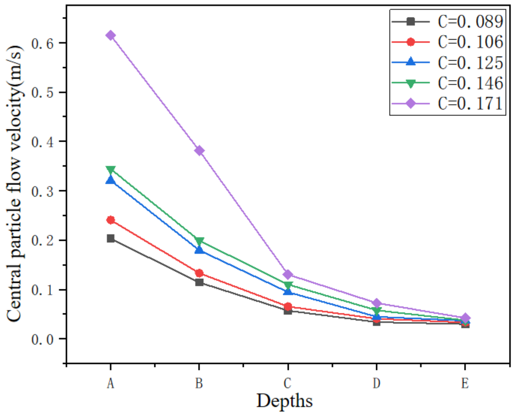


Fig. 11 - Comparison of central particle flow rates for different shrinkage rates

Simulation of unloading from curved funnel with different heights

When only a part of the hopper is curved, the dynamic lateral pressure of the silo wall, particle flow pattern and velocity change law are simulated by changing the shrinkage rate of the curved funnel, and the velocity of particles in the hopper is faster. Further study is made to change the height of the curved funnel in the discharge funnel to study the change rule of simulated silo discharge. The test model is divided into six variables, namely H (100mm), H (150), H (200mm), H (250mm), H (300mm), H (350mm), as shown in Fig.12.

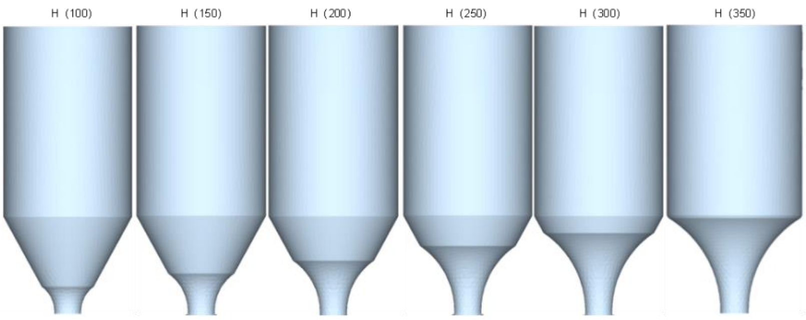


Fig. 12 - Unloading simulation test model

Effect of height of curved funnel on discharge pressure

The simulated maximum pressure values for six groups of curved funnel discharge with different heights are shown in Figure 13. When the height of the curved funnel is 100 mm, the maximum discharge pressure P of the silo is 3.56 kPa, which is a decrease of 11% compared to the maximum pressure value of the conical funnel group; when H=150 mm, the P is 3.33 kPa, which is a decrease of 16.7%; when H=200 mm, the decrease is 18.7%; when H=250 mm, the decrease is 21%; when H=300 mm, the decrease is 29.7% and 22.4% for H=350 mm.

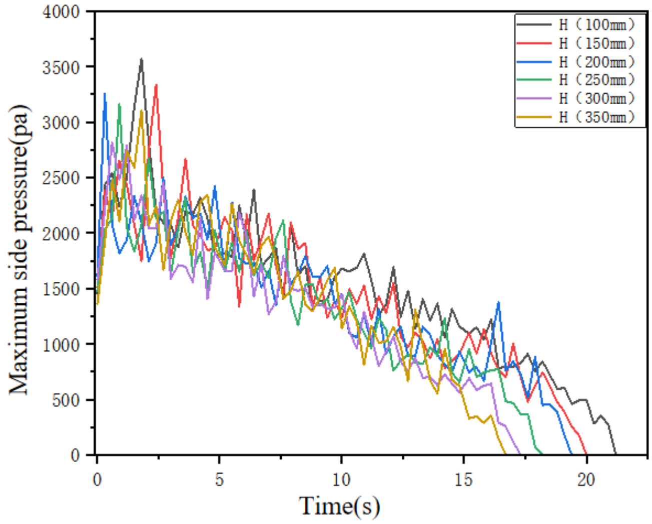


Fig. 13 - Maximum pressure values for different heights of curved funnel discharge simulation

From the above simulation test, it can be seen that the pressure variation law during unloading is similar to the discussed law. The influence of curved funnel with different height on the dynamic side pressure of silo discharging is also different. Among them, the simulation group with the height of 100 mm of curved funnel has the smallest unloading pressure drop, and the simulation group with the height of 300 mm has the largest unloading pressure drop.

Unloading flow analysis of curved funnel silos

The unloading flow pattern was analyzed, as shown in Figure 14, which compares the unloading particle flow pattern of the seven simulation groups.

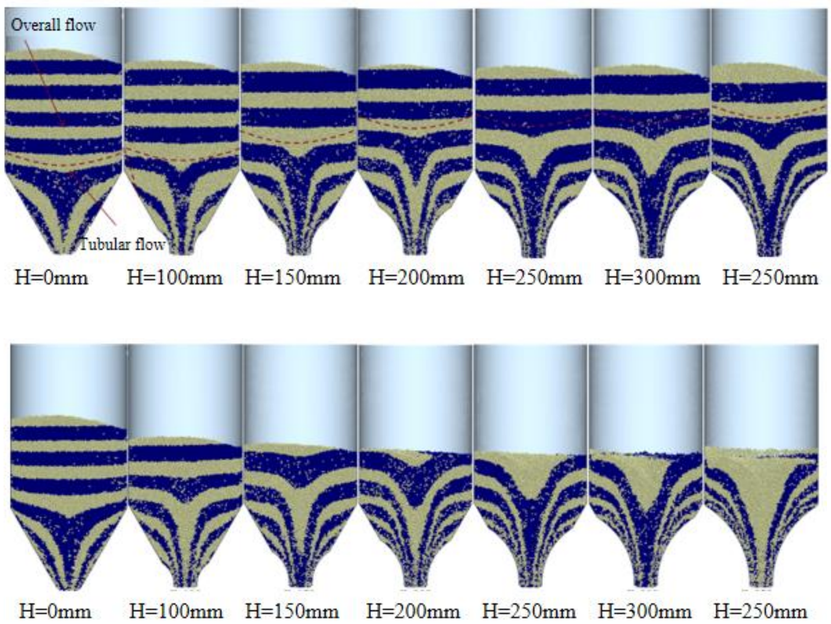


Fig. 14 - Comparison of particle flow regimes in the simulation group from t=6s to t=12s

The above analysis shows that when the height of the curved funnel is small, the critical positions of the two flow forms are low; with the increase of the height of the curved funnel, the critical positions also rise. From the conical funnel H=0 mm simulation group to the H=250 mm simulation group, the critical position of the flow situation in the subsequent simulation group also increased with the increase of the curved funnel height, but the amplitude was not obvious. With the increase of the height of the curved funnel, the flowability of the particles in the silo also increases.

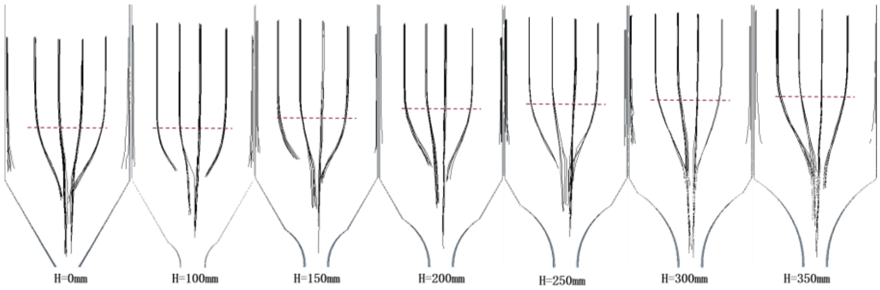


Fig. 15 - Critical positions of the two flow patterns

Unloading flow rate analysis of curved funnel silos

As can be seen from Figure 16, the particle flow rate in the curved funnel silo is larger than that in the conical funnel silo, and distributed along the wall-center-wall of the silo, the particle flow rate follows the law of slow-fast-slow change. The particle flow rate of the simulation group with a curved funnel height of 200 mm is significantly higher than that of the other simulation groups, and the other simulation groups follow the law that the particle flow rate increases with the increase of the curved funnel height.

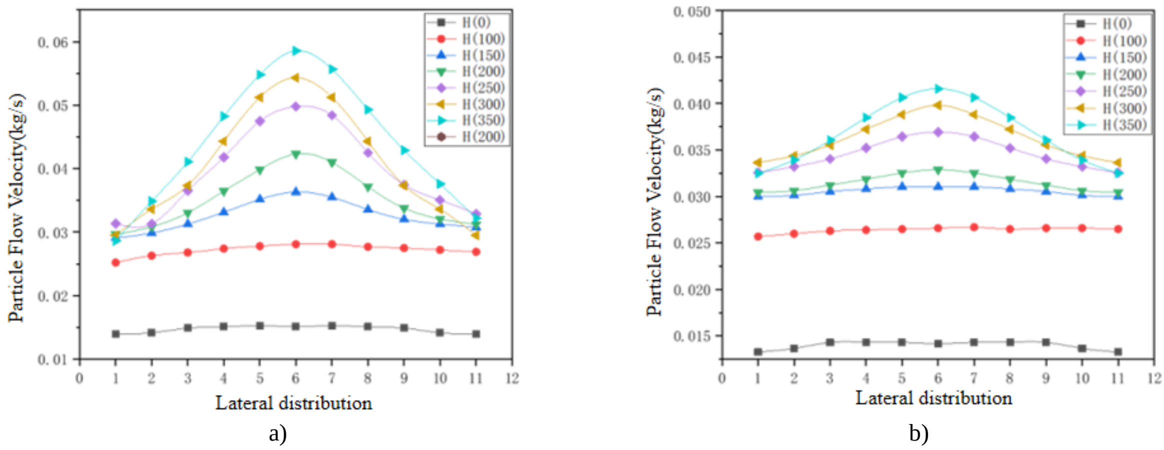


Fig. 16 - Mean particle flow velocity within regions a to b

From the above analysis, as the height of the curved funnel increases, the particle mobility becomes better and the particle flow rate is accelerated, which speeds up the outflow of particles from the top of the silo and reduces the time that the mixed flow situation exists.

Quantitative analysis of particle fluidity

In this paper, a dimensionless parameter, the Froude number, has been chosen as a means of quantitatively analyzing the mobility of particles.

The Froude number is the ratio of the inertial force to the gravitational force of the particles and is specified as follows:

$$F_r = \frac{v}{\sqrt{g \bullet L}} \tag{2}$$

where:

v is the velocity of the particle; v is the gravitational acceleration; L is the characteristic length of the object.

By analyzing the above formulas, Lehmann derived the non-square Froude number for axisymmetric containers as shown below:

$$F_r = \frac{M}{\rho_s \cdot \sqrt{g} \cdot D_r^{2.5}} \tag{3}$$

where:

M is the average discharge rate; ρ_S is the bulk density of the particles; g is the gravitational acceleration; D_r is the diameter of the outlet.

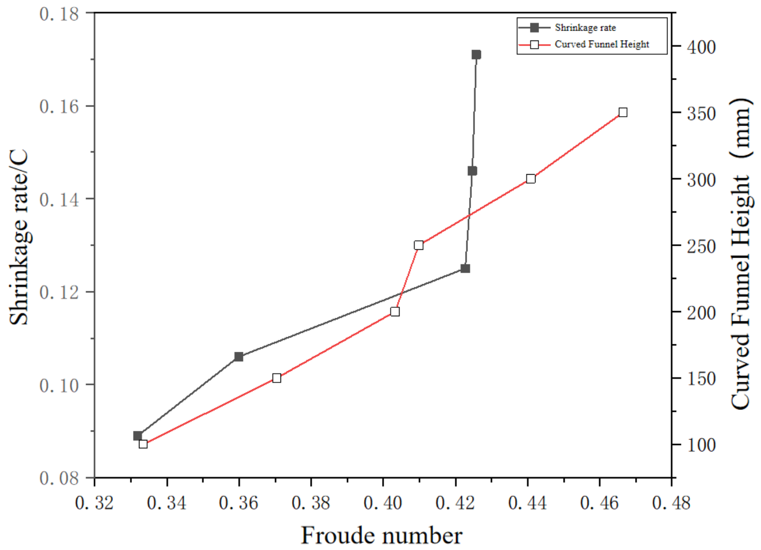


Fig. 17 - Relationship between variables and Froude number

Figure 17 shows the trend of Froude number for shrinkage C=0.089 to 0.171 and the trend of Froude number for height H=100 mm to 350 mm. The results show that the Froude number increases as the shrinkage rate increases and slows down after C=0.125; the Froude number increases as the height of the curved funnel increases and the rise rate increases after H=250 mm.

CONCLUSIONS

In this paper, the unloading of curved funnel silo is simulated. The effects of shrinkage rate and the height of curved funnel on discharge flow pattern and velocity were analyzed, the influence trend of curved funnel on particle flow was quantitatively analyzed, and the influence of the decrease of maximum lateral pressure at C=0.146 compared with that of curved funnel on discharge flow pattern and flow rate was analyzed, and the influence of curved funnel on particle flow capacity was quantitatively analyzed. It was found that different shrinkage rates and heights of curved funnel silos had different reduction of maximum lateral pressure compared with conical funnel silos. However, because the dynamic discharge pressure is affected by the complex flow characteristics of the internal particles, and does not change in a fixed law, the maximum side pressure drop is optimized at H=350 mm. During the simulated unloading process, the flow characteristics of the particles change with the change of shrinkage of the curved funnel. As the shrinkage increases, the critical position of the flow transition of the particle flow rises, the "V" shape of the central particle becomes more obvious, the flow velocity of the particles is accelerated, and the difference of the flow velocity of the particles in the lateral distribution is larger, but the trend of the particle flow velocity rise slows down when the shrinkage increases to a certain level. The flowability of particles changes significantly with the height of the curved funnel.

From the macroscopic level of analysis, with the increase of height, the critical position of the flow shape transformation rises, but with the increase of height to 250 mm later, the trend of the critical position rising slows down, and the end of the mixed flow is advanced; from the microscopic level of analysis, with the increase of height, the flow rate of particles accelerates, and the flow rate of the central particles is significantly larger than that of the surrounding particles. The flowability of the particles was quantitatively analyzed using a dimensionless parameter, the Froude number. The results showed that the Froude number increased with the increase of shrinkage, but slowed down after C=0.125; the Froude number increased with the increase of height, and the rise rate increased after H=250 mm. The flowability of the particles becomes better with the increase of the Froude number, which quantitatively expresses that the curved funnel improves the flowability of the particles.

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REFERENCES

[1] Ayuga F., Guaita M., Aguado P.J., (2001). Discharge and the eccentricity of the hopper influence on the silo wall pressures [J]. *Journal of Engineering Mechanics*, Vol. 127, pp. 1067-1074.
[2] Cundall P.A, Strack O.D.L., (1979). A discrete numerical model for granular assemblies [J]. *Geotechnique*, Vol. 29, pp. 47-65.
[3] Du Mingfang, Zhang Zhao, Zhou Jian., (2004). Numerical simulation of granular flow with silo pressure and its flow pattern（筒仓压力及其流态的颗粒流数值模拟）[J]. *Special Structures*, Vol. 04, pp. 39-41.
[4] GB 50322-2011 *Design specification for steel plate silos for grain* [J].
[5] Jenike A.W., (1987). A theory of flow of particulate solids in converging and diverging channels based on a conical yield function [J]. *Powder technology*, 1987, Vol. 50, pp. 229-236.
[6] Johnston T., (2001). Silo Technology-Pressure Measurements During Flow in a 23.4 m Diameter x 66.7 m High Raw Meal Blending Silo at a Cement Plant [J]. *Bulk Solids Handling*, Vol. 21, pp. 149-152.
[7] Matchett A.J., (2007). The shape of the cohesive arch in hoppers and silos-Some theoretical considerations [J]. *Powder Technology*, Vol. 171, pp. 133-145.
[8] Mathews J C, Wu W., (2016). Model tests of silo discharge in a geotechnical centrifuge[J]. *Powder Technology*, Vol. 293, pp. 3-14. [J]. *Science, Technology and Engineering*, Vol. 20, pp. 2384-2389.
[9] Mellmann J, Hoffmann T, Fürll C., (2014). Mass flow during unloading of agricultural bulk materials from silos depending on particle form, flow properties and geometry of the discharge opening[J]. *Powder Technology*, Vol. 253, pp. 46-52.
[10] Qu Hengxu, (2012). Analysis of pressure change in the range of decompression cone of cement silo（水泥筒仓减压锥范围内压力变化分析）[J]. *Journal of Jiamusi College of Education*, Vol. 05, pp. 417-418.
[11] Wang Peiyan, (2023). Mechanism study on the influence of typical conical fluid change on silo unloading（典型锥形改流体对筒仓卸料的影响机理研究）[D]. *Henan University of Technology*, Vol. 34, pp.712-719.
[12] Wan J., Wang F., Yang G., (2018). The influence of orifice shape on the flow rate: A DEM and experimental research in 3D hopper granular flows [J]. *Powder Technology*, Vol. 335, pp. 147-155.
[13] Wang Ruiquan, Liu Hongru, Xu Xiaojuan, (2001). Experimental study on grain inlet and outlet of vertical silo with decompression tube（立筒仓减压管进出粮试验研究）[J]. *Grain Circulation Technology*, Vol. 03, pp. 16-17.
[14] Wieckowski Z., (2000). Numerical modeling of silo discharge [M]. *Computing in Civil and Building Engineering*. Vol. 84, pp. 764-771.
[15] Xu, Z.J., Liang, P.F., (2022).Modified lateral pressure formulaof shallow and circular silo considering the elasticities of silo wall and storage materials [J] *Scientific Reports*, Vol. 55, pp.772-781 .
[16] Yuan Fang, Du Qian, Xu Zhijun., (2020). Dynamic lateral pressure of silo sidewall unloading with built-in pressure-reducing tube（内置减压管的筒仓侧壁卸料动态侧压力）[J]. *Science, Technology and Engineering*, Vol. 20, pp. 2384-2389.
[17] Yuan Fang, Jiang Xuejia, Zhang Jian, (2019). Comparative study on discharge pressure of double side-wall unloading silos with different height-to-diameter ratios（高径比不同的双侧壁卸料筒仓卸料压力对比研究）[J]. *Journal of Henan University of Technology (Natural Science Edition)*, 2019, Vol. 40, pp. 108-113.
[18] Zhao Song, (2013). Silo storage pressure analysis and its application（筒仓贮料压力分析及其应用）[D]. *Wuhan University of Technology*, Vol.44, pp.833-841.