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Vibration induced flow in hoppers: DEM 2D polygon model

Feras Y. Fraige [a], Paul A. Langston [b,*], Andrew J. Matchett [c], John Dodds [d]

[a] *Faculty of Mining and Environmental Engineering, Al-Hussein Bin Talal University Jordan, Ma'an, P.O. Box 20, Jordan*
[b] *Chemical and Environmental Engineering, Nottingham University, University Park, Nottingham NG7 2RD, UK*
[c] *Chemical Engineering, University of Teesside, Middlesbrough TS1 3BA, UK*
[d] *Centre RAPSODEE, Ecole Des Mines, Campus Jarland-81013 Albi, France*

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Abstract

A two-dimensional discrete element model (DEM) simulation of cohesive polygonal particles has been developed to assess the benefit of point source vibration to induce flow in wedge-shaped hoppers. The particle–particle interaction model used is based on a multi-contact principle.

The first part of the study investigated particle discharge under gravity without vibration to determine the critical orifice size (B_c) to just sustain flow as a function of particle shape. It is shown that polygonal-shaped particles need a larger orifice than circular particles. It is also shown that B_c decreases as the number of particle vertices increases. Addition of circular particles promotes flow of polygons in a linear manner.

The second part of the study showed that vibration could enhance flow, effectively reducing B_c. The model demonstrated the importance of vibrator location (height), consistent with previous continuum model results, and vibration amplitude in enhancing flow.

Keywords: Bulk solids; Vibration; DEM; Hoppers; Materials handling; Polygon

1. Introduction

1.1. Background

Processing of granular and powder materials is important in many engineering applications. These encompass operations such as storage, conveying, mixing, separation and reaction. These range from the small scale, for example, pharmaceutical or food processing operations, where composition control may be critical, to the large scale, for example, minerals storage where wall stress and silo-quake may be important. Bulk solid behaviour of granular materials is generally more unpredictable than for gases and liquids and problems such as unsteady flows often occur in the course of handling and processing.

The design of hoppers to achieve a smooth and reliable mass flowrate for a specified material has long been a subject of interest to both researchers and process engineers, such as Jenike (1967), Enstad (1975), Williams (1977) and more recently Langston, Nikitidis, Tuzun, Heyes, and Spyrou (1997); Kozichi and Tejchman (2005). Although hopper design has been greatly advanced by the introduction of pre-measuring the various flow properties of the material encountered (Kamath, Puri, Manbeck, & Hogg, 1993), the determination of a range of flow parameters for a bulk solid can be an expensive exercise (Arnold, 2003). Moreover, the classic shear testers often suggest larger hopper outlets than is actually required (Enstad, 1975) and most practical design methods are based on theoretical-empirical approaches. Conventional mass-flow hopper design tends to give tall hoppers with steep sides and large outlets. This gives problems in areas of limited space and in conditions where small or modest flowrates are required.

Vibration is often used as a means of initiating and/or controlling flow. It is relatively inexpensive and can be fitted as a "bolt-on" to existing hoppers. However, the mechanics of vibration are complex and there is much confusion as to how vibration actually works (IMechE, 1998). Indeed, in some circumstances, vibration is used to compact and consolidate materials rather than dilate and induce flow. Some workers see vibration as a means of ensuring flow in situations that are on the limit of conventional flow, and of modest effect (Bradley, 1998). Roberts (1997) has provided the most complete body of work on the

* Corresponding author. Tel.: +44 115 951 4177; fax: +44 115 951 4115.
E-mail addresses: dr.feras@ahu.edu.jo (F.Y. Fraige), P.Langston@nottingham.ac.uk (P.A. Langston).

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use of vibration in hoppers. He developed a modified, vibrating, Jenike shear cell and a Jenike-type method of analysis. He also reported modest improvements in flow with the application of vibration. Matsusaka was able to get cohesive materials to flow through very small capillary tubes by use of vibration—well beyond the limits of standard design (Matsusaka, Urakawa, & Masuda, 1995; Matsusaka, Yamamoto, & Hiraoki, 1996; Matsusaka, Urakawa, Furutate, & Masuda, 1998). Matchett (2004) used a continuum approach to model limiting states during the application of vibration to a hopper wall. He assumed a circular arc principal stress orientation, originally proposed by Enstad (1975), modified to operate in principal stress space. This provided a rational method for positioning a vibrational device in the hopper and was based upon standard continuum material properties with no need for sophisticated vibrational cells. The model was a pseudo-static, limit analysis with no dynamic terms.

Other approaches to modelling have developed in recent years. With increasing computer power, simulation is becoming important in understanding particulate processing using techniques such as finite element or the discrete element method (DEM). Langston, Matchett, Fraige, and Dodds, 2008 used a DEM model of spheres to compare with the continuum model approach (Matchett, 2004).

1.2. Hopper vibration DEM spherical particle simulation

The previous DEM study of hopper vibration modelled cohesive spheres only (Langston et al., submitted for publication). For ease of presentation and to reduce the CPU requirements on the large number of simulations required the three-dimensional model of spherical particles was initially restricted to two-dimensional motion. That is translational motion in the x, z (vertical) axes and rotation about the y-axis. An arbitrary small particle size of 90–100 μm (normal distribution) was modelled to enable a reasonable comparison with the stress arc continuum model. This is small enough for cohesion. The obvious limitation of DEM is the computational CPU requirement. The number of particles was 500 which obviously implies a small hopper, but this was large enough to test the principles of the physics and compare with the continuum model. The second part of the study extended it to three-dimensions with 2500 spheres in a wedge-shaped hopper. The simulation size of 500 particles was deemed sufficient in the 2D study by virtue of the agreement in principle with the larger 3D study and the continuum model described below.

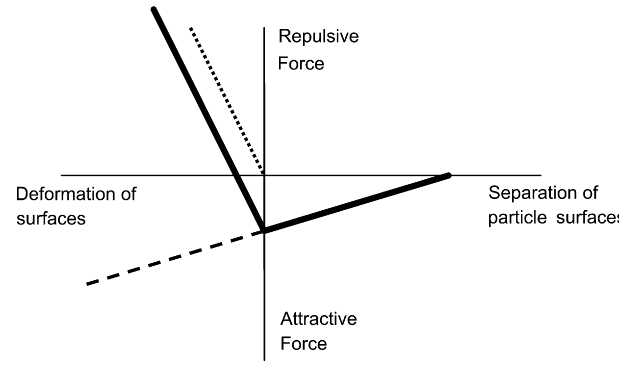

Fig. 1. Particle normal contact force model; showing cohesive (dashed) and repulsive components (dotted), and net force (thicker line).

The DEM model results agreed in principle with the continuum model findings. That is there is an optimal height at which to place the vibration to promote flow. In simple terms: too low and the material will form a stable arch above the vibration, too high and the vibration will not break the arch. The 3D simulations supported the general trends, showing similar behaviour, except that the cohesiveness was enhanced due to the increased co-ordination number in 3D. However, the main question here is, are the spherical particles representative of cohesive granular material? Hence there is the need for the current study.

1.3. DEM simulation of non-spherical particles

Džiugys and Peters (2001) and Langston, Al-Awamleh, Fraige, and Asmar (2004) review general methods of modelling non-spherical particles in DEM. Langston et al. (2004) and Li, Langston, Webb, and Dyakowski (2004) show how the method of sphere intersection (not union) was used to model sphero-disc flow. The particle shape was described by the region of intersection of two overlapping circles in 2D and overlapping spheres in 3D. Fraige, Langston, and Chen (2008) modelled cubic-shaped particles. These models were closely validated by experiment. This section briefly reviews some methods used to model polygons and polyhedra.

In polygons, polyhedra, and irregular shapes in general, the contact detection can be quite cumbersome, because the boundaries for these shapes cannot be represented by a single function as the case with spherical particles. Nezami, Hashash, Zhao, and Ghaboussi (2004) reviewed the 'common plane' (CP) technique for contact detection introduced by Cundall (1988). CP is a plane that bisects the space between the two contacting particles. The

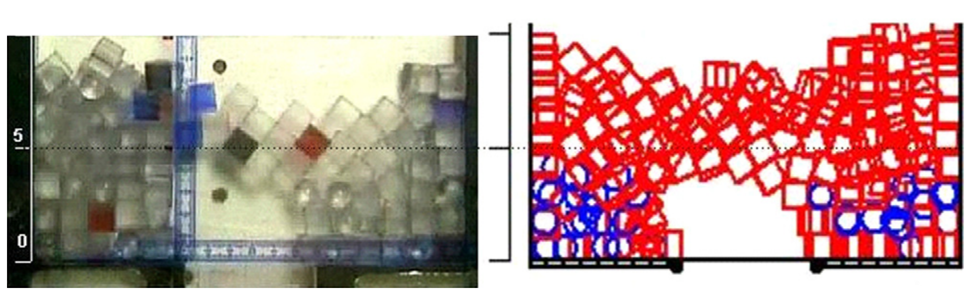

Fig. 2. An example of the experimental (left) and 3D DEM simulation (right) comparison of a stable arch in a small hopper for a mix of spheres and cubes.