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Experimental and numerical investigation on the influence of particle shape and shape approximation on hopper discharge using the discrete element method

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ABSTRACT

In this study experimental and numerical investigations with the discrete element method (DEM) on the discharge of spheres and polyhedral dices from a hopper are conducted. In DEM the dices are approximated by polyhedra and smoothed polyhedra respectively and hence allow examining the influence of sharply-edged and smooth particle geometries on the discharge properties. Simulation results are in good general agreement with the experiments and hence demonstrate the adequacy of DEM as well as polyhedral and smoothed polyhedral approximation schemes to simulate non-spherical particle geometries. Compared to spheres the dices exhibit an increased flow resistance and readiness to form pile-ups at the bottom walls of the hopper. Both phenomena are better approximated using polyhedral approximations of the dices, showcasing the influence of the selected shape approximation scheme on the numerical results.

1. Introduction

Granular materials are used in many application areas such as the energy, food or pharmaceutical industry, where they are usually stored in hoppers, silos or bunkers [1]. Due to the importance of the flow characteristics of the granular material for the operational stability and structural integrity of these units [2], a deeper understanding of the inherent flow mechanics is necessary to guarantee best possible design and operation. Nevertheless a general approach for designing a hopper is not yet available [3].

In recent years the discrete element method has proven to be a capable tool for predicting the processing of granular materials in various application areas. Particle shape approximation has been identified as one of the key challenges of DEM-simulations [4], due to its significant influence on the mechanical behavior of the granular materials. Still many discrete element codes represent particle shape by discs (in 2D) or spheres (in 3D). The advantage of using discs or spheres is their simplicity in terms of contact detection, resulting in the lowest possible computing effort. Moreover, the contact force models for interacting spheres and spheres contacting flat walls are well known and thoroughly tested [5–8]. While spheres are relatively easy to handle in a DEM-Code, they exhibit a different mechanical behavior on the single grain level as well as in larger assemblies, compared to the actual particle behavior in most application areas [9,10]. For this reason the physical meaning of the results obtained from these simulations is questionable [11].

In the following a brief overview of existing experimental and numerical studies on granular material with complex shapes in hoppers is given. Kohring et al. [12] conducted 2D DEM-simulations of convex polygons in a hopper. They identified four generic flow regimes, which depend on the inflow rate of the hopper. (A) Even with a fluctuating inflow rate the outflow rate remains steady; (B) while the outflow is steady, arching may occur if the fluctuations of the inflow rate are sufficiently large; (C) even without fluctuations arching will occur in the hopper, since the outflow varies with time and the mean time to blockage is nonzero; (D) the outflow is unsteady and the hopper is always blocked after some time.

Cleary and Sawley [13] investigated the outflow of superquadrics from a hopper in 2D DEM-simulations. They observed that particles with increasing aspect ratio result in a reduction of the outflow rate of up to 30%, compared to spherical particles. Particles with a higher angularity increased the flow resistance of the granular material and resulted in reduced mass flows of up to 28%, while a specific influence on the flow profile could not be detected.

Li et al. [14] conducted experiments and DEM-simulations with sphero-discs in a rectangular hopper. A quantitative comparison of the flow behavior, arching and discharge within the hopper for three different opening sizes revealed a good agreement between experiments and DEM-simulations. By comparison with spherical particles, the effect of particle shape on the discharge rate of the hopper was demonstrated. While a comparison with the experimental data was difficult (both particle shapes had slightly different volumes and material properties) the DEM-simulations led to 20–30% higher discharge rates for sphero-discs. Li et al. attributed this to discs having an easier flow path over each other, while spheres have a “bumpier ride.”

Fraige et al. [15] conducted numerical and experimental investigations of 200 spherical and cubical particles in a rectangular flat bottom hopper with flow patterns, flow rates and static packings being closely

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examined. Experimental and numerical results were in good agreement and demonstrated that cubes fill space more efficiently than spheres, while flowing less readily. Fraige et al. acknowledged that systems with larger numbers of particles need to be examined for a more comprehensive comparison between both particle shapes.

Tao et al. [16] conducted DEM-simulations with spherical and corn-shaped particles in a rectangular flat bottom hopper. The corn-shaped particles were approximated employing the multi-sphere method [17] and consisted of four overlapping spheres. Simulation results indicated that the vertical velocity difference between center and side walls and horizontal velocity of corn-shaped particles is smaller than for spherical particles, while the mean voidage in the hopper is smaller. Moreover, Tao et al. demonstrated by varying the ratio of width and length as well as height and width of the hopper, that the wall effect on the voidage is greater for spheres than for corn-shaped particles.

Wang et al. [18] investigated numerically the flow of 500 spheres, octahedra and tetrahedra from a rectangular hopper. Their 3D polyhedron model possessed rounded edges and vertices, acknowledging that real granular particles do not contain perfect vertices. They found that on an equal volume basis, spheres flow more readily than polyhedra and require a significantly smaller outlet size to enable particle flow. For a mix of spheres and octahedra they found a linear relationship between composition and critical outlet size.

Fraige et al. [19] compared DEM-simulations of spherical and polyhedral particles in a flat bottom rectangular hopper. The numerical results revealed a shape factor dependency of the discharge rate from the hopper with increasing particle angularity resulting in a reduction of the discharge rate of up to 49% and 41% for tetrahedral and octahedral particles respectively. Additional simulations with varying physical properties showed that the damping coefficient has a negligible effect, while a variation of the friction coefficient and frictional damping significantly influences the discharge process.

González-Montellano et al. [20] investigated the discharge of glass beads and maize grains from a hopper. While the glass beads were represented as spheres in their 3D DEM-simulations, the maize grains were approximated by a cluster of six overlapping spheres. In DEM-simulations as well as in corresponding experiments the mean bulk density at the end of the filling phase, the discharge rate and the flow pattern were recorded. For the glass beads a good agreement between simulations and experiments was achieved, but the simulation of the maize grains was found to have shortcomings. By modifying the friction properties of the material, acceptable predictions were obtained.

Mack et al. [21] conducted experiments and simulations with 322 spheres as well as a mixture of polyhedral dices with different numbers of faces in hoppers of three different angles α. In 3D DEM-simulations the dices were approximated as polyhedra with rounded edges and vertices. The obtained experimental results showed that polyhedra flow is slightly faster than the flow of spheres and it was assumed that the flat surfaces enable them to slide past each other more easily. Moreover, for a hopper cone angle of $\alpha = 30°$, polyhedra showed a greater tendency for arching (based on two experiments performed per particle geometry and α). For a flat bottom hopper they additionally observed a higher tendency for polyhedral particles to pile up in the corner of the hopper. A reasonable agreement between experiments and simulations in terms of static packing, flow behavior and hopper discharge rates was accomplished.

Höhner et al. [22] conducted numerical investigations on the influence of particle shape and shape approximation as well as hopper design on hopper discharge. For this purpose spherical particles were approximated by polyhedra with triangular surface elements and sharp edges and vertices as well as by the multi-sphere method [17] at three approximation levels, respectively. For comparison, the mass discharged from the hopper and the flow profile were monitored during discharge and compared with one another as well as with the reference solution of ideal spherical particles. It was shown that with increasing angularity the mass flow rate from the hopper is reduced and, in case of a flat bottom hopper, the residual filling quantity after discharge increases. An increased flow resistance could be observed, which resulted in arch-like void structures above the outlet of the hopper, indicating intermittent flow. Moreover, angular polyhedral particles predicted core flow with particle movement mainly localized in the center, while spheres and clustered particles predicted mass flow behavior with significant movement reaching far to the side walls of the hopper. The obtained numerical results demonstrated considerable differences between the discharge of polyhedral and clustered particles. Clustered particles did not reduce the mass flow rate and increase the flow resistance to the same extent as polyhedral particles. Höhner et al. attributed this to multi-sphere particles having relatively smooth surfaces, while polyhedra possess multiple sharp vertices and edges, indicating that the type of particle shape approximation is another significant parameter that has to be considered in DEM-simulations.

While the studies mentioned above focus on symmetrically shaped particles, it needs to be mentioned that most industrial relevant granular media exhibit irregular non-symmetrical particle geometries. Wang et al. [23] presented two methods to approximate real particle shapes, the first using a multi-sphere approach and the second employing an equivalent ellipsoid that accounts for the moment of inertia of the real particle. The required data set to generate the particle-approximations is obtained using X-ray tomography. Latham et al. [24] presented 3D laser ranging (LADAR) and X-ray computed tomography as well suited methods to capture the surface structure of real particles. They identified the multi-sphere approach as well as meshed surface approximation as means of incorporating real particle shapes into the DEM. Since thousands of elements are required for close geometric approximation, Latham et al. identify real particle shape approximation as computational expensive and only adept for handling systems consisting of a small number of particles at present.

The research mentioned is not sufficient to fully understand the influence of particle shape and shape approximation on the discharge of granular material from a hopper. In this study hopper discharge experiments with spheres and five different types of polyhedral dices are conducted. Corresponding 3D DEM-simulations with polyhedral and smoothed polyhedral approximations of the dices are carried out. While the polyhedra possess sharp edges and vertices, for the smoothed polyhedra the edges and vertices are rounded. Both methods are able to approximate irregular real particles but will be used in this study to simulate symmetrical objects. By comparison between experiments and simulations the adequacy of the polyhedral and smoothed polyhedral DEM is shown and the effect of particle shape as well as the method of shape approximation on hopper discharge is investigated.

2. Discrete element method

For all simulations conducted in this study an in-house discrete element code of the Ruhr University Bochum was used. The code is well established and extensively tested for simulations of spherical and non-spherical particle geometries [22,25–27].

2.1. Force laws applied

The discrete element method monitors the movement and interaction of all particles in the investigated system. By calculation of the acting forces for all particle-particle and particle-wall contacts, the translational and rotational velocities as well as the positions of all particles can be determined. For this purpose the discrete element method allows particles to overlap and computes the resulting contact forces as a function of the overlap ξ as well as the relative velocity v_{rel} of the contact partners. A detailed overview of force schemes is given by Di Maio and Di Renzo [6,8] as well as Kruggel-Emden et al. [5,7].

The most frequently employed normal force laws in DEM-simulations are viscoelastic spring dashpot models [28]. The normal force F^n consists of two parts: while the elastic component ($F^{n,el}$) models elastic repulsion,