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Optimizing Design Parameters for Maximizing Mass Discharge Rates in Silos for Soybeans Using DEM Simulations

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The purpose of this study is to utilize the discrete element method (DEM) in combination with the design of experiment (DOE) approach to determine the appropriate key parameters for optimizing the discharge silo. The researchers employed a full factorial design of the experiment and response surface methodology to establish the mass discharge rate (MDR) of soybeans from the silo. By employing an optimal exact methodology, the study identified suitable values for the discharge angle and outlet width of the hopper that would result in the maximum mass discharge rate. The findings demonstrate the effectiveness of the silo discharge design and provide valuable guidance for designing silos and hoppers.

1. Introduction

Silo and hopper systems play vital roles in the handling and storage of bulk materials. Previous research in hopper discharge behaviour has focused on various aspects of silo design. Jenike (1961) pioneered the investigation of key flow patterns in discharged silos, distinguishing between mass flow and funnel flow. Subsequent studies aimed to uncover the complex flow patterns inherent in silo discharge. These studies can be categorized into three groups: wall pressure analysis, segregation and clogging behaviour, and mass discharge rate (MDR) of granular flow. The first cluster of research focused on wall pressure analysis. Masson and Martinez (2000) explored the impact of wall stress on bulk material flow using distinct element simulation, highlighting the significance of friction and particle contact stiffness. Goda and Ebert (2005) employed the discrete element method (DEM) to study bulk material behavior in three-dimensional pyramid storage silos, revealing mass flow in hopper-bottomed silos and funnel flow in flat-bottomed silos. Gonzalez-Montellano et al. (2012) investigated the distribution of normal wall friction and pressure during silo filling and discharge using DEM, observing linear pressure trends for glass beads and improved behavior for maize. Kobylka and Molenda (2014) examined unsymmetrical pressure distribution in wheat silos caused by non-uniform humidity, eccentric filling, and discharge, proposing a stress ratio representation to guide wall pressure distribution and load distribution. Kobylka et al. (2017) studied stress distribution evolution in wheat silos, detecting low-amplitude pulsations and sudden changes in wall stress during discharge. Grabowski et al. (2021) analyzed cohesionless quasi-static pressure in silos via DEM, illustrating forces and shear localization and emphasizing the influence of sand void ratio and silo wall roughness. The second cluster of research focused on segregation and clogging behaviour. Khatchatourian et al. (2014) used DEM to study soybean movement in mixed-flow dryers, identifying varying seed velocities near silo walls during discharge. Combarros Garcia et al. (2016) investigated segregation in heaps and silos through DEM simulations and empirical experiments, confirming the phenomenon and noting the discharge order of fine and coarse particles. Kwon and Ryu (2020) explored the discharge characteristics of rod-shaped particles, pinpointing high initial filling, narrow hopper outlets, and low slope angles as primary causes of clogging. The third group of studies centered on the MDR of granular flow. Gonzalez-Montellano et al. (2011) validated and experimentally investigated discharge flow in glass bead and maize grain silos using DEM, noting fluctuating MDR with higher values for glass beads. Balevicius et al. (2011) and Unac et al. (2012) employed DEM to study material flow patterns in different silo

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shapes, considering rolling resistance and confirming the applicability of Beverloo's equation. Gonzalez-Montellano et al. (2012) employed DEM to simulate filling and emptying processes in silos, highlighting its potential for studying bulk material behaviour. Zheng et al. (2017) developed a predictive model for MDR in conical hoppers using an elastoplastic model, incorporating outlet velocity factors and complex dependencies of bulk material properties. Huang et al. (2021) aimed to maximize MDR through optimized curved discharge hopper design, achieving a 137.9% increase in MDR through shallow discharge angles and larger hopper heights. Chen et al. (2022) investigated the relationship between MDR and bulk material temperature in silo flow, observing enhanced granular temperature near the outlet correlating with higher average MDR.

Overall, these studies have provided valuable insights into silo and hopper design aspects, including wall pressure effects, segregation and clogging phenomena, and MDR optimization. However, no specific research on the optimal design parameters for discharge in a wedge plane-flow hopper for silos and hoppers was found in the literature review. Hence, this study aimed to explore the relationship between the aperture of the wedge plane flow and the maximum discharge rate of soybeans. The findings have potential implications for industrial processes.

2. The discrete element method

Cundall and Strack (1979) are credited with pioneering the discrete element method (DEM), which involves simulating bulk materials as individual particles. The application of the Hertz-Mindlin contact model specifically to soybeans was incorporated into DEM simulation (2010). The DEM model incorporates elastic and damping elements for both normal and tangential forces. The formula for calculating contact forces in the normal direction (denoted as $\mathrm{F_e}$) is represented by Equation 1.

$$\mathrm{F_e} = \frac{4}{3}\mathrm{E'}(\mathrm{R'})^{\frac{1}{2}}(\delta_\mathrm{e})^{\frac{3}{2}} + \mathrm{C_e}(\delta_\mathrm{e}\mathrm{v}_{\mathrm{r/e}})^{\frac{1}{4}} \tag{1}$$

$$\mathrm{E'} = \left(\frac{1-\mathrm{v_i^2}}{\mathrm{E_i}} + \frac{1-\mathrm{v_j^2}}{\mathrm{E_j}}\right) \tag{2}$$

$$\mathrm{R'} = \frac{\mathrm{r_i r_j}}{\mathrm{r_i + r_j}} \tag{3}$$

Where Equation 2, 3 can be substituted into Equation1, $\mathrm{E'}$ and $\mathrm{R'}$ are the equivalent of Young's modulus and radius. δ_e and $\mathrm{v}_{\mathrm{r/e}}$ are the normal overlap and relative velocity between soya beans; the equation for the normal damping coefficient $\mathrm{C_e}$ is indicated as in Equation 4.

$$\mathrm{C_e} = -2\sqrt{\frac{5}{6}}\,\frac{\ln \mathrm{e}}{\sqrt{\ln^2 \mathrm{e} + \pi^2}}\left(2\mathrm{m}^*\mathrm{E'}\sqrt{\mathrm{R'}}\right)^{\frac{1}{2}} \tag{4}$$

The tangential contact force $\mathrm{F_t}$ consisted of the stiffness component ($\mathrm{F_{k,t}}$) and the damping component ($\mathrm{F_{d,t}}$) as in Equation 5.

$$\mathrm{F_t} = \mathrm{F_{k,t}} + \mathrm{F_{d,t}} = 8\mathrm{G'}\sqrt{\mathrm{R'}\delta_\mathrm{e}\delta_\mathrm{t}} + \mathrm{C_t}\sqrt[4]{\delta_\mathrm{e}\mathrm{v}_{\mathrm{r/t}}} \tag{5}$$

$$\mathrm{G'} = \left(\frac{1}{\frac{2-\mathrm{v_i}}{\mathrm{G_i}} + \frac{2-\mathrm{v_j}}{\mathrm{G_j}}}\right) \tag{6}$$

$$\mathrm{C_t} = -2\sqrt{\frac{5}{6}}\,\frac{\ln \mathrm{e}}{\sqrt{\ln^2 \mathrm{e} + \pi^2}}\left(8\mathrm{m}^*\mathrm{G'}\sqrt{\mathrm{R'}}\right)^{\frac{1}{2}} \tag{7}$$

Where Equation 6, 7 can be substituted into Equation 5, $\mathrm{G'}$ is the equivalent shear modulus, and $\mathrm{C_t}$ is the tangential damping coefficient; i and j represent two soya beans. The dynamic friction in DEM simulation was then formulated by the torque on the contact surface as illustrated in Equation 8.

$$\mathrm{T_i} = \mu_\mathrm{r}\mathrm{F_e}\mathrm{R_i}\omega_\mathrm{i} \tag{8}$$

The μ_r is the rolling friction coefficient between two contacting particles, ω is the relative angular velocity of the soya beans.

3. Materials

Figure 1(a) and (b) illustrate the geometric characteristics of the soybean, as explained by Boac et al. (2010). To construct the DEM model for soybeans, EDEM software from DEM Solutions Ltd. in Edinburgh, UK was utilized to generate a single sphere. The dimensions of the silo and hopper for the experimental designs were determined through the application of CAD software and can be observed in Figure 1(c). Furthermore, Figure 1(d) visually represents the actual silo and hopper model. The material properties of the DEM model are illustrated in Table 1 based on the references to material parameter properties (Boac et al., 2010).

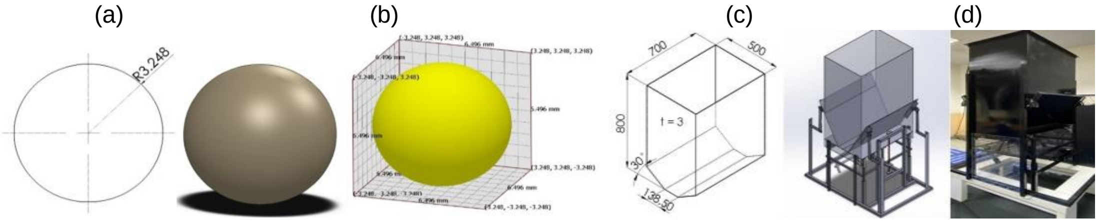

Figure 1: Soya grain model for DEM. (a) Soya grain dimensions, the diameter of single soya grain is 6.496 mm. (b) Soya grain DEM model. (c) The dimension of the experimental silo and 3D model of laboratorial silo (d) The actual laboratorial silo.

Table 1: DEM micro material properties of Soya grain and steel plate from literatures

Material type	Parameters	Values
Material Properties		
Soya grains	Poisson's ratio	0.25
	Solid density (kg.m-3)	1228
	Elastic modulus (GPa)	1.04
Steel	Poisson's ratio	0.3
	Solid density (kg.m-3)	7800
	Elastic modulus (GPa)	198
Interaction parameters		
Coefficient of static friction	Soya grain-Soya grain	0.45
	Soya grain-Steel	0.30
Coefficient of dynamic friction	Soya grain-Soya grain	0.05
	Soya grain-Steel	0.05
Coefficient of restitution	Soya grain-Soya grain	0.60
	Soya grain-Steel	0.60

4. Methodology

The methodology consisted of identifying the main parameters that affected the MDR rate, full factorial screening efficient parameters through DEM simulation, designing the experiment through the response surface methodology (RSM), creating MDR through a quadratic equation model, and searching the optimal factors that were influenced the maximum MDR rate. The process could be illustrated in Figure 2(a).

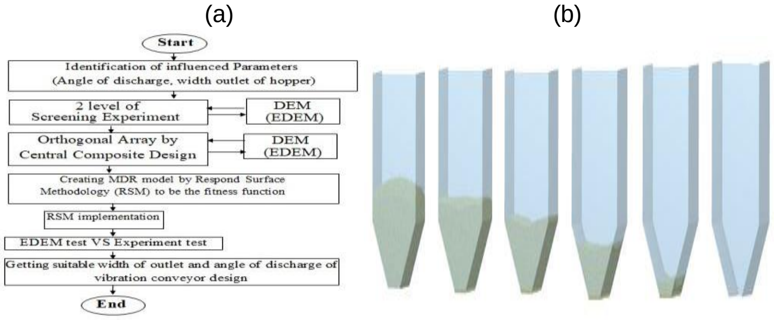

Figure 2: (a) Flow chart of research methodology. (b) The DEM simulation procedure encompassed the entire process, starting from the filling stage and continuing until the completion of the discharge stage.

For DEM simulated condition as shown in Figure 2(b), the time step for DEM simulation is 1.5 µs, the filling time is 10 s, the total filling mass is 100 kg, and the discharge time is 10 s. The main design variables chosen for investigation, as outlined in the research conducted by Lu et al. (2022), involve the angle of discharge and the dimensions of the hopper outlet. The ranges of appropriate parameters namely angle of discharge (A) and width outlet of hopper (B) for the discharge silo were determined by selecting low and high levels, as indicated in Table 2.

Table 2: Parameters and levels for the discharged silo design.

Screening Experiment (Unit)	**Symbol**	**Level**	
		Low	**High**
1. angle of discharge (°)	A	30	60
2. width outlet of hopper (mm)	B	80	138.5

The factor screening process was employed to evaluate both main and interaction effects. The 2-factor of the full factorial method with two levels was illustrated in Table 3. All the design experiments then created parameter processes in EDEM simulation to investigate the maximum MDR. The MDR results were then considered for suggesting influent factors through analysis of the significance of factors.

Table 3: Full factorial screening experiments through EDEM simulation software.

No.	**Factors**		**MDR (kg/s)**
	A	**B**	
1	30	138.5	50.02
2	60	138.5	73.35
3	30	80.0	19.23
4	60	80.0	29.21

Once the screening process was completed, the influential factors were selected and utilized in the response surface method (RSM) through the application of Factorial Cub Central (FCC, α = 1) for the design of the experiment. Subsequently, the RSM was employed to design and execute the simulated experiments. Before constructing the quadratic model for the mass discharge rate (MDR), a designed array was established through the RSM, and the MDR outcomes obtained from the EDEM software were recorded in Table 4.

Table 4: Design and results of RSM design experiments.

Run Order	**Factors**		**MDR (kg/s)**
	A	**B**	
1	60	80.00	29.21
2	30	138.50	50.02
3	45	109.25	41.23
4	45	109.25	41.23
5	30	80.00	19.23
6	45	109.25	41.23
7	45	138.50	61.40
8	45	109.25	41.23
9	45	80.00	23.36
10	30	109.25	24.07
11	60	138.50	73.35
12	45	109.25	41.23
13	60	109.25	49.79

After creating RSM experiments, the fitness equation had to be provided based on the MDR results from the DEM simulation as illustrated in Equation 9.

$$\mathrm{M} = \mathrm{k}_0 + \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{k}_\mathrm{i}\mathrm{X}_\mathrm{i} + \sum_{\mathrm{i}<\mathrm{j}}^{\mathrm{m}} \mathrm{k}_{\mathrm{ij}}\mathrm{X}_\mathrm{i}\mathrm{X}_\mathrm{j} + \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{k}_{\mathrm{ii}}\mathrm{X}_\mathrm{i}^2 \tag{9}$$

Where M is the MDR output, k is the constant value, m is the number of design variables, k_i are the linear coefficients, X_i are the independent factors, k_{ij} are the coefficients of the cross-product value, and k_{ii} are the coefficients of quadratic values. The fitness function was obtained through RSM methodology; the MDR model was employed to find the suitable parameters based on DEM simulation tests as shown in Equation10, 11 respectively.

$$\text{Find } \mathrm{X} = [\mathrm{A}, \mathrm{B}] \tag{10}$$

$$\text{Maximum} \quad \mathrm{M}(\mathrm{X}) \tag{11}$$

$$\text{Subject to: } 30 \leq \mathrm{A} \leq 60\ (°), 80 \leq \mathrm{B} \leq 138.5\ (\mathrm{mm})$$

Other material parameters were used from Table 1.

5. Results and Discussion

In the screening procedure, the DEM input parameters (low and high levels) were set in Table 2. The full factorial method was created for the MDR output simulation as 4 EDEM conditions as indicated in Table 3 by setting an actual operating time for 20 s. The MDR outputs from the DEM simulation were considered as the dependent response whereby the MDR output values had a range from 19.23 kg/s to 72.35 kg/s as indicated in Table 3. Table 5 indicated the comprehensive results from the full factorial design. The total percentage that was contributed from angle of discharge (A) and width outlet of hopper (B) is more than 95%.

Table 5: DEM parameters from the full factorial design of experiment according to their order of the contribution percentage.

Symbol	Effect	Mean Square	% Contribution	Contribution Order
A	16.6	277.3	16	2
B	37.5	1403.87	81	1

The quadratic model for the mass discharge rate (MDR) was developed using the response surface methodology (RSM), as presented in Table 4. To validate and generate the predicted MDR model for the discharge silo simulation, an analysis of variance (ANOVA) was performed. The ANOVA process involved a backward elimination approach, and the relevant parameters such as "df" (degree of freedom), "Adj SS" (adjusted sum of squares), "Adj Ms" (adjusted mean square), "F-Value" (ratio of variation between sample means and variation within the samples), and "P-Value" (probability indicating significance) were considered. Table 6 displays the results of the ANOVA analysis, indicating that the P-Value of the two main effects and their interaction term were all less than 0.05, except for the interaction term which was equal to 0.05. This implies that the angles of discharge and outlet width of the hopper have a significant interaction effect on achieving the maximum mass discharge rate for soybeans. Furthermore, the response surface methodology was utilized to create a polynomial equation, represented by Equation 12, to optimize the mass discharge rate by considering angle of discharge (A) and width outlet of hopper (B).

$$\mathrm{M\ (kg/s)} = -21.152 - (0.176 \times \mathrm{A}) + (0.301 \times \mathrm{B}) + (0.0076 \times \mathrm{A} \times \mathrm{B}) \qquad (12)$$

Table 6: ANOVA table for the MDR output (after backward elimination).

Source	df	Adj SS	Adj MS	F-Value	P-Value
Model	3	2752.8	917.6	104.6	0.00
Linear	2	2708.2	1354.1	154.4	0.00
A	1	580.6	580.6	66.2	0.00
B	1	2127.6	2127.6	242.6	0.00
Interaction	1	44.6	44.6	5.1	0.05
A*B	1	44.6	44.6	5.1	0.05
Error	9	78.9	8.8		
Lack-of-Fit	5	78.9	15.8		
Pure Error	4	0	0		

Addition: S = 2.96, R-Sq = 97.21%, R-Sq (adjust) = 96.28%.

Substituting Equation12 into Equation11 to be a fitness function, the angles of discharge and outlet width of the hopper were obtained as the optimal values. Thus, the optimal value of the discharge angle was provided at 60° and the outlet width of the hopper was 138.5 mm given the maximum mass discharge rate of soybeans at 73.35 kg/s based on a DEM simulation result with the actual performing times of 20 s. The empirical tests of the discharged rate of soybeans based on the optimal parameters of 20 tests provided the average MDR output at 73.66 kg/s. Moreover, the mass discharge rate for the mass flow equation according to Marcela et al. (2018) was 81.008 kg/s which was higher than the DEM simulation and experiment tests at 10.44% and 9.97% respectively.

6. Conclusions

This study, utilizing DEM simulation to uncover the key operational factors affecting the discharge silo for soybeans, can be summarized as follows: The investigation employed a combination of the full factorial experimental design, response surface methodology, and optimal exact methodology to identify the primary parameters of the discharge silo through DEM simulation. The disparity in MDR rates between the DEM simulation and experimental testing was found to be only 0.41%. The projected quadratic polynomial equation provided a clear elucidation of the connection between the mass discharge rate and the two influential DEM parameters. Subsequently, the optimal parameters were determined using the quadratic model to accurately predict the mass discharge rate of soybeans. This research has the potential to serve as a structural guide for the design of discharge silos by integrating DEM simulation with experimental design techniques.

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