The 8th TSME International Conference on Mechanical Engineering
12-15 December 2017
Bangkok, Thailand

CST0013

Numerical investigation into the segregation of agricultural seeds during filling and discharge flow in silos

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Abstract. In this study, numerical investigations were carried out on the granular materials discharge from a hopper using the discrete element method (DEM). The DEM was used to investigate the influence of material filling in the silo and discharge process, including dynamic interactions between materials in the silo (filling and discharge), particle size, and friction on the granular materials as well as force distribution. Emphasis was given to the effect of variables related to factors such as particle characteristics, material properties, and geometrical constraints. Traditional methods for silo design take into account some material properties and flow patterns. However, it is not possible to accurately predict dynamic loads in silos with these methods. Consequently, numerical methods have begun to be applied to the design of silos, making it possible to better understand the interaction between each particle and between the particle and wall of silos. For the numerical method, it was necessary to consider additional parameters of the materials such as mechanical properties, physical properties and interaction properties that describe the behaviour of materials usually stored and flowed in silos. The purpose of this work was to provide values for different size ratios and material properties considered for silo design methods. It also aimed to understand the coefficient of static/rolling friction and other possibilities. The basic mechanisms for these effects are discussed in terms of interaction between particle-particle and the particle-wall of a silo, particle size distribution (PSD) and the coefficient of friction and discharge rate.

1. Introduction

Paddy is the main food of most people in Southeast Asia. There are about 30% of the world's paddy fields. [1] Physical properties and mechanical properties of paddy are important for the design of the equipment. Including mathematical analysis to optimize the storage performance. The properties of materials used in mathematical models include bulk density, solid density, shear modulus, Poisson's ratio, the coefficient of restitution, the coefficient of static friction, and coefficient of rolling friction. There are numerous studies on how to test [2] include the size and shape of the sample material.

Hoppers are critical devices that are widely used during the processing and handling of bulk/granular materials. One of the biggest problems with hoppers is the steady flow of particles and discharge flow rates of the particles. This issue is associated with the complex flow patterns of granular materials inside the hopper. Accurate prediction of discharge rate is necessary for dependable design and working of hoppers. Janssen analysis showed that above a certain height, the weight of the particle within a hopper is supported by frictional forces on the walls of the silo. [3]. Thus, the pressure on the bottom of the hopper is independent of fill height. Since the overburden pressure has a significant influence on the discharge rate through the orifice. The segregation of bulk solids is a highly important issue in storage and transportation. The segregation can have a detrimental effect on the quality of a product, especially in the case of food and mixed cereals where strict ratios of the constituents are required. The nature of segregation depends on many factors such as the geometry and the surface properties of the particles, velocity gradients, and boundary conditions [4] illustrates a broad range of possible mechanisms for segregation nicely when filling and when emptying silos of various design. Carson et al.[5] explain that due to differing frictional, different materials will move at different velocities. The product having a higher friction will have a lower velocity. Mosby et al. [6] explains in detail of the heap segregation is often described as one form of segregation where in fact it is a combination of several individual segregation mechanisms interacting with each other. Williams [7] explain the sifting mechanism is one of the most common causes of separation. When particles of different sizes are poured into a silo, the small particles concentrate under the filling point while the large particles roll down the pile to the edges. Small particles also fall through the voids produced by the large particles.

Discrete Element Method (DEM) is becoming an increasingly popular method for simulation analysis and visualisation of the materials flow and impact on other particle or the wall of the geometry. The principle of DEM is to track any time stepping simulation, each particle rotation and trajectory in the geometry to evaluate the position and orientation of the particles and then to calculate the interactions between the particles themselves and also between the particles and their environment. The particle movement in the silo is sliding and rolling that provide to the size distributions [8]. DEM has been used by many authors to study the particle flow properties of silos such as segregation processes [9] flow velocity[10] pressure distribution [10, 11] and flow patterns [9, 10].

This work focuses on simulating particle flow in a conical-shaped silo using the discrete element method (DEM). The particles are modelled as inelastic, frictional, cohesionless spheres. These parameters include silo and hopper shape, the coefficient of friction between particle – wall of the silo and between particle–particle and particle size ratio. This paper presents a study of the application of DEM simulate the material movement in the silo has been used to analyse the segregation of bulk materials flow. The spherical particle shape injected at the top of the silo with the initial location of the two sizes of the particle are mixing already before falling to the silo. This paper also illustrates the DEM simulation of the particle mixing and segregation in the silo with different particle sizes ratio force of particle in silo storage, particle size distribution, coefficient of friction and discharge rate of two sizes of particles, small and large with size ratio 1.0, 1.25, 1.5, 1.75, 2 and 3. Therefore, the DEM method was developed to simulate the mixing and segregation of bulk materials during filling and discharge in the silo with these techniques and details of the modelling are presented in this paper.

2. Discrete Element Method

In recent years, numerical simulation has become one of the most useful techniques for modelling particle flows. The DEM method has been developed and widely used to study interactions between the particles and their environment. Particles flow have been described in many references [12-14]. The motion of each particle is based on rotational and translating motions according to Newton's second law. The equations are as follows.

$$m_i \frac{dv_i}{dt} = \sum(F_{ij}^n + F_{ij}^s + m_i g) \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_j (R_i \times F_{ij}^s - \mu_r R_i \left|F_{ij}^n\right| \widehat{\omega_i}) \tag{2}$$

where m_i, I_i , v_i and ω_i are the mass, the moment of inertia, translational velocities and rotational velocities of particle i , respectively. F_{ij}^n, F_{ij}^s and $m_i g$ represent the normal contact force, the tangential contact force imposed on particle i by particle j and gravitational force, respectively. R_i represents a vector from the centre of particle to contact surface, μ_r represents the coefficient of rolling friction and $\widehat{\omega}_i$ is a unit vector equal to ω_i divided by its magnitude. The contact force model between the particles and particle-wall are based on a spring-dashpot model, which is proposed by Cundall and Strack [15].

The complex model was developed by Hertz-Mindlin model. Hertz [16] proposed the normal contact force between two particles include the normal force and normal displace in the normal direction and Mindlin and Deresiewicz [17] proposed a generally tangential force model. Hertz-Mindlin no-slip model and frictional slider in the tangential direction for the particle-particle and particle-wall contacts [18]. The magnitude of the normal force between two particles is given as [13]:

$$F^n = -k_n \Delta x + C_n v_n \quad (3)$$

The magnitude of the tangential force is given as:

$$F^t = \min[\mu F^n, k_t \int v_t dt + C_t v_t] \quad (4)$$

where k_n and k_t are the normal stiffness and tangential stiffness respectively, Δx is the particle overlap, v_n and v_t are relative normal velocity and relative tangential velocity respectively, C_n and C_t are the normal damping coefficient and tangential damping coefficient respectively, C_n depends on the coefficient of restitution, e defined as the ratio of the normal component of the relative velocity after and before the collision.

$$C_n = -2\ln(e)\frac{\sqrt{m_{ij}k_n}}{\sqrt{\pi^2 + ln^2(e)}} \quad (5)$$

$$m_{ij} = \frac{m_i m_j}{m_i + m_j} \quad (6)$$

where m_{ij} is the reduced mass of two particles i and particles j. In addition, the DEM simulations investigate the particle contact force, particle velocity occurring when material motions and impacts in the silo tester. The interaction of particle contact effect from the coefficient of static/rolling friction between particle-particle and between particle-wall will be considered. The interaction force between particle-particle and particle-wall are analysed to understand their influence in terms of typical flow features in silo under different particle size ratio are considered in the bin section, hopper section and axial directions.

3 Initial and Boundary Condition

The geometry of the conical-shape silo and type of particles used in this simulations are described in this section. To produce accurate DEM simulations the physical properties of the materials (paddy) and the silos (steel) have been used to aid in the determination of the interaction properties, as shown in Table. 1. The processes used for many of these tests have been reported previously [19], including the particle shape and particle size of the particle model used in the DEM simulations. Subsequently, in the DEM simulations, the particles were set with a fixed spherical particle size.

The calculation of the required number of particles was based on 80% by volume of the conical silo samples tested (Table 1). A simplification was made in the calculation of the number of particles required, that being there was no accounting for the void space that would exist between the particles. The simulation configurations are built to the conical shape of the silo (50L) with the volume of particle 40L.

3.1 DEM Model Parameters

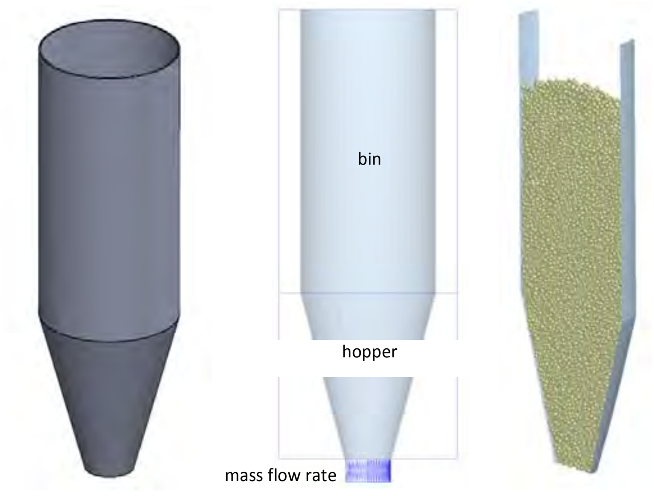
A model particle is a spherical shape, rigid property, and no liquid bridge between each particle was used in this study. However, this study is to investigate effects of the mixing and segregation of the two different particle size movement in the silo which two states; filling and discharge. Thus, the particles of a simple model were used based on the similarities between the various sizes of mixing and segregation. Table 1 lists the parameters of the model particles and interaction between particle contact and environment. The particle density corresponds to that of regular paddy. The other parameters in the contact model were determined according to a previous study [19]. At this stage, it was not possible to simulate the actual number of particles in the silo within a reasonable computing time due to the limitation of the computer. For example, larger spherical particles should be used in the DEM simulation, resulting in the smaller number of particles and the reasonable computing time. To determine the optimal particle size, the effect of particle size on the particle motion was investigated. The particle movement in the conical-shape silo was simulated with various particle size ratio as shown in Table 2. The coefficient of static friction μ_s was adjusted to keep the ratio μ_r constant, while the other parameters were the same as shown in Table 1. The number of particles in each simulation was determined to keep the particle filling volume constant. In all cases, the simulation was carried out under the constant gravity of the particle falling.

Table 1 Properties of paddy, stainless steel

Properties	steel	particle
Particle density (kg/m^3), (ρ_s)	8000	1200
Loose-poured bulk density (kg/m^3), (ρ_b)	-	-
Poisson's ratio (ν)	0.4	0.4
Shear modulus (Pa), (G)	7.7x10^{10}	1x10^8
Particle coefficient of restitution, (e)	0.5	0.5
Particle coefficient of static friction, (μ_s)	0.6	0.6
Particle coefficient of rolling friction, (μ_r)	0.1	0.1

3.2 Geometry and systems

The geometry shows a three-dimensional representation of the conical-shape silos was used in this simulation work, as presented in Figure 1(a). The conical silo consists of a bin cylindrical is the 300 mm diameter, and 630mm high whereas the hopper is 370mm high, 15° angles of a hopper, 100 mm diameter of the outlet at the bottom of the silo (Figure 1b) and the number of mesh cell is 239,900. A 3D model was created using a computer-aided design (CAD) software. The three-dimensional CAD drawing was imported into the EDEM to take into account its complex geometries accurately. Figure 1c shows the thin slice of a large at the middle of the conical cross-section silo for presented. The silos of vessel sizes (50L) were used in the DEM simulation. These dimensions completely satisfied the geometric similarity.



(a) (b) (c)

Figure. 1 Schematic of the conical silo domain that model (a) full conical-shape silo, (b) 3 sections of silo and (c) thin slice of a large at the middle of the conical cross-sectioned silo

3.3 DEM Particle Shape Generation

The particle shape and size of paddy were more dimensions hard to determine by measurement of the materials. The simulated mass of the particle model was matched with the experimental data for the mass of material, bulk density and angle of repose [15]. Subsequently, particle models in the DEM simulations were set with a fixed size and shape. All particles were generated from an injection plane and allowed to fall due to gravity alone to the bottom of the silo in 5 sec. The particle size and particle shape of the paddy model, material properties and interaction between particle-particle and between particle-wall selected for simulation by DEM software are shown in Table. 1. The base particle shape used in the current DEM simulations is spherical with the principal dimensions, d = 9.00 mm. A total of six simulations are performed for a mono-dispersed system using five different size ratios of loading. Table 2 summarises the dimensions and number of particles required for the five small particle sizes used in the simulations. A series of simulations were devised to investigate the effect of variation in particle size, keeping the massive particle, P1, the same for all simulations and varying the size of the small particle for each simulation completed. P2 to P6 are arbitrarily sized particles to generate increasing ratios of large to small particles. It should also be noted that for both the large and small particles (50:50 % by volume) used in these DEM simulations, a mono-sized particle generation was used in the setup of the simulations, based on the upper side of each size distribution [20]. This was applied in the interests of minimising simulation time and should still provide adequate simulation results to show trends based on variation in particle size. The calculation of the required number of particles was fill levels at 80% of the silo volume, also shown in Table 2. A simplification was made in the calculation of the number of particles required, that being there was no accounting for the void space that would exist between the particles, which has led to a slight overprediction of the number of small and large particles required.

Table 2 Dimensions of simulated particles and the number of particles required for the DEM simulations

Particle	d (mm)	Large to Small Particle Size Ratio	Number of Particles Large / small
P1	9.00	-	60000 / 0
P2	7.20	P1/P2 = 1.25	30000 / 56,000
P3	6.00	P1/P3 = 1.50	30000 / 99,000
P4	5.14	P1/P4 = 1.75	30000 / 155,000
P5	4.50	P1/P5 = 2.00	30000 / 240,000
P6	3.90	P1/P6 = 2.50	30000 / 840,000

Paddy materials were chosen as the test material for investigation of the flow mechanisms of the particles within conical-shape silos. The coefficient of friction was a selection of the materials test because the purpose of the investigation was to visualise the particles flow in the silos tester, to measure the flow pattern, discharge rate generated as a result of the simulation. This is also vital for the DEM simulations replicating the tests. The conical-shaped silo requires same operating conditions to follow of particles. This condition will be presented in this study without air effect around the silo tester.

3.4 DEM Simulation Conditions

The DEM simulations were performed using an HP Z240 workstation, with 16 GB RAM and four processor cores. The total simulation run time for a 16 sec simulation varied between 6 and 18 hours, depending on the combination of particle sizes simulated. Material flow in the silos was investigated via DEM simulation using the same six different parameters of the coefficient of static friction as described for the simulation and also for a range of different particle sizes. The simulated material was randomly generated by allowing the particles to fall under gravity, with no initial velocity from an injected plane, the particle forming a natural heap inside the silo. The initial homogeneous mixture of the large and small particles is achieved by the particles being randomly generated via the injection plane. After the formation of the heap was complete, the gate at the bottom of silo will be open for a total of 11 seconds in all simulated cases.

4. Results and Discussion

4.1 Simulation of Filling and Discharge

Different DEM models were performed to describe the movement of particles in a silo at the filling and discharge states. The first step of the simulation process comprised particle filling into the silo, which were generated randomly with two sizes of particles. The virtual factory plate was mixed completely before falling to the bottom of the silo. The particles generated were allowed to fall under gravity until the silo was full. The level of the particles in the silo was 40L (number of particles is shown in Table 2). During the filling process, the outlet of the silo was closed. Filling was deemed to be complete when all particles were static, and the state was identified by the value of the kinetic energy of the entire system being negligible. The next step involved particle discharge from the silo. When the particles reached a static state, the plate blocking the outlet of the hopper was removed so that the particles could begin to discharge. The discharge simulation continued until all particles had exited the silo. Figure 2 illustrates the particles position and particle velocity at 6-time steps (t=1, 2.5, 5.0, 7.5 10 and 15 sec), with the particles filling and being discharged from the conical-shaped silo.

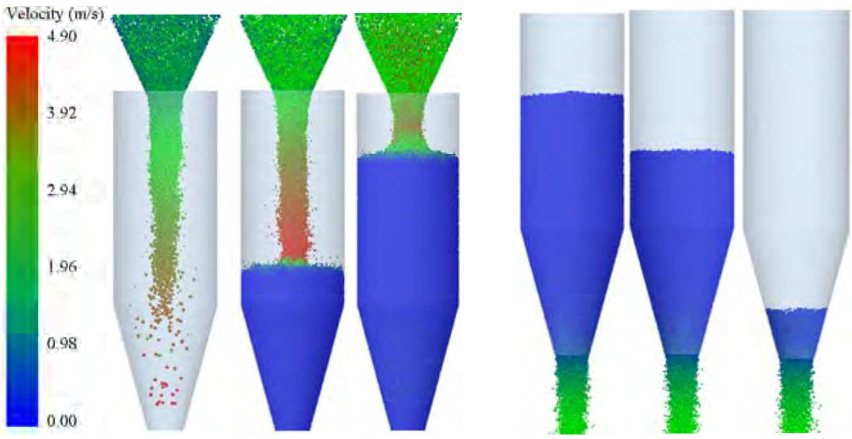


Figure 2. Simulation of filling process at (a) 1sec, (b) 2.5sec (c) 5sec and discharge process at (d) 7.5sec, (e) 10sec and (f) 15sec.

4.2 Segregation

The effect of particle size ratio on the influence of particle separation during filling in a silo was investigated. It was found that smaller particles tended to move to the centre of the silo, while large particles rolled and collected near the silo wall. If flow does not occur along the silo wall during discharge, small particles discharge first and the large particles last. The DEM simulation investigated the segregation of particles and the combination of particle sizes detailed in Table 2. The percentage of each size particle in each simulation of the silo was determined via post-processing. This analysis was performed for the entire simulation to graph the movement of particles throughout the silos based on the initial different size ratio loading condition in the silo. Figure 3 shows simulation snapshots of an equal volume fraction binary mixture capturing the progression of the mixture from an initial mixed state, just before the commencement of discharge. The particles in Figure 3 are coloured by diameter, with the large particles being yellow and the small particles being red. For the simulation proceeds, the small red particles move through the voids of larger counterparts and arrange into a highly-ordered packed structure at the bottom, as indicated by the final snapshots for all cases. However, the addition of a size ratio degree for particles in the silo causes this band of red particles to not only diminish in height with the gradual appearance of the major yellow particles lower in the bed, but the uniformity and order also decrease since the size disparity disrupts the structured packing, as seen in the corresponding cases (Figure 3d and e). Although the difference in the order of packing for the small particles is not as apparent between Figure 3(d and e), there is a major difference between the final state of a mixture with the fixed distribution of sizes (Figure 3a) and the two cases with high particle size ratio (Figure 3d and e). This suggests that adding a slight distribution in size aids the flow of all particles, which can be seen by the appearance of larger particles toward the bottom.

4.3 Total force of particle in silos storage.

The effect of particle size ratio on the influence of particle force distribution within the silo during storage was investigated by DEM simulation. The simulation shows that total force is occurring on each particle size ratio. A lot of small particle movement is apparent to the voids between large particles. When the ratio of particle size increases, the result is a dramatic decrease in the total force acting on the system, especially in the middle section of the silo, as shown in Figure 4. This distribution shows an ever-decreasing trend with increased particle size ratio, reaching a maximum at the hopper outlet and with no peak at the silo wall/hopper transition. This also explains the greater unexpected pressure values obtained during filling compared to during emptying.

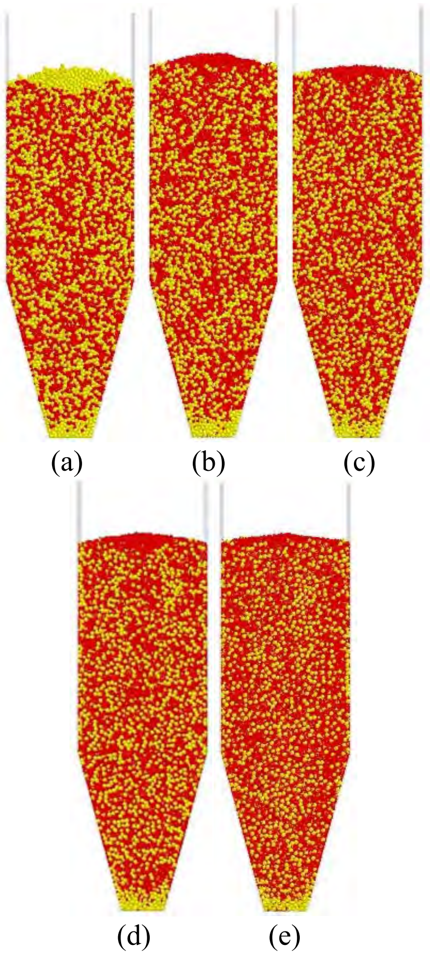


Figure 3. Side view of DEM simulations for binary equal volume mixtures with different size ratios (a) 1.25, (b) 1.5, (c) 1.75, (d) 2.0 and (e) 3.0 at the end of filling (small size = red colour and large size = yellow colour)

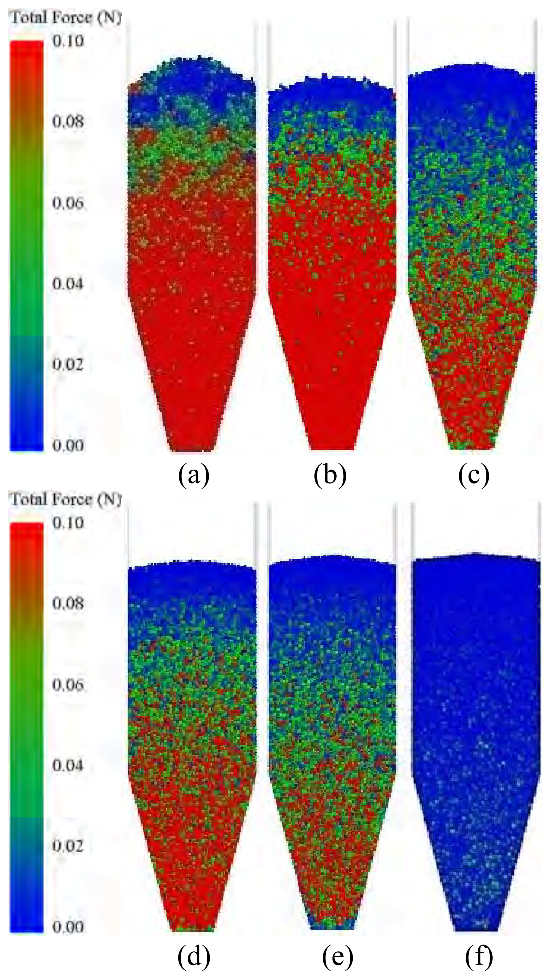
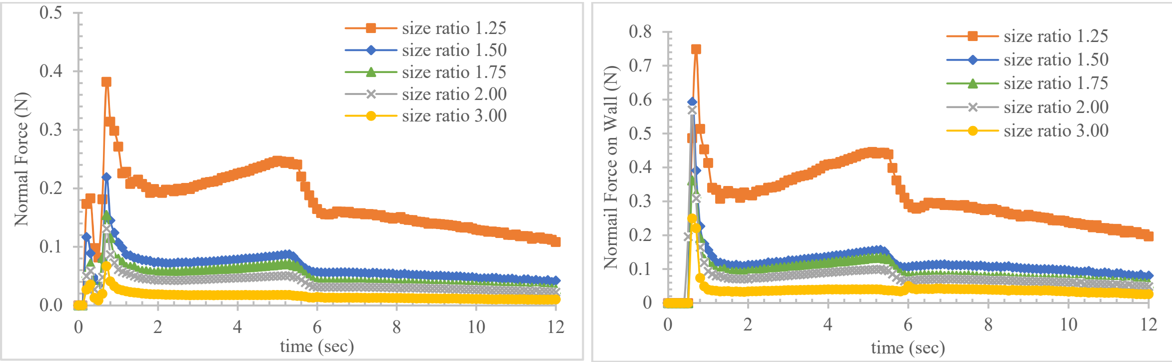


Figure 4. Illustration of the total force at the middle of the silo with different size ratios (a) 1.0 (b) 1.25, (c) 1.5, (d) 1.75, (e) 2.0 and (f) 3.0 at storage time

The normal force distribution is predicted in a silo (Figure 5a) with different particle size ratios. However, particle size ratio increase was observed to decrease the force in the silo, and its behaviour was very similar compared with various size ratios. During filling of the particles in the silo, it can be seen that the normal force continuously increases until the end of the particle filling. In the vertical section of the silo, normal force values are lower than for the particles on the wall. In the transition zone, particles are rearranged with the smallest particles moving into the spaces between larger particles. Normal force decreases until the particles stop moving. Further down in the final process of particle discharge, it can be seen that normal force gradually decreases until the silo is empty.

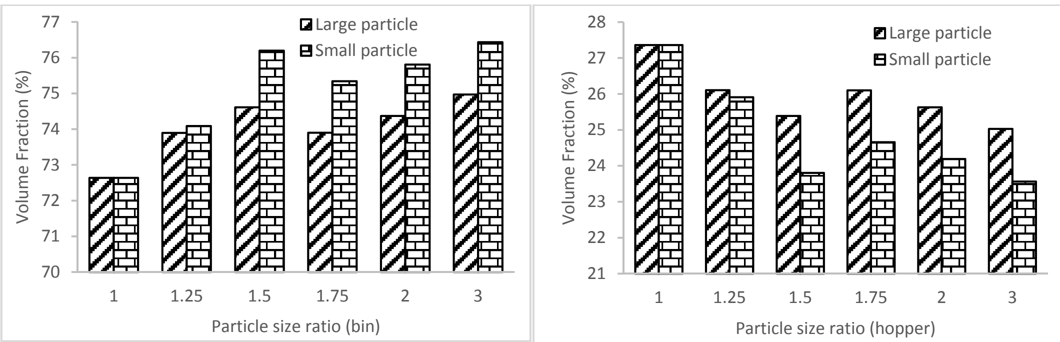


(a) (b)

Figure 5. Illustration of normal force in the silo with different size ratios (a) normal force on the particles (b) normal force on the wall

4.4 Particle Size Distribution

DEM simulations were also performed for various values of small volume fraction with the size ratio of the particles, as shown in Table 2. DEM segregation of two sizes of particles is illustrated in Figure 6, comparing different particle size ratios in the range of 1.0 - 3.0 for small particles and large particles in the bin section (Figure 6a) and hopper section (Figure 6b). Though this difference is small, it is consistent. It can be seen that the combination of particle size ratio increases with volume fraction increase in the bin section and decrease in the hopper section.



(a) (b)

Figure 6. Volume fraction in (a) bin section and (b) hopper section

4.5 Particle–particle and particle-wall friction

The coefficient of friction has an important role in determining the hopper discharge rate. In order to determine which type of friction between particle–particle and between particle–wall dominates the discharge rate, each coefficient of friction between each particle was varied from 0.2 to 0.8 and a constant coefficient of rolling friction at 0.1. Figure 7 compares the results for the four cases. It is clear that the coefficient of friction between particle–particle exhibits a much more significant influence on the mass flow rate discharge from a hopper. For the case of large coefficient of friction between particle–particle, the mass flow rate is lower than the value for the low friction of coefficient between particle–particle cases. These results suggest that the coefficient of friction between particle–particle is the primary controlling factor in determining the mass flow rate. Also, the coefficient of friction between particle–particle is expected to have a more significant role in determining the mass flow discharge rate since most of the interactions in a flowing hopper system are between particles.

4.6 Mass Flow Discharge Rate
Based on this simulation, a parametric study was performed to determine which values of the friction coefficients and discharge rate become independent of the various size ratio of the particle fill in a silo. Figure 8 shows the results obtained from the parametric study. In the figures, the particle discharge rate of four particle size ratios is plotted against the time step. Higher particle size ratio shows an increase in the mass discharge rate.

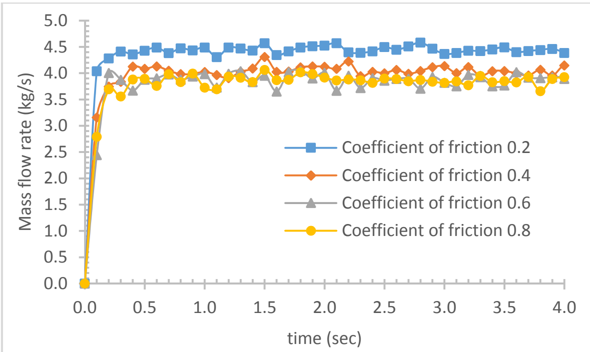


Figure 7. Mass flow rate from the silo plotted against time for a range of coefficients between particle–particle values

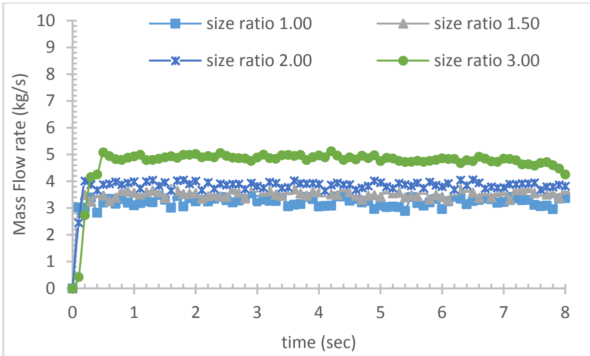


Figure 8. Mass flow discharge rate plotted as a size ratio of particles

5. Conclusion
DEM simulation was carried out to determine the movement behaviour of each particle of material, both entering a silo until full and after discharge of the material from the hopper. It can be seen from the image showing the discharge behaviour of the material from the silo at the outlet by predicting the movement of materials at different particle size ratios. The accuracy of the DEM simulation is based on the accuracy of the modelling variables as well as the sizes and shapes of the model materials. As the testing programme was being performed, mixing and segregation could be seen. The mixing indices used to represent the segregation are present in each test. The particle model and the parameters of paddy, which are validated for a mixed size and coefficient of friction, are suitable for modelling as well as silo discharge. The particle movement behaviour of granular materials draining inside of the silo was studied via a mathematical model using DEM simulation. Marked differences in particle size in the silo affected the mass flow discharge rate of granular materials and force on the silo wall. Segregation mechanisms of the particle movement effects were quite visible. Normal particle force effects decreased as each test progressed. As the variability in size of particles increased, total force was shown to be the highest in the hopper and decreased in the bin.

Acknowledgement
Thank you to the Department of Materials Handling and Logistic Engineering, Faculty of Engineering, King Mongkut's Institute of Technology North Bangkok. This support the area for experiment and software for simulation.

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