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DEM modelling of silo load asymmetry due to eccentric filling and discharge

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ABSTRACT

The discrete element method is a promising approach to simulation of certain mechanical phenomena that cannot be modelled by means of the continuum mechanics approach. One of these phenomena is the anisotropy of loads exerted by granular deposits on the elements of a storage structure. In this project, DEM simulations were performed to examine the asymmetry of silo wall loads during eccentric filling and discharge of a model silo. The silo, with a diameter of approximately 26 particle diameters and a height of 2.5 silo diameters, was filled with 30,000 spherical particles. The configuration of the simulations reflected the conditions (but not the scale) of earlier laboratory tests on the filling and discharge of a 2.44-m diameter model flat-floor silo used for storage of wheat. The simulations were observed to adequately reproduce the qualitative behaviour of the loads during filling and discharge in the laboratory tests. The simulations underestimated the vertical wall loads compared with the experimental results. This underestimate is likely a result of the perfect spherical shape of the particles and the relatively weak damping of the translational and rotary vibrations in the test model.

1. Introduction

Granular materials present a complex mechanical response to an external load, and even an assembly of mono-sized spherical particles may display strong anisotropy. The initial structure of a deposit is determined by the method of deposition or compaction. The contact between grains may undergo tangential forces of various values and directions depending on the load history. When a granular material is subjected to mechanical loading, friction is mobilised in the contact areas to an extent that allows the material to withstand deformation. Only the boundary states are visible to an external observer when motion in the contact area takes place. The effects arising from material discontinuity or non-homogeneity pose new difficulties that cannot be treated efficiently using methods based on continuum mechanics.

The main industry interest in the development of granular mechanics is improvement of the efficiency of such technological operations as storage, handling and processing. Scientific interest is mainly focused on finding an efficient method for the description of the material behaviour as well as an explanation for its peculiarities.

Numerous problems in civil engineering and silo technology have been solved through the application of phenomenological laws, such as the analytical Janssen's [1] method of load estimation on structural members of a storage silo or Jenikes description of granular solid flow [2]. As soon as the efficiency of numerical methods became practical, this approach was employed by engineers to a variety of problems, including a project involving a large number of laboratories around the world aimed at the estimation of stresses in a silo, as reported by Holst et al. [3,4]. Physicists have searched for a description of granular media based on a more theoretical framework. In this work, the areas of research interest are the granular flow from a silo (e.g., [5–10]), jamming during discharge (e.g., [11]), questions of packing structure [12,13] and contact network evolution under load [14,15].

Eber [16] pointed to specific difficulties in the analysis of conglomerates of discrete particles under a mechanical load. In a conglomerate of a large number of granules, the positions and orientations of the individual contacts are not defined, and the contact itself is determined only through friction, which introduces another indefinite property of the assembly. Numerical methods based on a microstructural approach appear to be a promising tool for tackling such tasks. One of these methods, the Discrete (or Distinct) Element Method (DEM), is based on tracking the motion of each individual particle in the assembly and obtaining detailed information regarding the system behaviour. The trajectory and rotation of each particle in the system are obtained in simulations using a numerical time integration scheme. The contact forces at each contact point are evaluated at each step and are resolved into normal and tangential components. Newtons' second law of motion is then applied to determine the motion of each particle due to any unbalanced force. The main limitation of DEM application in design is the computational requirements because the method uses an explicit time integration scheme and iterative calculations with a notably short time step.

Based on consideration of the individual contact conditions between particles in a granular assembly, DEM appears to be a promising tool for treating phenomena originating in the non-homogeneity,

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discontinuity or anisotropy of granular bedding. One of the main problems in silo technology is the asymmetry of load distribution due to non-axial filling or discharge, and non-symmetrical silo wall loads are considered to be a major cause of silo failures. However, no design method for prediction of loads for this discharge condition has gained general acceptance [17]. As shown by Molenda et al. [18] in their laboratory model tests, non-axial filling of a silo intensifies or weakens the load asymmetry during discharge, depending on the location of the filling and discharge gates. Selected data from that study have been used for comparison with the DEM simulations performed in this research.

The objective of this project was to examine the applicability of DEM to modelling of the asymmetry of silo wall loads due to eccentric filling and discharge.

2. Previous work

The experimental tests were conducted in a cylindrical flat-floor, corrugated-walled steel grain silo [18]. The silo measured 2.44 m in diameter and 7.3 m in height. The walls and floor of the silo were each supported independently on three load cells to isolate the wall and floor loads.

Soft red winter wheat with a moisture content of 13% (wet basis) and an uncompacted bulk density of 760 kg/m^3 was used for the tests. A fill chute was installed at the top of the silo to concentrate and direct the stream of grain parallel to the silo axis. The silo was initially filled to a height-to-diameter ratio (H/D) of 2.0 for each test.

To execute the eccentric filling, the model silo was loaded from a moveable fill chute located along a radial line at an eccentricity ratio of 0, 0.5 or 0.75. The eccentricity ratio (ER) is defined as the ratio of the distance from the silo axis to either the fill location or the discharge gate divided by the radius of the silo. Grain was then discharged from the silo out of one of five discharge orifices located at an ER of 0, ± 0.5 or ± 0.7. For both an ER of 0.5 and 0.7, two different eccentric discharge gates were used, located on opposite (plus or minus) sides of the silo on one of the major axes parallel to the loading axis. The discharge orifices were 89 mm in diameter, which produced a discharge flow rate of 260 kg/min and a vertical velocity along the silo wall during mass flow of 3.1 m/h. The locations of the fill chute, the discharge orifices and the load cells associated with the wall cylinder are shown in Fig. 1. The fill chutes are designated by the symbol (F), and the locations of the discharge orifices are designated by the symbol (D). The wall and floor loads were measured during loading, retention and discharge at 1-min intervals until the discharge was completed.

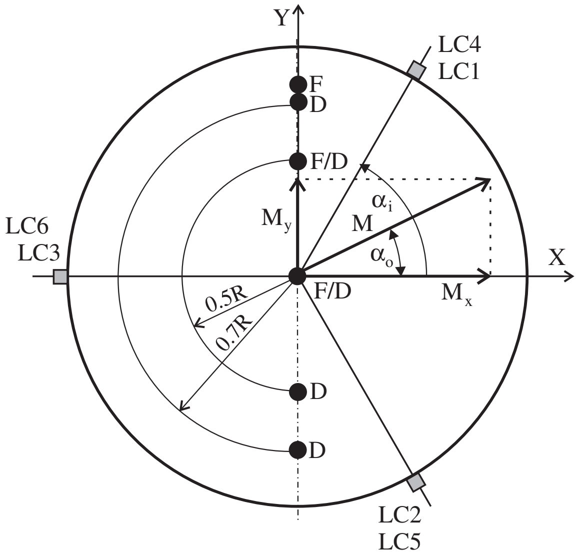

Fig. 1. Location of load cells (LC), filling chutes (F) and discharge orifices (D) in the model grain silo.

The total vertical floor loads, F_{vl}, and the total vertical wall loads, W_{vl}, were calculated using the following equations (see Fig. 1):

$$F_{vl} = F_1 + F_2 + F_3, \tag{1}$$

$$W_{vl} = F_4 + F_5 + F_6, \tag{2}$$

where:

F_{vl}	vertical forces carried by the floor (floor load cells Nos. 1, 2 and 3)
W_{vl}	vertical forces carried by the wall (wall load cells Nos. 4, 5 and 6).

Fig. 2 illustrates the typical relationships between the vertical loads and time during the filling/discharge of the model silo; the data recorded during the retention period of 30 min were removed from the plot. The total vertical load (T_{vl}), W_{vl} and F_{vl} are drawn to show behaviour typical of free-flowing granular materials. The filling and discharge rates are proportional to time, showing the effect that allowed for the development of an hour-glass. A portion of the load is supported by the floor of the silo, and the remaining portion of the load is supported by the wall due to the action of friction between the grain and the wall. In the case of the presented results, 0.56 of T_{vl} is supported by the floor and 0.44 of T_{vl} is supported by the wall at the end of the fill phase. Opening of the discharge orifice results in a so-called “load shift”, involving a change of direction of the principal stresses, a decrease in F_{vl} and an increase in W_{vl}.

The longitudinal bending wall moments of the silo about each of the major axes were calculated using the following equations:

$$M_x = R_w(F_4 \sin\alpha_4 + F_5 \sin\alpha_5 + F_6 \sin\alpha_6), \tag{3}$$

$$M_y = -R_w(F_4 \cos\alpha_4 + F_5 \cos\alpha_5 + F_6 \cos\alpha_6), \tag{4}$$

where:

M_x	moment about the X-axis of the floor,
M_y	moment about the Y-axis of the floor,
α_i	angular coordinates of load cell number i with respect to the X-axis,
R_w	distance of the load cell from the axis of the silo.

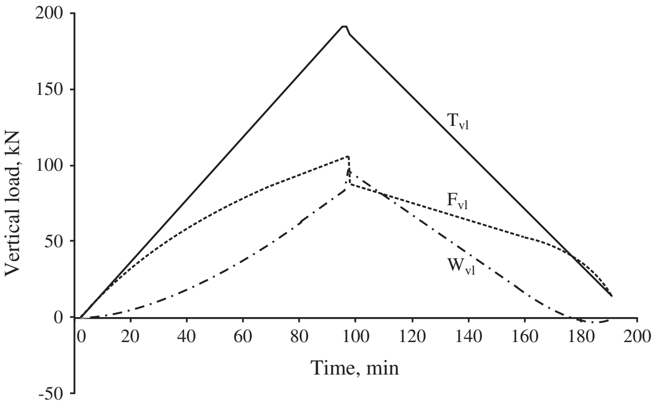

Fig. 2. Vertical loads: total grain weight, wall and floor loads during filling and discharge of a flat-floor silo with a 2.44-m diameter.