Computers and Chemical Engineering 40 (2012) 22–32

Contents lists available at SciVerse ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Modeling, numerical analysis and simulation

Three dimensional discrete element models for simulating the filling and emptying of silos: Analysis of numerical results

C. González-Montellano*, E. Gallego, Á. Ramírez-Gómez, F. Ayuga

BIPREE Research Group, Universidad Politécnica de Madrid, Madrid, Spain

ARTICLE INFO

Article history:
Received 24 October 2011
Received in revised form 20 January 2012
Accepted 7 February 2012
Available online 16 February 2012

Keywords:
Discrete element model
Silo
Hopper
Pressures
Flow
Bulk density

ABSTRACT

The discrete element method (DEM) is a promising technique that allows the mechanical behaviour of the material stored in silos and hoppers to be studied. The present work analyses the numerical results obtained by two three-dimensional DEM models that simulate the filling and discharge of a silo for two materials: glass beads or maize grains. The aim of the present work was to assess the capacity of these models to predict the behaviour of the studied materials. To guarantee the maximum representativeness of the results, many of the simplifications usually used in DEM models were avoided. The results analysed included the vertical distributions of the normal pressure, tangential pressure and mobilised friction, the horizontal distribution of normal pressure, velocity profiles and the spatial distribution of the bulk density. The results of this analysis highlight the potential of DEM models for studying the behaviour of granular materials in silos and hoppers, provided that simplifications are minimized.

1. Introduction

Silos are structures designed for the storage of very different granular materials in the agricultural, food, mining, chemical, pharmaceutical and other industries (Langston, Tüzün, & Heyes, 1995). Given the size these structures can sometimes reach, their design must take into account structural safety as well as adequate functioning. Meeting the requirements of structural safety demands knowledge of the pressures a stored material will exert on the silo walls, while meeting the requirements of functionality demands an understanding of the factors that affect the flow of the stored material during discharge.

Traditionally, analytical procedures have been used to determine the values of pressures inside silos (Janssen, 1895; Reimbert & Reimbert, 1956) and for predicting the characteristics of the flow pattern (Jenike, 1964). However, these procedures are too simplistic and usually cannot be used to describe situations other than those for which they were formulated. These problems led to the use of numerical techniques for the study of the pressures and flow characteristics in silos. One of these is the finite element method (FEM) (Zienkiewicz & Taylor, 2005), which has been used with relative success to predict the pressures and flow patterns generated in silos (Sadowski & Rotter, 2011a, 2011b). However, this method contemplates the granular mass as a continuum, preventing it from being able to correctly simulate dynamic conditions such as those encountered during discharge. Other numerical methods were therefore sought, such as the discrete element method (DEM) (Tijskens, Ramon, & Baerdemaeker, 2003). This allows the individualised simulation of all the particles making up a granular mass (Cundal & Strack, 1979). The DEM is therefore particularly indicated for the mechanical study of granular materials, both under static and dynamic conditions.

The DEM allows one to obtain a great deal of detail on the variables governing the behaviour of granular materials. In the research setting, this affords a great advantage over the experimental techniques commonly employed. Indeed, many researchers are now using DEM models to describe the distribution of pressures in silos (Goda & Ebert, 2005; Masson & Martinez, 2000), the flow patterns produced (González-Montellano, Ayuga, & Ooi, 2011; Ketterhagen & Hancock, 2010), segregation phenomena (Ketterhagen et al., 2007) and discharge rates (Balevicius, Sielamowicz, Mroz, & Kacianauskas, 2011; Mankoc et al., 2007). However, this method is still being developed. The capacity of many computers does not meet the demands of the technique, obliging the use of simplifications (González-Montellano, Ramirez, Fuentes, & Ayuga, 2012) that do not always represent reality well. In addition, there are currently very few valid procedures for measuring the material properties involved in numerical models (Asaf, Rubinstein, & Shmulevich, 2007), meaning they often have to be estimated. Finally, many of these models have not been experimentally validated; the adequate correspondence of numerical results with reality cannot always, therefore, be guaranteed.

* Corresponding author at: ETSI Agrónomos, Avda. Complutense s/n, 28040 Madrid, Spain. Tel.: +34 91 336 5620; fax: +34 91 336 5625.
E-mail address: carlos.gonzalez.montellano@upm.es (C. González-Montellano).

0098-1354/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compchemeng.2012.02.007

The aim of the present work was to analyse the numerical results obtained by two DEM models (one for glass beads, the other for maize grains) used to simulate the filling and emptying of a small silo equipped with a hopper. The values for the properties of the studied materials were considered representative since they were largely determined experimentally. The values for those that could not be measured were adjusted using the process of validation and calibration described by González-Montellano, Ramirez, Gallego, and Ayuga (2011b). Simplifications were avoided to prevent any interference with the results obtained. Thus, the models used were of a 3D nature instead of the simplified 2D models commonly used, and the shapes of the particles simulated were as close to reality as possible. In addition, the virtual silo was filled progressively, not *en masse* as is usually the case. While the *en masse* filling method notably reduces the calculation time required, it leads to errors in the prediction of pressure values (González-Montellano et al., 2012).

The present work exhaustively analyses the numerical results obtained with these models in order to better understand the pressures, flow patterns and the distribution of bulk density occurring in silos. The vertical distributions of normal pressure, tangential pressure and mobilised friction on the silo walls, as well as the horizontal distribution of the normal pressure were all examined. The flow pattern developed during the discharge of the silo was also studied via examination of the velocity profiles, the mass flow index associated with each profile, and via the direct observation of the discharge. Finally, the distribution of the bulk density inside the silo during filling and discharge was studied. With the aim of understanding the influence of particle shape and size on the above-mentioned variables, the numerical results obtained for the two studied materials were compared. Silo filling and discharge are real situations in which many phenomena are still not well known. Unlike the experimental procedures, the discrete element method is a good technique to obtain a great deal of detail them.

In addition, all these results are compared with the expected behaviour during silo filling and emptying. This will allow assessing whether the DEM models developed in this work have better predicting capabilities than oversimplified models. In that case, assumptions considered in these models should also be taken into account to study other specific and more complex silo problems. Some of these problems are: asymmetric loads on the walls, their causes and their practical evaluation; the effect of friction forces on silo walls and the load distribution in stiffened silo walls; the effect of corrugated walls on the pressure distribution; the peak pressures on the transition between the vertical section of the silo and the hopper, etc. (Ayuga, 2008). All these problems, not completely resolved nowadays, will be better known and analysed with appropriate DEM models.

2. Methodology

2.1. Discrete element models

The DEM models used in the present work (M1 – glass beads, and M2 – maize grains) were designed to simulate the filling and discharge of a small silo with a square cross section, equipped with a hopper (a truncated square pyramid) on its lower face (Fig. 1). The virtual silo was filled progressively to avoid the errors caused by the more commonly used *en masse* filling method (González-Montellano et al., 2012). Thus, the particles were progressively generated from a virtual square surface in the upper part of the silo (Fig. 2). These particles fell under gravity into the silo until reaching a static position. The height of the column of the material (measured from the outlet to the centre of gravity of the cone of material on the column's free surface), H_m, was ≈0.88H (where H is the total height of the silo body without the hopper) for the glass beads and 0.81H for the maize grains. Once the virtual silo was full, the wall closing the hopper outlet was removed, allowing the discharge simulation to proceed. From this moment on, the simulation continued for 4.5 s.

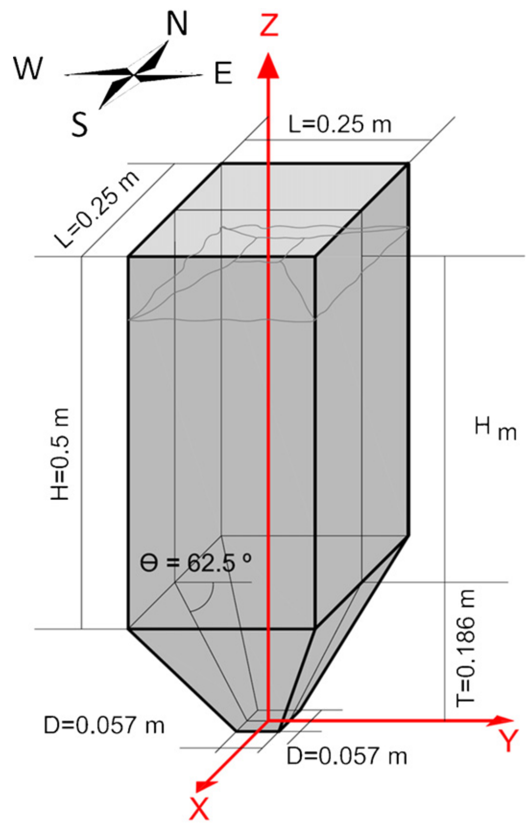

Fig. 1. Shape and dimensions of the simulated silo.

All simulations were performed using commercial EDEM Academic 2.3 (2010) software. In all simulations the Hertz-Mindlin elastic, non-linear contact model was employed for the simulation of particle–particle and particle–wall contacts (Tsuji, Tanaka, & Ishida, 1992). With the aim of taking into account the dissipation of the system's energy, viscous damping was contemplated in the normal and tangential directions for each contact, along with frictional damping in the tangential direction. In all simulations a time step (Δt) of constant value was used, fixed as the 20% of the critical time step (Δt_c), which in turn was calculated from the Rayleight time (t_R) (Li, Xu, & Thornton, 2005). The resulting Δt values were 1.84×10^{-6} s and 5.06×10^{-6} s for the glass beads and maize grains respectively.

2.2. Material variables

Table 1 shows the values of the variables associated with each material and the properties of interaction taken into account in the DEM models. The values shown correspond to those obtained by González-Montellano, Ramirez, et al. (2011). In the latter work, preliminary values for most of the variables were obtained by direct measurement. Their use led to the construction of different DEM models for silos; these were experimentally validated by comparing the flow predicted numerically with that observed in a real experiment. When the validation was negative, the preliminary values were progressively corrected via a calibration procedure. The values finally obtained via this process were those used in the present work, considering methacrylate as the wall material.