Particuology 18 (2015) 42–49

Contents lists available at ScienceDirect

Particuology

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

Prediction of flow patterns during silo discharges using a finite element approach and its preliminary experimental verification

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ARTICLE INFO

Article history:
Received 7 February 2014
Accepted 24 April 2014

Keywords:
Silo
Discharge pattern
Flow boundary
Double-cone insert
FE analysis
Preliminary verification

ABSTRACT

Obtaining a reliable discharge of particulate solids from a storage silo is a prerequisite to securing operational adequacy in solids handling processes. If a silo is poorly designed, an unreliable interrupted discharge often occurs. In this study, an in-house finite element (FE) program was modified to predict the particulate solids flow patterns during discharges from silos, and the effect of a double-cone insert on such flow patterns. In FE modeling, a Eulerian approach was adopted with an assumption of steady-state flow—a state that greatly facilitated investigations on the effects of double-cone inserts on the flow of particulate solids. Predictions were carried out on whether the discharge was in mass flow or funnel flow, associated with the inclination angle of the silo's hopper. Predicted results were in agreement with the Jenike Chart, and proved that an upper lateral pressure ratio value gave a better critical hopper half angle to achieve mass flow (EN 1991-4, 2006). The shape and size of the stagnant zone were further discussed to address the flow channel boundary between the flowing and static solids if the discharge was in a funnel pattern. Results also showed the effects of a double-cone insert on the flow patterns which converted silos from funnel flow to mass flow up to a certain hopper inclination angle and would improve the flow pattern even for shallower angles. Experiments were carried out to verify some of the predicted results. Some qualitative comparisons were made between the predicted results and experimental measurements, which indicated that further efforts are needed in predicting the shape of the stagnant zone (flow channel boundary) during funnel flow discharges.

Introduction

The storage of particulate solids in silos is a common practice in the handling processes of particulate solids. Concern has been raised on the operational adequacy during silo discharge in the following procedures. In general, silos with steep hoppers and smooth walls lead to mass flows, securing a reliable flow where all the solids are moving once discharge starts, whereas silos with less inclined hoppers or rough walls develop funnel flows, causing interrupted, unreliable, and even impeded discharges (Campbell, 2006; Drescher, 1992, 1998; Jenike, 1964, 1987; Michalowski, 1987; Novosad & Surapati, 1968; Perry, Rothwell, & Woodfin, 1976; Rao & Venkateswarlu, 1973; Rotter, 1998, chap. 36; Rotter, 2001). With the progress of a discharge, a mass flow pattern may switch to funnel flow when the upper surface of the solids reaches a critical height (Benink, 1989; Drescher, 1992). In funnel flows, there is a flow channel boundary between flowing and static solids, most likely above the hopper walls. Prediction of the whereabouts of such a boundary is important in identifying the locations of the pressure transitions along the wall of a silo, an issue that remains to be addressed (Carson, Goodwill, & Bengtson, 1991; Johansen, 2004; Matchett, 2006, 2007; Nedderman, 1995). The concept of an effective hopper wall friction coefficient (a critical hopper half angle θ_{cri}) was proposed to differentiate the steepness of a silo hopper into steep or shallow hoppers, which was then used to attempt to develop criteria for predicting pipe or mixed flow during a concentric-channel funnel discharge (Ding, Rotter, Ooi, Enstad, & Xu, 2013; EN 1991-4, 2006; Rotter, 1998, chap. 36; Rotter, 2001).

The importance of avoiding flow disruption and quality variation and the desire to eliminate the stagnant zones associated

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http://dx.doi.org/10.1016/j.partic.2014.04.015

with funnel flows normally requires mass flows rather than funnel flows in silo designs. Based on the measured flow properties of particulate solids, mass flow silos can be designed with a degree of confidence, often with rather steep hoppers (Drescher, 1992; Jenike, 1964, 1987). Meanwhile, attempts have also been made to obtain mass flows in silos with reasonably shallow hoppers. Making the walls of silos smoother (using a smooth material for silo walls decreases friction) or mounting flow aid inserts into the silo are among adopted approaches (Ding, de Silva, & Enstad, 2003; Härtl et al., 2008; Jenike, 1964, 1987; Johanson, 1968; Tuzun & Neddermann, 1982, 1985; Wojcik et al., 2007).

Theoretical methods are still limited to simple situations where silo flow patterns can be addressed. This is mainly because the behavior of complex particulate solids under static and flow scenarios is not understood when obtaining an analytical solution (Campbell, 2006; Cates & Wittmer, 1998; Edwards & Mounfield, 1996). As an alternative, numerical modeling is considered in this study for predicting the effects of flow aid devices on flow patterns.

Many computational approaches have been developed to simulate silo discharge behavior when addressing flow patterns and/or wall pressure distributions (Cundell & Strack, 1979; Gunies, Ragneau, & Kerour, 2001; Haussler & Eibl, 1984; Karlsson, 1996; Keiter & Rombach, 2001; Masson & Martinez, 2000; Rotter, Holst, Ooi, & Sanad, 1998; Rotter, 1998, chap. 36; Runesson & Nilsson, 1986; Sanad, Ooi, Holst, & Rotter, 2001; Watson & Rotter, 1996; Zhao & Shan, 2013). These approaches are mostly based on finite or discrete element approaches. While the behavior of individual particles has been thoroughly studied using the discrete element method, using finite elements (FE) is also widely adopted for modeling particulate solids as a continuum. With either a Lagrangian, a Eulerian, or a combined arbitrary Lagrangian–Eulerian approach, models have been created and implemented using finite elements to predict various aspects of silo discharge such as the development of shear bands, and the influence of inserts in silos (Ayuga, Guaita, Aguado, & Couto, 2001; Ding et al., 2003a; Ding, 2004; Karlsson, Kilsinski, & Runesson, 1998; Schuricht, Furll, & Enstad, 2009; Vidal, Couto, Ayuga, & Guaita, 2006; Wojcik & Tejchman, 2009). Based largely on soil mechanics, various constitutive models were adopted for particulate solids in a storage state. The most commonly implemented of these models are, for example, the Drucker–Prager model, Mohr–Coulomb model, and the very latest efforts such as the non-local hypo-plastic and non-coaxial models (Bohrnsen, Antes, Ostendorf, & Schwedes, 2004; Nielsen, 1998; Roscoe, Bassett, & Cole, 1967; Symes, Gens, & Hight, 1984; Yang & Yu, 2010; Yang, Ooi, Rotter, & Wang, 2011; Zhu, Mehrabadi, & Massoudi, 2007).

Direct observation in experiments when studying silo discharge patterns is rather challenging because of the opaque nature of particulate solids (Joba, Dardenneb, & Pirarda, 2009). The advantage of numerical approaches over experimental measurements is obvious when charting internal movements; for example, displaying velocity profiles across sections of a silo. It well suits the purpose of identifying the boundary of a channel between flowing and static solids during silo discharge as stated previously. With an in-house FE-based coded silo model, this study focuses on investigating the display of the velocity profiles, silo discharge patterns associated with the inclination angle of the silo's hopper, how a double-cone insert affects flow patterns during silo discharging, and the flow channel boundary in a silo where mass flow has not been achieved. Results obtained are presented. In addition, the predicted results were qualitatively compared with results available from some references, and from experimental measurements carried out to verify the model.

Basic features in silo and its FE model implementation

Methodology and approaches

Silo discharging processes present complicated challenges when implementing a FE model. The challenge lies first in selecting an approach that can describe a process as it occurs during discharge, and second in defining a suitable constitutive model that can approximate the complex behavior of particulate solids under pressure and shear forces. Assumptions were made on both these aspects to simplify the FE implementation.

Depending on the requirements in practice, particulate solids can be discharged either freely or under a controlled pattern through the outlet, where a fixed boundary is prescribed and the Eulerian approach is favored. In other regions (the top and contacting surfaces between the solids and walls of the silos), the boundaries change when discharge occurs and a Lagrangian approach is required. A combined Lagrangian–Eulerian formulation provides a complete description of the silo discharging process (Ding et al., 2003a; Ding, 2004; Wojcik & Tejchman, 2009; Yang et al., 2011). Considerable efforts were made to model silo discharging processes with this combined Lagrangian–Eulerian approach on an Abaqus platform; an error of singularity as "an invalid floating-point operation" was encountered during modeling. The author reported this error to the Abaqus Consultancy. Over a period of months of consultations, it transpired that the error was difficult to correct within the existing software, and would be addressed in a forthcoming version (Ding et al., 2003a; Ding, 2004). The author then resorted to the in-house FE-coded silo model.

The silo code was initiated by POSTEC, Tel-Tek Norway and developed in collaboration with Lurål University, Sweden (Ding, Wojcik, Jecmenica, & de Silva, 2003; Karlsson et al., 1998; Karlsson, 1996; Runesson & Nilsson, 1986; Schuricht et al., 2009). It was radically modified for the purpose of this study. A Eulerian approach was adopted in the silo code. To use this approach, it is necessary to fix all the boundary conditions. As mentioned above, it is reasonably easy to fix the boundary at the outlet. To constrain the upper surface means that the particulate solids have to be backfilled at the same rate as the discharge from the outlet, similar to an operation carried out in silo recycling, which can be modeled in the FE model as a steady-state discharge process. Because the work also focused on investigating the effect of inserts on the flow, this state was still regarded as acceptable. At the same time, this approach does not lead to deformation of the meshes as is otherwise encountered with the Lagrangian approach, and avoids issues of singularities as caused by, for example, more severe deformation of the meshes. For the same reason, this approach also has advantages in simulating the flow of particulate solids around the inserts, one of the concerns of this study.

An assumption in modeling the particulate solids in the silo was that it was a one-phase continuum and was adopted in the silo code. In the code, particulate solids were treated based on the principles of plasticity theory, with the Mohr–Coulomb/Drucker–Prager model's yield/failure condition to describe its flow behavior. The reader is referred to standard textbooks on soil- or geo-mechanics, or further in the Abaqus manuals (2004/2012) for general descriptions, and the publications (Karlsson, 1996; Runesson & Nilsson, 1986) for specific treatments. Admittedly, it is a coarse approximation of the complex mechanical behavior of particulate solids, but it describes the fact that the particulate solids have a limited capacity for sustaining stresses, and undergo a plastic flow.

Setting parameters related to the constitutive model for particulate solids. An assumption was made for the parameters of shear viscosity (μ) and bulk viscosity (κ), set as $\mu = 1 \times 10^5$ Pa and $\kappa = 9 \times 10^5$ Pa, based on the fact that these two parameters can not