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Analysis of Silo Asymmetry Normal Pressures due to Eccentric Discharge using DEM Simulation

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ABSTRACT The eccentric discharge of bulk solids from a silo can lead to asymmetry in the normal pressure distribution around the silo walls. The non-uniformity and eccentricities of the wall loads, which would cause bending stresses in the circumferential direction at various levels, can have serious structural consequences. Understanding how the wall loads are affected by eccentric discharge is an aspect of silo design of major importance. In this study, the wall loads during the eccentric discharge were investigated by performing a range of DEM simulations for a coal silo with two outlets when only one outlet is in operation. Apart from the information regarding the flow patterns developed during discharge and the corresponding normal wall loads that are generated, the simulations enable an appreciation of the transient flow patterns that occur as the stress fields change from 'active' to 'passive' states when flow is initiated. Of particular interest are the distributions of the normal pressures around the periphery of the silo wall at a height defined as the 'critical transition' where the flow down the wall converges as a result of a "hopper type" flow channel forming above the cylinder/hopper transition. The wall loads distribution has been investigated under two situations, namely, with or without localized dead zones due to build-up of bulk solids within the silo. The DEM results indicate that the wall loads on the side furthest from the eccentric discharge location are larger than those on the side nearest the eccentric discharge location, the results being comparable to those derived from AS3774 (1996) and EN 1991-4 (2006). The DEM results also show the significant variation in the wall load distributions which could affect the structural integrity of the silo. The DEM simulations are also used to explore the effects of the particle-wall friction coefficient.

1. INTRODUCTION

Silos are widely used for storage of bulk solids in the mining, chemical and agricultural industries. Many cases of silo failures occur each year, which cause not only loss of contained material but also loss of life in some cases. The reasons for some cases may be attributed to a lack of appreciation at the design stage of the exact nature of the loadings to be encountered, including both the value and variation of loads. The consideration of loads acting on a silo wall is a particularly important aspect of silo design and performance to ensure the integrity of the silo structure. It is clear that the loads are directly related to the flow pattern developed in the silo, which is dependent on material flow properties as well as silo configurations. The eccentric discharge of bulk solids from a silo can lead to asymmetry in the normal pressure distribution around the silo walls. The non-uniformity and eccentricities of the wall loads, causing bending stresses in the circumferential direction at various levels, can have serious structural consequences. Understanding how the wall loads are affected by eccentric discharge is an aspect of silo design of major importance.

The solids-induced silo loads have been studied for over a century by making the use of the widely varying approaches. Various attempts have been made to develop international standards for wall loads where Australian Standard AS 3774 [1] and Eurocode. EN 1991-4 [2] are the most modern and complete silo design codes in use today. While experimental laboratory scale model studies, reported by several authors [3, 10], have been, in the past, instrumental for corroborating silo load theory, logistically such experimental work is not easy to perform. With the advancement of simulation techniques, such as finite element analysis (FEA) and discrete element modelling (DEM), the need for experimental work has diminished. FEA has been a powerful technique used to estimate the pressures in silos. However, FEA method deals with the granular mass as a continuum so that it is unlikely to analyse dynamic behaviour of particulate materials during silo discharge from the point of view of individual particles. Apart from the advantages of DEM as a research tool, it has become increasingly beneficial in solving industrial problems [4, 5]. As is now well established, DEM is described as a numerical method that can be used to simulate the flow of granular bulk solids, with the basic principle being to model each individual particle as a separate entity that can undergo a range of forces as observed in reality. These forces typically include gravity and contact forces with other particles and walls, as well as cohesive and adhesive forces if the bulk solid is cohesive in nature. Calculations for the forces, and resulting displacements, are made for every particle at very small time steps throughout the simulation. As a result, DEM simulations are often computationally intensive.

The storage of bulk solids in large tonnages is often accomplished using multi-outlet silos with either flat or hopper bottoms. Such silos may be subjected to eccentric loadings and/or discharging inducing bending stresses in the walls in addition to hoop tension. In this study, the wall loads in symmetrical filling and discharge for a coal silo with two outlets were simulated for DEM model validation purpose. Then, the normal pressure is investigated by performing a range of DEM simulations for the same silo during eccentric discharge, where only one outlet is in operation. Also studied are the effects of the particle-wall friction factor and the material build-up in a silo on the pressure distribution around silo periphery during eccentric discharge.

2. DEM MODEL

The DEM software Rocky is used to model the wall loads of the silo in this study. This software utilises a hysteresis linear spring model for the normal force interactions and an elastic-frictional force model in the tangential direction. Rolling resistance is implemented according to the type C model described in Ai et al. [6], while adhesive forces between particles and walls and cohesive forces between particles and particles are included through a simple constant force model.

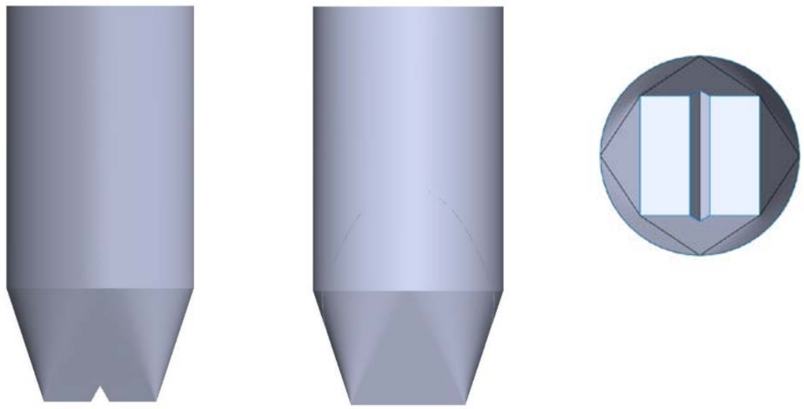
Calibration of DEM parameters is a widely published area, with the work of Coetzee and Lombard [5] and Wensrich and Katterfeld [7] being recent examples. For obvious reasons, the correct calibration and selection of DEM parameters is one of the most important steps in this simulation method. This has led to the development laboratory characterisation tests which build upon the well established test procedures for bulk solids handling applications. While the validation of the simulation results can sometimes be achieved by employing bench scale model tests, in some cases the opportunity is presented to use full scale validation of the DEM model. This is typically achieved by comparing the DEM model to data taken from site in the form of photos, videos and throughput analysis.

In this study, the modelling parameters within the DEM software are chosen based on the interpretation of the measured flow properties of the bulk material, e.g. bulk density, wall friction, and internal friction. The material stored in the silo is coal. Standard flow property testing was performed for this material using a direct shear tester. The internal strength of the coal sample indicated an effective angle of internal friction of approximately 45-50º, while the bulk density of the coal was approximately 1000 kg/m^3. The wall friction angle was 25-30º, and angle of repose testing for this coal revealed an approximate angle of repose of 35-40º. The material parameters used in DEM simulation are given in Table 1.

Table 1 Material Parameters Used in DEM Simulation

Bulk Density	1000 kg/m^3
Particle-Particle Friction Coefficient (pf)	0.7
Rolling Friction Coefficient (rf)	0.4
Particle-Wall Friction Coefficient (wf)	0.5

Presented in Figure 1 is the configuration of the simulated two-outlet silo. The discharge from the silo is via two rectangular openings. If the discharge is mainly by one outlet at a time, as does happen, non-uniform draw-down in the silo will occur. The cylindrical section of the silo is 20 m internal diameter and 30 m internal height above the hopper and cylinder transition level. The hopper section of the silo is formed with an internal geometry that directs the flow of bulk material from the cylindrical section to the two rectangular openings. The hopper height is 12 m, and the inside dimensions of the outlets are 5 m and 12 m. The hopper half-angle for both the long side and the short side is 18.4º.



(a) End View (b) Side View (c) Plan View

Figure 1 Configuration of the Simulated Silo

In the simulation of this silo with a capacity in excess of 10,000 tonnes, the complete particle size distribution of the material could not be used as the computational costs associated with the simulation of real cases are very high. As such the spherical particles with the size of 200 mm were chosen. The total number of particles was 1.4 million and it took approximately 24 hours for each simulation.

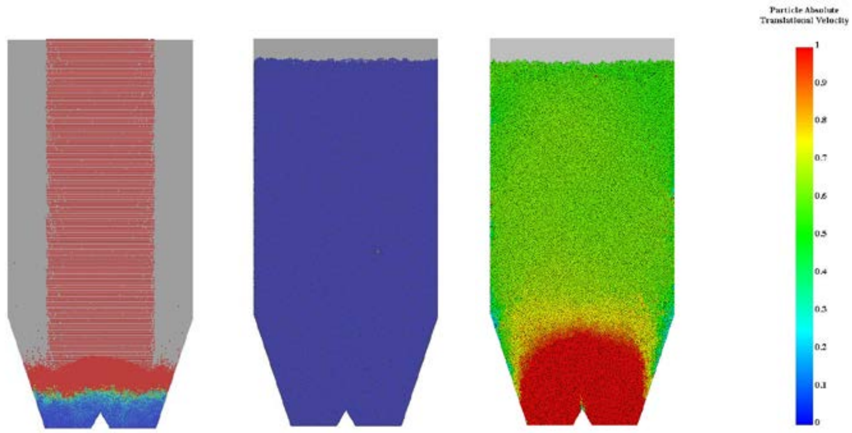
The simulation commences with the particles filling into the empty silo with both outlets closed. The filling continues until the silo is filled and the particles are allowed to settle for 5 s (simulation time). At this point, one outlet or both outlets of the silo are opened instantaneously and the particles are discharged from the opened outlet(s). In this study, symmetrical filling and discharge with both outlets closed and open are modelled for the purposes of model validation. Finally, the eccentric discharge case, where only one outlet is opened, is simulated.

3. RESULTS AND DISCUSSION

3.1 Symmetrical Filling and Discharge

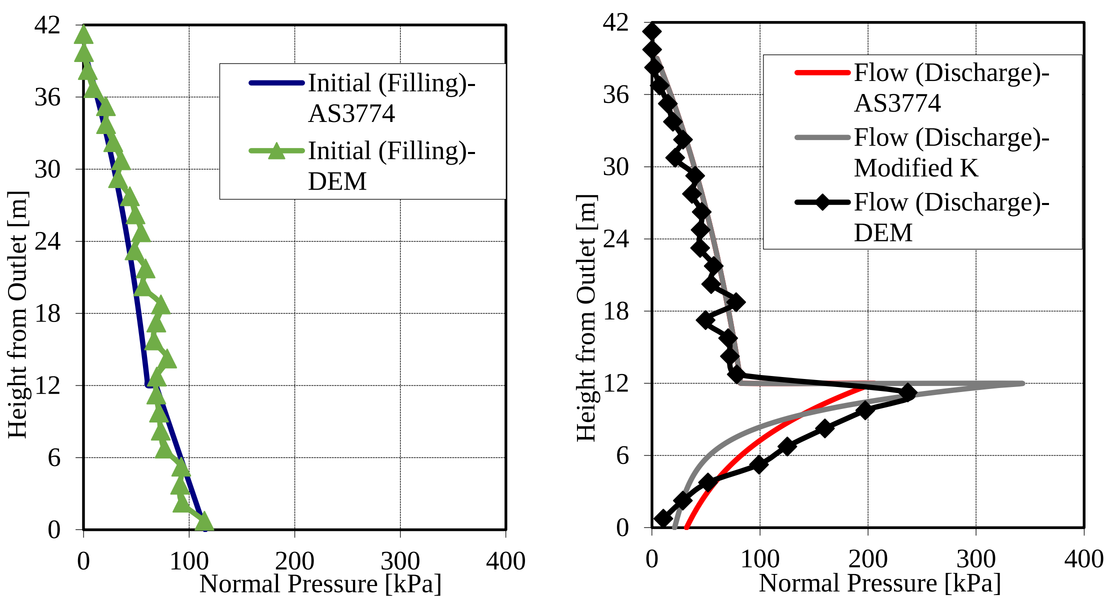
Figure 2 shows the DEM simulation snapshots of symmetric filling and emptying processes. The particles were generated progressively on a circular surface in the upper section of the silo and then allowed to fall under gravity until the silo was filled. Both gates were fully opened to allow the material to be discharged from the outlets immediately upon the silo was full and the particles had settled. The snapshot of the DEM results in Figure 2 (c) shows a mass flow pattern during discharge due to the relatively small hopper half angle (18.4º). The mass flow pattern is also predicted according to the design charts of Jenike [8]. The simulation was undertaken for symmetrical filling and discharge and the normal pressure results are plotted in Figure 3. During filling it can be seen that the normal pressure increased along the silo height, reaching the maximum value just above the cylinder-hopper transition level. Below this level the wall pressure was again generated in hopper section. Similarly, the wall load results during discharge show a gradual increase, but with a pressure surge appearing at the transition as expected by other researchers [9-12]. Below the silo-hopper transition, however, unlike the trend shown in Figure 3(a) (filling stage), there was an immediate sharp reduction in normal pressure, which was in good agreement with the previous studies [11, 13]. The reason for this is that the stress fields change from 'active' to 'passive' states when flow is initiated [14].

Also, included in Figure 3 are the normal pressure results obtained from AS3774-1996 [1]. The equation for the calculation of the modified pressure ratio K_{hf} value [15] was also used, and the results are provided for the flow (discharge) condition. While particle size (200 mm) used in this DEM simulation is very large, within the scale of the silo it is found to provide an acceptable solution without compromising the results. It can be seen that both results obtained by DEM simulation and Australian Standard agree well with each other during filling and discharge.



(a) Progressive (b) Filling (c) Discharge

Figure 2 Simulation of Filling and Empty



(a) Initial (Filling) (b) Flow (Discharge)

Figure 3 Normal Loads during Filling and Discharge

3.2 Eccentric Discharge

The wall loads during the discharge operation were studied by performing a range of DEM simulations for the coal silo with only one outlet opened. The outlet eccentricity was 0.175 times silo diameter, being larger than the critical value of 0.1 as defined in AS3774 [1]. Figure 4 shows a snapshot of the discharge of material via an offset flow channel or rathole and the stationary material formed the rathole to the far side (opposite to the outlet in operation) of silo walls. The flow channel extended all the way to the top surface. Clearly, the eccentric discharge of bulk solids from a silo has led to asymmetry in material flow pattern, resulting in the eccentric distribution in normal pressure around the silo walls (Figure 5). This would deteriorate the structural integrity of the silo. The emphasis of this study is mainly placed on the wall loads in the cylindrical section of the silo above the cylinder-hopper transition as the silo failure often occurs in the cylindrical section. The normal pressure results at the cylinder section are presented in Figure 5 for the eccentric discharge where only the outlet at the near side (left) is open during discharge. It is noticed that near the transition level the normal wall pressure is higher on the far side than that on the near side where the abrupt inward pressure was also observed, which has also been found in the early pioneering study by Jamieson [16]. This eccentric load distribution is incorporated in the Australian Standard AS3774 [1]. At the upper section of the silo, however, the normal pressure on near side was higher, which agreed with the findings obtained using FEA [17]. The reason for this change is probably that the stress field on the near side shifts from "active" to "passive" states. Moreover, the pressure values for both sides are identical near the silo top. It seems logical that the normal pressure on the cylinder periphery further away from the cylinder/hopper transition would be less influenced by the eccentric discharge.

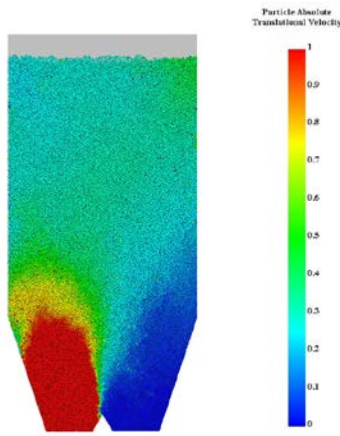


Figure 4 Snapshot of Material Eccentric Discharge (DEM)

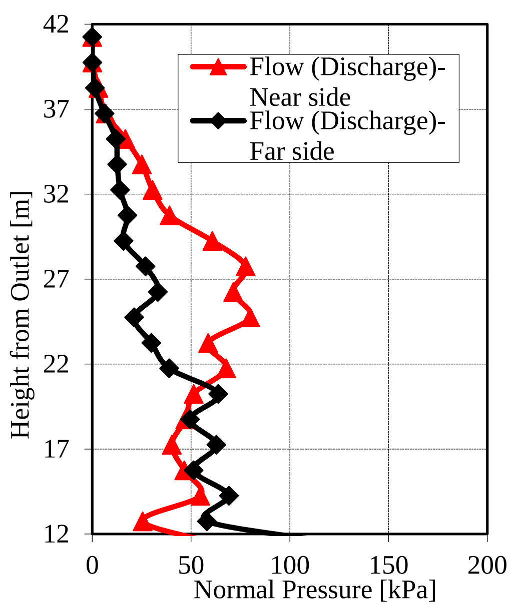


Figure 5 Numerical Results for Normal Pressure on Cylinder Section of Silo during Eccentric Discharge

Of particular interest of this paper are the distributions of the normal pressures around the periphery of the silo wall at a height defined as the ‘critical transition’ where the flow down the wall converges as a result of a “hopper type” flow channel forming above the cylinder/hopper transition. For this 30 m in height cylindrical section, this critical transition height can be given as 1 m. The results at this level plotted, in Figure 6, show the non-uniformity and eccentricities of the wall loads, which would cause bending stresses in the circumferential direction, may result in silo failure. In addition, the changes in stress fields from ‘active’ to ‘passive’ due to flow convergences giving rise to ‘switch stresses’ would no doubt contribute to structure damage.

Sadowwski and Rotter [18] performed shell buckling calculations using Eurocode 1993-1-6 (2007) [19] and proved that a silo which was safe under symmetric loading could fail under eccentric discharge. Roberts and Ooms [20] presented a case study analysis of two concrete silos of similar scale to those of this present study. The silos each had seven outlets symmetrically placed. The walls were constructed assuming hoop stress with the steel reinforcement located circumferentially in the centre of the walls. No allowance was made for bending. Not surprisingly, cracks appeared within a few months after commissioning. The silos had to be strengthened by steel cables wrapped circumferentially around the walls, an expensive operation. No doubt the silos were poorly designed as uniform, symmetrical loading was assumed. However the measured hoop stresses varied by as much as 2.9:1 due to the variation in normal pressure from the active flow channel above each feeder outlet to the stationary, non-flowing region between adjacent feeder outlets. It therefore is necessary that the non-uniformity in wall stress caused by the eccentric discharge should be given special attention to when a silo being designed.

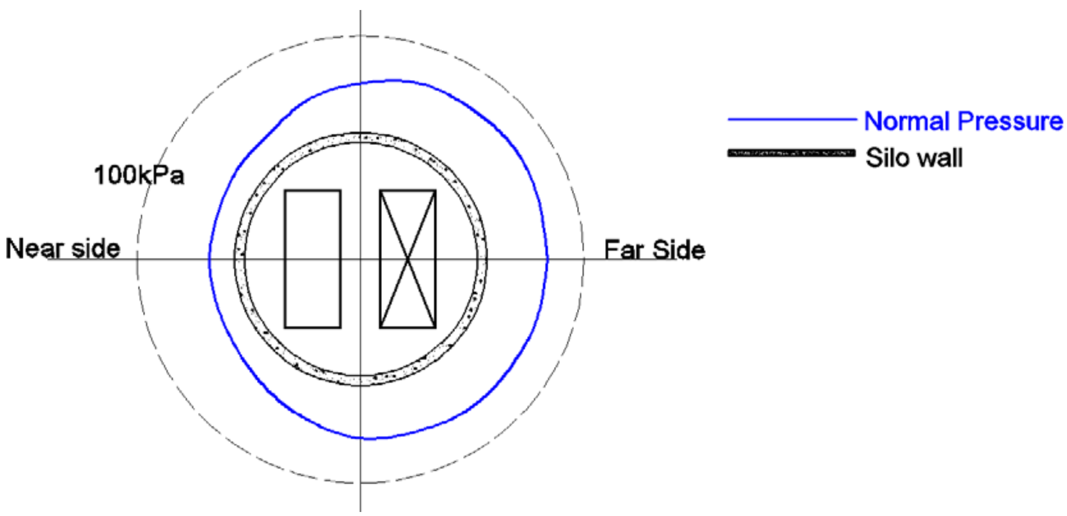
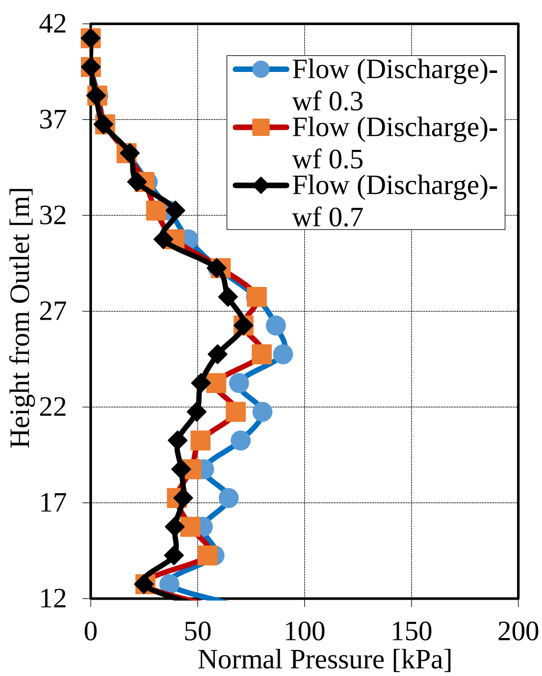


Figure 6 Numerical Results for Pressure Distribution around Silo Periphery at 1 m above Transition Level

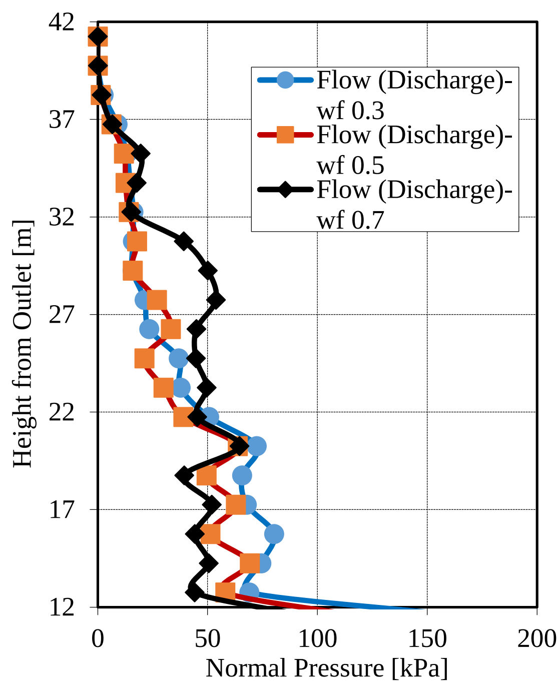
3.3 Influence of Particle-Wall Friction Coefficient

The friction coefficient of a silo wall in relation to the stored particles is one of the most influential factors in the determination of the normal pressure on the wall. This coefficient can change throughout the wall life - usually it reduces in value due to abrasions or lubrication of the wall [17], or may possibly rise as a result of wall corrosions or chemical reactions with the contained material [21]. Both variation directions in the friction coefficient need to be fully considered in the design of a silo. There have been some research studying its effects for symmetric cases [22-24] as well as eccentric discharge with single hopper [17]. A decreased normal pressure was found with an increase in friction coefficient for both situations. Silos with multi-outlets have been widely used in bulk material handling industries. It is worthwhile to understand how their wall pressure being affected by the particle-wall friction coefficient during eccentric discharging operation as the structural integrity have to be guaranteed during operation.

The normal pressures on silo wall near side and far side were simulated using DEM at varying particle-wall friction factor and plotted in Figure 7. It can be seen that the wall loads on both the near side and the far side of the cylinder reduced with increasing particle-wall friction coefficient. This relationship has been well established in symmetric studies. DEM simulations also provided important information on the pressure distributions above the girth of the silo. The normal pressure distributions around the silo periphery at 1m above the level of the transition for different particle-wall friction factors are compared in Figure 8. From the DEM results, it can be seen that the wall pressure with particle-wall friction factor of 0.5 on the near side is marginally larger than that with the factor of 0.7, whilst a larger change can be seen on the far side. It is also noticed that the pressure difference between both sides is slightly increased at a decreased friction coefficient, being similarly found in the study by Vidal et al. [17].



(a) Near Side



(b) Far Side

Figure 7 Effect of Wall Friction coefficient on Normal Pressure on Cylindrical Section - Eccentric Discharge

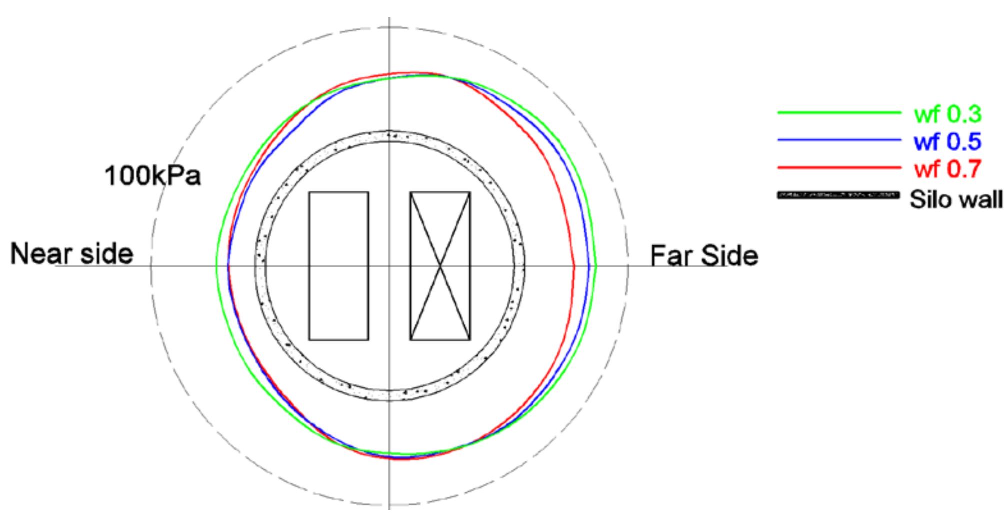


Figure 8 Wall Friction factor vs. Normal Pressure Distributions around Silo Periphery at 1 m above Transition Level

3.4 Material Build-up in the Silo

Many cohesive bulk solids gain strength due to consolidation during prolonged storage time. The experimental results [15] showed for a coal sample at 10% moisture content, the strength gained is considerable after five days storage. This cohesive strength of the material is a contributing factor to the build-up in the silo. If the silo has been operating constantly under one outlet in operation, a build-up in the silo is expected to occur for cohesive bulk material. In this study, it is assumed the material build-up is on the right hand side of the silo. More cohesive particles could be used to form the build-up in the silo, however, the use of two types of materials in the silo may affect the wall loads differently due to the different (frictional) properties. In this study, a simplified approach has been adopted by adding an artificial wall in the silo to simulate the material build-up. The particle-wall friction coefficient for this artificial wall can be set the exactly same as that for the particle-particle.

DEM simulation has been conducted to investigate the pressure distribution when the discharge is influenced by the build-up. Figure 9 shows a snapshot of the discharge of material influenced by the build-up. It can be seen that the stationary material formed adjacent to the build-up due to relative high friction coefficient. Figure 10 presents the pressure distribution around the silo periphery at 1m above the level of the transition (material build-up in the silo). Demonstrated is the presence of switch stresses from 'active' to 'passive' taking place caused by the build-up of coal adhering to the wall. The ratio of maximum pressures far side to near side is approximately 4, which is significantly greater than that obtained with no material build-up in the silo where it is about 2. This variation will cause much greater bending moments and stresses. Therefore, for a high cohesive strength material, the silo wall structure needs to be designed for the worst case including eccentric loading or discharging as well as potential material build-up. In addition, regular inspection and cleaning of the storage equipment is necessary to ensure that build-up of material does not occur.

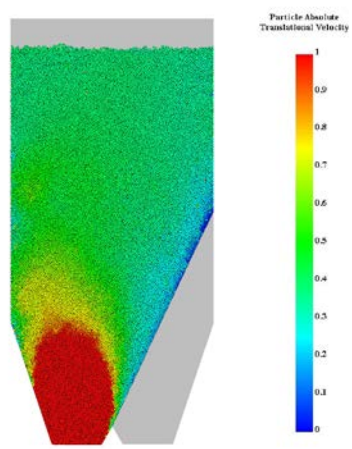


Figure 9 Snapshot of Eccentric Discharge in Silo with Material Build-up (DEM)

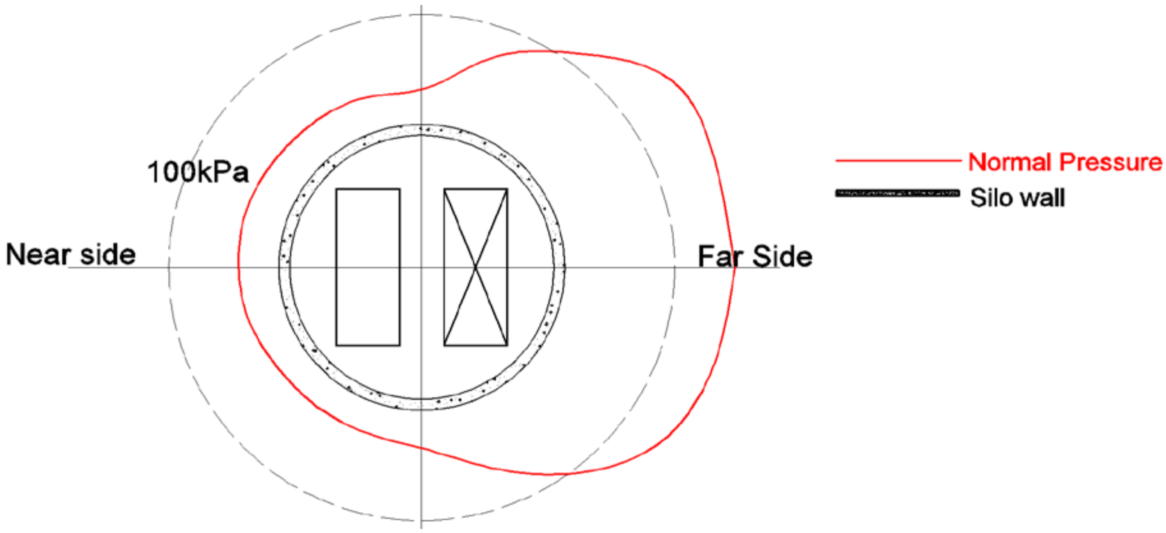


Figure 10 Pressure Distribution around Silo Periphery at 1 m above Transition Level (Material Build-up in Silo)

4. CONCLUSIONS

In this study, the wall loads during filling and discharge operations were investigated by performing a range of DEM simulations for a large silo in excess of 10,000 tonnes with two outlets. The DEM simulation results compared well with those based on the Australian Standard in both symmetric filling and emptying processes. Asymmetry in the normal pressure distribution around the silo walls has been studied during the eccentric discharge of bulk solids from the silo where only one outlet is in operation. The DEM results indicate that the wall loads on the side furthest from the eccentric discharge location are larger than those on the side nearest the eccentric discharge location. The simulation snapshot revealed the discharge of material via an offset flow channel or rathole and the stationary material formed the rathole to the far side of silo walls.

The effects of the variation in particle-wall friction coefficient were also modelled using DEM, and the results show that the pressure difference between the near and far sides only slightly increased with a decreasing friction factor for this eccentric discharge situation. Also, cohesive bulk solids under prolonged eccentric discharge operation is likely to lead to material build-up in a silo. The simulation results demonstrated that the presence of this material build-up would greatly enlarge the variation in the normal pressure around wall at a given silo periphery level. This would no doubt induce significantly greater bending moments and stresses.

It is most important that the non-uniformity in wall stresses caused by all possible eccentric loading and discharge conditions as well as potential material build-up be given special attention when a silo is designed.

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