DEM study of granular flow around blocks attached to inclined walls

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Abstract. Damage due to intense particle-wall contact in industrial applications can cause severe problems in industries such as mineral processing, mining and metallurgy. Studying the flow dynamics and forces on containing walls can provide valuable feedback for equipment design and optimising operations to prolong the equipment lifetime. Therefore, solids flow-wall interaction phenomena, i.e. induced wall stress and particle flow patterns should be well understood. In this work, discrete element method (DEM) is used to study steady state granular flow in a gravity-fed hopper like geometry with blocks attached to an inclined wall. The effects of different geometries, e.g. different wall angles and spacing between blocks are studied by means of a 3D DEM slot model with periodic boundary conditions. The findings of this work include (i) flow analysis in terms of flow patterns and particle velocities, (ii) force distributions within the model geometry, and (iii) wall stress vs. model height diagrams. The model enables easy transfer of the key findings to other industrial applications handling granular materials.

1 Introduction

Dense granular flow is widely encountered in bulk material handling industries. In this particular flow regime, the flow dynamics are controlled by momentum transfer during particle collisions, and friction between grains or particle and containing walls, respectively [1]. In industrial applications, forces acting on containing walls, originating from particle flow dynamics, can cause serious problems to plant parts and equipment, resulting in interrupted operations and high costs for the plant operator [2].

The relationship between depth inside a silo structure and the resulting wall pressure had already been established by Janssen at the end of the 18th century [3]. Over the years the theory has been further developed for dynamic conditions and to account for geometrical discontinuities like the transition from vertical silo wall to inclined hoppers in the lower sections [4–6]. The onset of particle movement in the silo, as well as geometrical discontinuities along the wall, are associated with a sharp increased wall pressure, a so-called switch [7]. A great part of the available literature concentrates on performance aspects and the design of silos and hoppers (for example see [8,9]). This work, however, aims to describe the effect of complex wall structures, present for structural or functional reasons, inside an expanding geometry under continuous operations which

are usually not considered when studying silo discharge. This particular setup has been chosen, as the technical motivation for the presented research is to better understand the flow at the near wall region of the ironmaking blast furnace shaft. The resulting outcomes, however are presented in a general way in order to be able to apply and extend them to other applications as well.

This paper presents the results of a DEM simulation study of the flow behaviour of steady-state dense granular flow around blocks attached to a wall in a hopper-like geometry. The effect of block spacing and different wall inclination angles, with respect to flow structure, particle velocities, and resulting forces and wall stresses have been studied.

2 Model description

In this work, the discrete particle simulation (DPS) technique based on the discrete element method (DEM) originally developed by Cundall and Strack [10] is used to model the granular flow system. The analyses have been carried out with the DEM code LIGGGHTS® [11].

Several model geometries were constructed featuring different wall angles (α) and number of blocks, i.e. spacing (s) between blocks (Fig. 1). All geometries exhibit the same model height, width at the top, model

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thickness, block size, and position of the first (top) and last (bottom) block. Periodic boundary conditions have been applied to the front and back of the model geometry to limit the total number of particles. A summary of the geometric dimensions of the considered cases is presented in Table 1.

Table 1. Geometric dimensions of the simulation cases.

Parameter	Value(s)
wall angle, α	90°, 85°, 80°
block spacing (mm), s	900, 600, 400
no. of blocks	5, 7, 10
model thickness (mm)	100
block size (mm)	150 x 150

Fig. 1. Set-up and dimensions of the model geometry.

At the beginning of each simulation, the geometry is filled with monosized spherical particles exhibiting a diameter of 25 mm. After filling, particle settling takes place for 3 seconds, after which all particles above a height of 6.2 m are removed from the simulation domain. Subsequently, particles are inserted at the top with an insertion rate of 800 particles per seconds, which at a particle density of 1081 kg/m³ corresponds to 6.15 kg/s. With the onset of particle insertion, particles at the bottom of the geometry are removed from the computational region at the same rate as particles are inserted at the top. This ensures that the number of particles inside the domain stays constant throughout the simulation. Only particles residing within a distance of two particle diameters from the bottom of the geometry are candidates for removal by spatially random selection. After a macroscopic steady-state flow is reached, particle positions, velocities and forces are recorded for further analysis. Material parameters and simulation conditions are given in Table 2.

3 Results and discussion

The results presented are representative simulation outcomes that have been chosen to demonstrate some of

the key findings of this study.

Table 2. Material parameters and simulation conditions.

Parameter*	Value(s)
particle shape	spherical
particle diameter (mm), d_p	25
particle density (kg·m ⁻³), ρ_p	1081
Young's modulus (Pa), E	10 ⁷
Poisson's ratio, ν	0.3
sliding friction coefficient, μ_s	0.4
rolling friction coefficient, μ_r	0.1d _p
coefficient of restitution, e	0.1
time step (s), Δt	0.00005

*uniform values for all material types/pairs

3.1 Flow structure

Different colours have been assigned to the particles in the simulation, which allows the identification of different flow zones inside the geometry. Fig. 2 illustrates the flow structure of the cases with 90° and 85° wall inclination angle and a block spacing of 600 mm, after the same number of particles have been inserted into and discharged from the domain. Blue particles originating from the initial filling process can be observed between and on top of blocks. These areas can be identified as stagnant zones. Each green or red particle layer consists of 1000 particles. In both cases the layered structure is preserved during descent, although in the case with the inclined wall, the layers become progressively thinner and layers misalign towards the bottom of the geometry. Zones of mixed particles occur in the transitioning region from stagnant to moving particles.

Fig. 2. Flow structure for the cases with 90° (the left) and 85° (the right) wall inclination angle, and 600mm block spacing.

3.2 Particle velocities

The same two cases are chosen to examine the influence of wall inclination angle on the particle velocity

distribution inside the simulation domain (Fig. 3). The particle velocities of 100 different time steps have been averaged over a period of 200,000 simulation time steps, which corresponds to 10 s. In the case of 90° walls (left), the velocity is relatively constant along the geometry height, except for the regions near the blocks. In the case with an 85° wall angle (right), the velocity decreases as the cross-sectional area of the geometry increases. The effect of blocks on the velocity distribution is greater in the case of the inclined wall, as can be seen by the width of the velocity transition region between the block faces and the bulk flow region in Fig. 3. Phenomena observed in analysis of the flow structure in Fig. 2 can be explained by observations made from the velocity distribution. For example, with an 85° inclined wall, the diagonal misalignment of the layers in the middle region of the geometry coincides with the velocity contour line between 0.8 and 0.9 m/s. Similar observations can be made at other transition areas.

Fig. 3. Particle velocity distribution for the cases with 90° and 85° wall inclination angle, and 600mm block spacing.

3.3 Forces

Like the particle velocities, the magnitudes of the individual particle force vectors, i.e. total force on each particle, resulting from particle-particle and particle-wall interactions, respectively, as well as from gravity, have been averaged over their spatial location within the domain. The force distribution for different wall angles and a block spacing of 600 mm is shown in Fig. 4. Overall, the forces inside the domain are smaller at a decreasing wall angle (from left to right). As expected, the force within the domain increases with distance from the top due to the increasing weight exerted by overlying particles. Large forces in the regions near the blocks are most dominant in the case with vertical walls (left) and as wall angle decreases, the forces at the block edges also decrease.

The influence of block spacing on the force distribution is illustrated in Fig. 5. Large forces occur at

the block edges and front faces of the protruding blocks. Forces at the particle-wall interface cannot be attained from these plots. To identify the influence of block spacing on the stress in the regions between blocks a wall stress analysis of these areas is presented in the next section.

Fig. 4. Force distribution inside the geometry for cases with 90° , 85° and 80° wall inclination angle, and 600mm block spacing.

Fig. 5. Force distribution inside the geometry for cases with 900mm, 600mm and 400mm block spacing, and 85° wall inclination angle.

3.3.1 Wall stress analysis

Normal and shear stress acting on each mesh element of the model geometry have been recorded and averaged over time for the period of macroscopic steady-state particle flow. Each of the three diagrams in Fig. 6 compares the normal stress along the height of the wall for the cases with the same block spacing, but different wall angles. For easier comparison, only the stress acting on the wall area between blocks is shown. In all cases the overall stress increases from the top to the bottom of

the domain. With inclined walls ($\alpha < 90^\circ$) wall stress decreases significantly compared to the cases with straight walls ($\alpha = 90^\circ$), especially when block spacing is wide (see Fig. 6a). For the cases with 85° and 80° wall angle, the difference is less significant.

For each area between two neighbouring blocks, the stress increases vertically in the downward direction, i.e.

the stress below a block is at a minimum and reaches a maximum in the area above the next block. The magnitude of these minimum and maximum values is dependent on the vertical location along the geometry, resulting in a steep stress gradient in the cases of 400 mm block spacing and a more gradual increasing wall stress for wider spacing.

Fig. 6. Normal stress acting on the wall in the areas between attached blocks. The effect of wall angle is demonstrated for block spacing of a) 900mm, b) 600mm and c) 400mm.

4 Conclusion

These results demonstrate the influence of wall angle and block spacing on different flow characteristics and the resulting wall stress. The following conclusions can be made:

In the case of vertical walls the particle flow showed relatively uniform behaviour along the domain height with respect to flow structure and particle velocity. At inclined walls, however, particle layers became progressively non-uniform and the particle velocities were observed to decrease towards the bottom of the geometry.

Observations of flow patterns in cases with inclined walls were consistent with the results obtained from velocity analysis and can be explained by these.

The differences between the results of different wall inclination angles, e.g. between 85° and 80° were less significant than those between vertical and inclined walls. The trends observed in these results may need further study to establish their validity.

Large forces could be observed in the areas of the block edges protruding into the bulk flow area. Further analysis of this region, focusing on the interaction of particles and walls may be revealing, as this is where the transition from bulk continuum-like flow to discrete interaction dominates.

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