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DEM simulations of loads on obstruction attached to the wall of a model grain silo and of flow disturbance around the obstruction

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ABSTRACT

In the design of a storage silo usually an axially symmetric state of stress is assumed. However, unsymmetrical pressure distribution may occur because of such factors as: non-uniform humidity of the material, eccentric filling or/and discharge, and additional construction elements inside the deposit. Small internal construction members act similarly to structural imperfection and can initiate buckling, while larger flow obstacles can markedly alter the stress distribution.

A study was conducted to numerically simulate the effect of plane (2D) or block (3D) obstruction attached to the wall in a model grain silo holding wheat. This work compares the results of earlier laboratory testing and numerical simulations using the discrete element method (DEM).

Series of the DEM simulations were performed with an assembly of 75 000 spherical particles with random uniform distribution of diameters with a mean of 3.8 mm and range of ± 1% placed in the cylindrical container with a diameter of 0.12 m. The set-up of DEM simulations reproduced earlier laboratory tests performed in the model grain silo, 1.83 m in diameter with flat floor and corrugated wall. Despite the very large difference in the number of particles in real and simulated deposits, the results of simulations and laboratory testing were in fairly good agreement.

1. Introduction

Complexity of geometry and variability of properties of individual particles result in difficulties in an analytical description of numerous phenomena observed in mechanical behavior of granular media. Additional difficulty poses usually an undefined degree of mobilization of friction forces between particles until Mohr–Coulomb strength criterion is attained and sliding occurs.

For conditions where analytical estimations are not possible, laboratory modeling has been used, but due to difficulties or impossibility of scaling also this method was not always efficient.

The design and the control of storage facilities based on silos is one of the branches of technology where the control of behavior of the granular material is crucial for economic efficiency and safety reasons. In the design of storage silos usually an axially symmetric state of stress is assumed. However, unsymmetrical pressure distribution may occur because of such factors as: non-uniform humidity of the material, eccentric filling or/and discharge (e.g. [1]), and additional construction elements inside the deposit. Moreover, such effects as the shape of the flow channel, dead zones, loads on buried construction members or material segregation remains devoid of proper interpretation [2].

Damage of equipment or disturbances of operation of storage structures [3,4], as well as laboratory examinations [5–7] point out to difficulties in the precise estimation of loads exerted by the granular material on construction members buried in it. No recommendations may be found in design codes regarding the method of estimation of loads allowing consideration of stagnant zones in the granular material accumulated on structural members or geometry of the flow channel. According to Benson et al. [8], in tall and narrow silos sometimes sound resonance is produced by stick–slip friction between the wall and the granular material. The occurrence of flow pulsations is determined primarily by the surface properties of the granular material and the wall.

With substantial development of computer technology of recent decades some effects that could not be efficiently treated with earlier available approaches may be simulated using numerical methods. The distinct element method (DEM) originally proposed by Cundal and Strack in 1979 [9] is considered one of the promising methods in that regard. One of its possible applications is the estimation of flow patterns and loads exerted by the granular bed on construction members buried in it. One of recently reported projects is that of Moysey et al. [7] where DEM was used for the determination of some process conditions in a moving bed of the chemical reactor applied in production of pure nickel from gaseous nickel carbonyl. The authors simulated the drag force acting on objects held stationary in a moving bed of nickel pellets with diameters in the range from 1 to 10 mm and compared results with those of laboratory testing. The authors observed an excellent

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agreement of results of simulation results and measurements of the drag force. The project results pointed out to other possible questions that might be treated with DEM such as intensity of force fluctuations due to its frictional nature or that the small horizontal plates do not disturb the flow and thus could be used as a probe of the stress in the granular bed. Kobyłka and Molenda [10] adopted somehow similar approach to examine the question of loads on disk inserts of various diameters immersed in grain. These authors found that estimated vertical loads on disks during discharge corresponded fairly well to the experimental results. However, in the case of the largest disk loads from numerical estimations were nearly two times higher than the experimental measurements. This was probably due to arching as the gap between the disk and the wall was too small to allow free flow. In the other project Kobyłka and Molenda [11] used DEM to study another peculiarity of behavior of granular bedding observed in practice — load asymmetry due to eccentric filling or discharge of storage silo holding wheat. Even in the case of centric filling static moments bending wall and floor of the silo were observed as a result of non-perfect axial filling. The results of simulations were found to adequately reproduce the behavior of loads during filling and discharge. The effects due to the outflow of particles were reflected in the simulations as well. Authors obtained the transition from mass to funnel flow at h/D of approximately 1.4, which is in agreement with an experimental result. However, some deficiencies of simulations were noted, namely, too small a number of particles used and oversimplification of assumptions.

This article reports the study that was conducted to simulate the effects of plane (2D) or block (3D) obstruction attached to the cylindrical wall of the model silo storing wheat that were earlier tested in a laboratory experiment [6]. The DEM software (LIGGGHTS) as developed by Kloss et al. [12] was used.

2. Materials and methods

2.1. Silo testing — earlier work

DEM simulations reported in this article have been conducted to model earlier laboratory tests performed in flat floor model grain silo [13,14]. Soft red winter wheat with a moisture content of 11.3% (wet basis) and uncompacted bulk density of 772 kg/m^3 was used for the tests. The 1.83 m in diameter corrugated wall silo was 5.75 m high (filled to a maximum H/D of 2.75). It exhibited the mixed flow during discharge with grain sliding along the wall above the effective transition and grain remained stagnant below the effective transition (located at h/D of approximately 0.7). The wall and the floor of the silo were each supported independently on three load cells (see Fig. 2a). The silo was constructed to isolate the vertical wall loads from the floor loads. The load cells supporting the silo wall and the silo floor were evenly spaced around the circumference of the silo at an angular distance of 120°. This type of experimental configuration allows for the determination of vertical wall and vertical floor loads as well as the calculation of overturning moments on the walls and the floor of the silo. In the experiment, which was simulated for the comparison, the silo was centrally filled from a spout at a flow rate of approximately 2600 N/min, up to initial height-to-diameter ratio (H/D) of 2.75. After filling, the grain was allowed to equilibrate (detention) for a period of 0.5 h. The silo was then discharged through a centric orifice 7.2 cm in diameter that produced a sliding velocity along the bin wall during the mass flow of 3.1 m/h. The wall and floor loads were measured during loading, detention and discharge at 30-s intervals until discharge was completed. The loads were measured with an accuracy of ± 20 N.

Tests regarding load asymmetry due to obstructions attached to the silo wall were conducted using plane (two-dimensional) or three-dimensional obstructions (see Fig. 1a). The plane obstruction was an annular segment spanning 60° along the wall circumference and had a surface area of 0.189 m^2 or 7.2% of the bin cross-sectional area. The three-dimensional obstruction (block) used the base of the two-dimensional obstruction but was 0.5 m high and formed using smooth, galvanized steel. The obstructions were attached to the wall with their upper base at H_i/D ratios of 0.38, 0.81 and 1.26. These locations placed the obstructions within the stagnant zone, within the transition zone between the stagnant grain and the funnel flow, and in the mass flow zone. The lateral pressure was measured using earth pressure cells. Two Geokon 3500 pressure cells (Lebanon, New Hampshire) 23 cm in diameter with a 100 kPa range and accuracy of 0.25% of full scale (± 250 Pa) were used for measuring grain pressure.

Meridional distribution of horizontal pressure for filling was found lower than Janssen's estimation, particularly below the obstruction [14]. At the onset of discharge (maximum value of h/D coordinate on the plots at Fig. 2) a sudden increase in horizontal pressure was observed (see Fig. 2). Without an obstruction attached to the wall, a maximum pressure increase of 2.5 times the static pressure was observed. Dynamic pressure increases above the obstruction were a maximum of four times the static pressure. Conversely dynamic pressure increases below the obstruction were lower than the ones obtained without the obstruction. The data indicated that there are considerable additional loads exerted on a bin due to obstructions that may form during the storage that are not considered in the design codes.

Eurocode 1 [15] defines the lateral pressure ratio k as the ratio of the horizontal pressure on the vertical wall of a silo to the mean vertical stress in the solid at the same level. Usually an active (or static) stress exists during filling, while a passive (or dynamic) stress field develops during discharge. The traditionally used term "active" means the case when the higher principal stress σ_1 is oriented vertically, while σ_2, the lower one, is oriented horizontally [16]. These states of stress are accompanied by "active" and "passive" stress ratios.

Fig. 3 shows the stress ratio k against h/D ratio from experimental results for filling and discharge of the model silo. For calculation of k, values of lateral pressure measured at an h/D of 0.1 were used, while mean floor pressure was obtained as the ratio of vertical floor load to silo floor area. During filling of the silo, k increased with some fluctuations and slow local decreases until it stabilized at a value of approximately 0.43 at an h/D ratio of approximately 1.4. During the detention period of 30 min, k decreased slightly to a value of 0.41. After the initiation of discharge, k immediately increased to a value of 0.63 and slowly increased during continuous unloading to a value of 0.73. After the grain level decreased down to an h/D of approximately 0.7, the pressure ratio decreased rapidly to zero. The value of k of 0.41 was lower than 0.54 recommended for wheat by Eurocode 1. The dynamic to static wall pressure ratio measured was $0.73/0.41 = 1.78$ which was also higher than the overpressure factor of 1.15 recommended by Eurocode 1. This discrepancy in results may be attributed to the relatively low level of vertical pressure under which tests in the model silo were performed. For the case of a 1.83 m diameter silo and h/D of 2.0 the static floor pressure was 14 kPa. Thompson et al. [17] reported that typical storage conditions in a full size corrugated silo with a 15 m grain height, a vertical floor pressure of approximately 100 kPa was observed. The floor pressure in the 1.83 m in diameter model was more than seven times lower than in field conditions.

Tests on the model silo pointed out that while Janssen's equation can provide a simple estimation of the loads which might act on an obstruction buried in granular materials it fails to predict to a satisfactory degree a number of effects which alter the vertical loading on these obstructions. Some of these effects are stress history of the bulk, peak loads at the beginning of discharge, variations in the stress state in the stagnant zone of materials, load asymmetry and load fluctuations, and non-homogeneity of the material properties originating from variability of the packing structure of the bulk.

2.2. Simulation set-up

Numerical experiments were carried out in the cylindrical container with diameter $D = 0.12$ m and height $H = 0.33$ m ($H/D = 2.75$)