ARTICLE IN PRESS
PTEC-10796; No of Pages 12
Powder Technology xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Powder Technology
journal homepage: www.elsevier.com/locate/powtec

A numerical study of wall pressure and granular flow in a flat-bottomed silo

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ARTICLE INFO

Available online xxxx

Keywords:
Finite element modelling
Arbitrary Lagrangian–Eulerian formulation (ALE)
Wall pressure
Granular flow

ABSTRACT

This paper presents a numerical study of the granular flow in the discharge of a flat-bottomed model silo. The behaviour of the stored granular material is modelled using the finite element (FE) method based on an Arbitrary Lagrangian–Eulerian (ALE) frame of reference, which has shown advantageous performance over the classical FE methods in simulating the silo filling and discharge process in a series of studies leading up to this investigation. Experimental results have been used to validate the computational model using the ALE technique. The spatial distribution and time history of the pressures acting on the vertical silo walls predicted by the FE model are found to resemble well the test results. A semi-mass flow pattern has been predicted by the numerical model, which is very consistent with the corresponding experimental observation. With the validated numerical model, the flow behaviour specifically under a flat-bottomed geometry of silos is examined. Based on the velocity distribution in the granular material, a critical velocity ratio criterion is proposed and used to identify the flow channel boundary. A further numerical study has shown that the flow behaviour in the flat-bottomed silo is closely related to the shear strength of the material, which is represented by the internal friction angle for the cohesionless sand considered in the present study.

1. Introduction

Silos and hoppers are commonly applied in the storage, handling and transportation of bulk solids in industries. Since the end of the 19th century [1], silo behaviour in terms of pressure and flow has been extensively studied and progressive advances in knowledge have been achieved [2–7]. However, many aspects concerning the silo structure design still remain unresolved [8]. The determination of the pressures acting on the silo walls, which constitute the main loads in silo design, is an important one. Earlier studies of silo pressure suggest that the wall pressures during filling and storage can be well represented by Janssen type pressure equations [5,9,10]. However, there has been no consensus with regard to the discharge pressure due to its complex time and spatial variations. With a general lack of understanding and information on the discharge process, most national standards have defined silo discharge pressure using simply a multiplier applied to the filling pressure based on Janssen's theory and its modified versions [11]. As a matter of fact, the prediction of the wall pressures during discharge is particularly challenging, as the pressure tends to exhibit significant fluctuations and its distributions along the silo walls depend closely on the flow pattern developed throughout the silo. More work is still required to understand the detailed development of the flow pattern and the dynamic phenomenon so that the discharge pressure can be determined more accurately.

Concerning the general flow behaviour during discharge of silos, numerous experimental studies have been carried out [6,12–16]. General characterisation of the funnel flow, which may be subdivided into the semi-mass flow and the internal funnel flow, has been established for the flat-bottomed silos. In both types of funnel flow, some particles are stationary and there is a flow channel boundary separating the flowing and static particles. The difference between the two flows is that in the internal funnel flow the flowing particles do not come into contact with the silo walls, while in the semi-mass flow the flow boundary intersects the silo wall at some level.

The advancement in numerical methods and computer technology has also led increasing use of numerical simulation to study flow behaviour in silos [17–23]. While the finite element method is commonly adopted in analysing the flow in silos, one of the difficulties is the handling of mesh distortion due to the large deformation of the stored solid during discharge. In many previous studies, either a remesh-rezoning technique or an assumed failure boundary had to be used to describe the flow pattern developed in a silo during discharge in order to resolve the mesh distortion problem [24,25]. A new technique, known as the

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http://dx.doi.org/10.1016/j.powtec.2015.01.078
0032-5910/

Please cite this article as: Y. Wang, et al., A numerical study of wall pressure and granular flow in a flat-bottomed silo, Powder Technol. (2015), http://dx.doi.org/10.1016/j.powtec.2015.01.078

arbitrary Lagrangian–Eulerian (ALE) formulation, has been developed to combine the desired features of both the Lagrangian and the Eulerian approaches, particularly in describing the behaviour of solids under large deformations [26]. This technique has been applied to model the granular flow, and so far some satisfactory results have been obtained concerning the silo processes [21,27–29].

This paper presents a finite element (FE) simulation of pressure and flow in a flat-bottomed silo using an uncoupled Arbitrary Lagrangian–Eulerian (ALE) technique in the Abaqus/Explicit code [27] as part of a series of studies on the dynamic silo behaviour during discharge [28,29]. The ALE approach allows for the simulation of almost the entire silo discharge process without causing the mesh distortion problem. The geometry of the FE model is made the same as a silo experimentally studied at the University of Edinburgh [30] which is the derivative one of the original Danish silo [5], so that comparisons can be made directly. For completeness of the presentation, the key experimental results which are used in the present study are recapped and discussed in some necessary detail. The FE model is validated by comparing with the experimental results in terms of wall pressure and flow pattern in the silo. Through examining the velocity field in the silo, the Flow Channel Boundary (FCB) can be identified using a proposed FCB criterion for flat bottomed silos. A parametric study with respect to the effect of the internal friction angle of the granular material on flow behaviour in a flat bottomed silo has been performed. As far as the numerical study in this paper is concerned, the focus has been placed on the macroscopic phenomenon of discharge and the development of dynamic pressure on silo walls. For this purpose, a macroscopic elasto-plastic constitutive model (linear Drucker–Prager failure criterion with perfectly plastic flow rule) has been employed. A similar approach has been adopted in various numerical studies in this field [e.g. 24,25]. The model does not get into detailed shear localization, but it is capable of capturing in a macroscopic perspective the development of shear zones and the associated effect on the dynamic pressure on silo walls, which are deemed to be appropriate for capturing the macroscopic dynamic pressure and flow phenomena.

2. Overview of the experiment

The silo experiment was carried out in a flat-bottomed silo at the University of Edinburgh in the author's pervious study [30]. Dry sand without cohesion was used as the stored material in the silo. The silo consisted of a cylindrical part with a flat bottom, as shown in Fig. 1. The cylindrical part, which was made of epoxy walls of thickness 0.02 m, had an aspect ratio of about 6 (height 4.0 m, diameter 0.7 m). The outlet at the centre of the bottom is circular with a diameter of 0.04 m (see Fig. 2). In the silo walls were installed a total of 56 normal pressure measuring cells at eight levels: seven cells were allocated at each level and spaced 45° apart around the circumference (see Fig. 2). The pressure cells were mounted flushed on the inside of the silo walls and were covered with an epoxy adhesive mixed with sand. In this way the cells did not introduce any imperfections on the silo walls, or cause any change in wall friction [5]. Seven pressure cells, distributed along the same vertical line (labelled 5 at Generatrix 225°, see Fig. 2) are selected in the present study, and the normal pressure distribution along this vertical line is obtained from the recorded data. The seven selected cells, namely A5, B5, C5, D5, F5, G5 and H5,were located at the level of 0.35 m, 0.7 m, 1.05 m, 1.4 m, 2.1 m, 2.8 m and 3.5 m, respectively, above the silo bottom. Cell E5 was reported to be not working properly and thus was not considered in the present study.

The pressure cells were calibrated before they were mounted in the silo walls [30]. The pressure measurements were controlled using a data acquisition program, which recorded and analysed the data in real time. The recording was performed at 1000 readings per second. The model silo was originally constructed and instrumented by the well known team of Munch-Andersen, Askegaard and Nielsen as part of a very extensive study of silo pressure and flow and the model silo was re-established at the University of Edinburgh. For details of the full set of measurements and the general measurement reliability, a more detailed description can be found in the reference [5,31].

Each silo test was conducted as follows. First was the filling process, which took approximately 30 min. A storage period of 26 min followed. Then was the discharge, which took about 40 min. The testing silo facility was designed for distributed filling, which was achieved by feeding the dry sand in such a way that the surface was kept approximately horizontal throughout the filling process. The concentric discharge was operated by opening the outlet at the bottom and the sand was withdrawn under gravity. In this way, a discharge rate of about 0.1 m height fall per minute was recorded.

Fig. 3 shows the time histories of normal wall pressures recorded by the seven pressure cells at different height levels. The pressure increased progressively until the end of the filling and then kept almost constant during the storage period. Once discharge started, significant

Fig. 1. The experimental setup.

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