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A study on the influence of particle shape on the mechanical interactions of granular media in a hopper 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 mechanical interactions of particles with varying sphericity and aspect ratio in a rectangular hopper are conducted. In the DEM the test particles are approximated by four commonly used approximation schemes.

A decrease of particle sphericity or an increase of the aspect ratio results in an more uneven, intermittend particle flow and overall lower discharge rate. It was deducted from the measurement results that changing these geometric particle properties elevates the shear strength of the particle bed and, hence, has a significant influence on the discharge properties of a hopper.

Simulation results are in good general agreement with the experiments and thus demonstrate the adequacy of the DEM to predict the mechanical interactions in granular media consisting of non-spherical particles. The results presented in this study show only a minor influence of the method used to approximate particle shape within the DEM. Obviously the discharge characteristics are much stronger related to macroscopic geometric parameters than the fine scale resolution of particle geometry.

1. Introduction

1.1. Background

Granular media are of importance in various industrial processes as raw material as well as intermediate and final goods. Nevertheless the basic knowledge about the mechanical interactions in granular media is still incomplete. Although the influence of particle geometry on the mechanical properties of the overall particle system has been demonstrated in various studies, a systematic, qualitative and quantitative characterization has not been accomplished.

The discrete element method (DEM), as introduced by Cundall and Strack in 1979 [1], has proven to be a capable tool for predicting the dynamics of large particle assemblies. A comprehensive overview about the major applications of the DEM in recent years is given in [2]. Several authors such as [3–6] identified particle shape approximation as one of the key challenges of DEM-simulations, due to its significant influence on the mechanical behavior of granular materials. Nevertheless, most simulations conducted with the DEM involve spheres due to their simplicity in terms of contact detection, which results in lowest possible computing times. The major drawback of using spherical particle representation in the DEM is that most industrial granular materials exhibit a significantly different shape. As a result DEM predicts a deviating mechanical behavior on the single grain level as well as in larger particle assemblies, which renders the physical meaning of the obtained simulation results questionable [7].

For this reason several non-spherical particle shape approximation schemes have been proposed in literature. The most commonly used approaches include ellipsoids [5,8,9] and superellipsoids [10–12], clustered-spheres approaches [13–16], polyhedral [17–20], spherocylinders [21] and discrete function representations [12,22]. Most recently Molon et al. [23–26] presented novel models how to generate very realistic complex particle geometries for DEM-simulations.

A hopper is a technical unit which is usually employed for storage of granular media and which displays complex mechanical particle-interactions. For this reason hoppers are a common object for investigating the mechanical phenomena related to granular media. In the following a short overview over experimental and numerical studies on particle mechanics in a hopper is given. In compliance with the topic of this study, the overview prioritizes on investigations using granular media consisting of non-spherical particles.

1.2. Overview

Kohring et al. [27] have conducted two-dimensional DEM-simulations with convex polygons in a hopper. They identified four flow profiles which partly depend on the hopper filling rate and showed, that strongly fluctuating filling rates may lead to arching, and hence, permanent blockage of the hopper outlet. Due to the relatively small scope of numerical simulations, an influence of the hopper geometry and particle geometry on the tendency for arching could not be detected.

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Favier et al. [14] investigated the discharge of ellipsoids from a rectangular hopper experimentally and numerically using the DEM. In their experiments they used buttons with almost elliptical shape, which were approximated in their DEM-simulations as multi-sphere clusters. A comparison between experimental and numerical results revealed a good agreement between mass flow rates as well as vertical velocity profiles. On the other hand deviations with regards to the evolution of voidage during hopper discharge could not be explained by the authors. Moreover the investigated particle system consisted of 200 spheres, so that the significance of the obtained results for larger, more relevant particle systems is unclear.

Cleary and Sawley [3] investigated the outflow of superellipsoids from a hopper in two-dimensional 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 of equal volume. 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.

Langston et al. [21] also conducted DEM-simulations on the discharge of particles with varying aspect ratio from a rectangular hopper. In two- and three-dimensional DEM-simulations particles were generated as intersection of two circles and two spheres respectively as well as sphero-cylinders. While the discharge rate from the hopper did not display any sensitivity toward a variation of the aspect ratio in the 3D-simulations, a significant increase of the discharge rate with increasing aspect ratio could be observed for the 2D-simulations. The authors explained this behavior on elongated particles being able to flow past one another more readily than spheres.

Fraige et al. [19] conducted numerical studies on the discharge of cohesive, polygonal particles from a two-dimensional hopper. They developed a scheme for applying polygonal shapes with rounded edges and vertices in the DEM. The simulations results indicated, that discs are discharged more readily from the hopper and that the discharge rate increases with increasing roundness of the polygons, i.e. increasing number of vertices. Additionally Fraige et al. [28] developed an approximation scheme specifically designed for cubic particles in three-dimensional DEM-simulations. They conducted experiments and DEM-simulations on the discharge of acrylic glass cubes from a rectangular hopper and a comparison of the results obtained showed good agreement with regards to packing density and packing structure as well as discharge rate and flow profile. By using a single-contact model, with only a single contact point for a particle contact, and a multi-contact model, they showed additionally, that the definition of the contact zone has a significant influence on the simulation results. The multi-contact model showed a better agreement with experimental results.

Tao et al. [29] 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 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, the authors 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. [30] investigated numerically the flow of 500 spheres, octahedra and tetrahedra from a rectangular hopper. Their 3D smoothed polyhedron model possessed rounded edges and vertices, acknowledging that real granular particles do not contain perfect vertices and edges. They found that spheres flow more readily than polyhedra and require a 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. [31] conducted similar DEM-simulations with spheres and smoothed polyhedra 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 tetrahedra and octahedra respectively.

In contrast to the two previously mentioned studies Mack et al. [32] conducted experiments as well as simulations on the discharge of spheres and polyhedra from a hopper. For this purpose they used 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 smoothed 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 rate was accomplished. Due to the very small number of particles used in the hopper experiments and simulations a transferability of the results to larger particle systems is questionable.

González-Montellano et al. [33] 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.

Höhner et al. [6] also conducted experiments and simulations with spheres and polyhedral dices with varying sphericity in a hopper. In the DEM simulations the dices were represented as sharply-edged polyhedra and as smoothed polyhedra. With the exception of hexahedral particles they obtained a good general agreement between experiments and simulations with regards to discharge rate, flow profile and residual particle fraction in the hopper after discharge. In general they found that angular particles exhibit a lower discharge rate and a higher tendency to form pile-ups at the bottom walls of the hopper than spheres of similar volume and material. A comparison between both particle shape approximation schemes showed that sharply-edged particles lead to a slightly higher increase of the microstructural strength of the particle assembly, which further enhances the effect of decreasing particle sphericity.

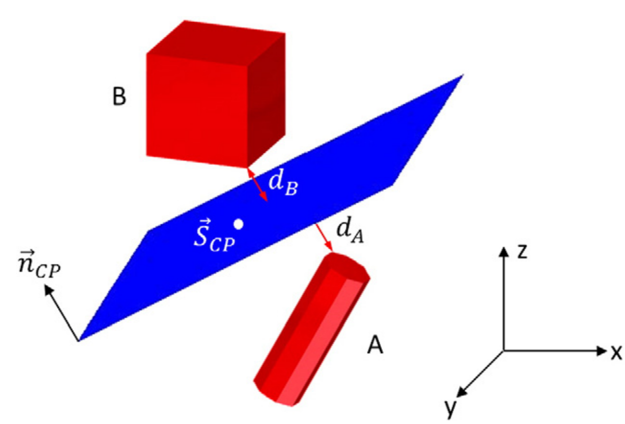

Fig. 1. Common Plane between two polyhedral bodies.