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Simulation of bulk density distribution of wheat in silos by finite element analysis

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A B S T R A C T

Bulk density is a critical parameter for predicting grain pressures in silos, determining the resistance to airflow, and estimating the grain mass in storage bins, so studying the bulk density distribution is critical for the storage security of wheat during storage. To investigate the bulk density distribution of the wheat bulk stored in an axisymmetric steel silo with flat bottom, the Modified Cam-Clay model was applied to calculate the bulk density of wheat at four different moisture levels at different depth and radius of the silo. The results showed that the bulk density of wheat at different depth was not uniform and it increased with increasing grain depth but decreased near the wall-bottom of silos. Moreover, it was found that the bulk density of the wheat decreased with increasing radius at the same depth and the same moisture content. Furthermore, the mean bulk density of a layer of wheat was negatively correlated with moisture content at the same grain depth and approached a plateau value when the wheat was close to the bottom of the silo at the same moisture content. The bulk density was adequately fitted as a function of the grain depth and moisture content in silos.

1. Introduction

Wheat is an important commercial crop and a major source of food with worldwide production of 672 Mt in 2012 (FAOSTAT, 2014). China, as the largest producer and consumer of wheat in the world (He et al., 2001), has a wheat production of 100 Mt per year in recent years. Due to the large production and China's grain storage policy, a majority of the wheat is stored for an average of three years (Li et al., 2011), which is longer than the common storage time in developed countries. Therefore, safe storage of wheat in silos is of great importance.

During storage, wheat is undergoing various forces, such as gravity loading, internal friction and the force in contact with the wall of silos (Thompson and Ross, 1983; Moya et al., 2006), which causes wheat to compress. Once the wheat is compressed it will come to result in the particle rearrangement and the reduction of void space, resulting in the rise of bulk density and the deformation of wheat particles. Bulk density is a critical parameter for predicting grain pressures in silos, determining the resistance to airflow, and estimating the grain mass in storage bins (Madiouli et al., 2012; Cheng et al., 2014). It was found that the bulk density varied with the internal pressure (Thompson and Ross, 1983). Therefore, the stress distribution can be determined by the bulk density distribution. The bulk density is negatively linked to the porosity of grain in silos, which is an important parameter for determining the effect of ventilation to reduce the moisture content for better storage of grains. Theoretically, the porosity of a layer of grain in a silo can be calculated by the bulk density of this layer, surface bulk density and surface porosity. Furthermore, it is known that the grain mass in storage bins can be determined by the bulk density distribution. In China, the weighing method and volume density method are commonly used to determine the total storage weight of grains (Ren, 2007), but the weighing method is inefficient, and the volume density method is calculated by the mean density, which is determined by multiplying the surface density by a correction coefficient, which is evaluated by experience, so the method is inaccurate. It is meaningful to investigate the density distribution of wheat calculated by the FEM in silos.

At present, most studies mainly focused on the mean density of small grain storage. The bulk density of soft red winter wheat was calculated by the initial bulk density and the change in height by

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using an apparatus consisting of a flexible pressure diaphragm and a dial gauge (Thompson and Ross, 1983). The gas pycnometer was commonly used to measure the density (Chung and Converse, 1971; Gustafson and Hall, 1972; Sereno et al., 2007). Chang (1988) measured the density of grain kernels by using a gas pycnometer with helium. Walker and Panozzo (2012) applied ellipsoid approximation from a 2-D digital image to estimate the volume and density of barley with approximately 800 grains per sample within three to 4 min. However, no study concerning the density distribution of the grain storage with different depth and radius and the relationship between the density and moisture content in a silo has been published so far.

In the latter part of the 20 t h century, finite element method (FEM) was increasingly applied by many international scholars to study the stress distribution of granular materials in silos because of the improvement of computer technology. This scientific-based numerical technology can contribute to a safer and quicker simulation of stress distribution. However, most researches mainly focused on the stress distribution of stored material during filling or discharge (Vidal et al., 2008; Wang et al., 2014; Goodey et al., 2017). No information is available on the bulk density distribution of the grain calculated by the FEM in silos. It is known that the bulk density of granular material in silos is directly related to its volume strain, so we can calculate the bulk density distribution of wheat in silos by the strain distribution.

The Modified Cam-clay model is a basic constitutive model which provides adequate results for predicting material behavior in conventional triaxial tests as well as in consolidation analysis. Moreover, the model is relatively easy to use and understand. And the model has fully considered the volume strain of the material. For these reasons, the Cam-clay model was chosen to calculate the bulk density of wheat.

The main objective of this research is to study the bulk density distribution of wheat in silos and the variations of bulk density with grain depth, radius of silos and moisture content by the Modified Cam-Clay model through ABAQUS. As an extension, a secondary objective is to establish an equation for the bulk density as a function of the grain depth and moisture content using the calculated bulk density by the modified Cam-Clay model.

2. Materials and methods

2.1. Tested material

Wheat, Ningmai 13, was produced in Nanjing, China. This crop was manually picked to remove the broken and immature grains. The initial moisture content was 12.46% w. b. The moisture contents of the wheat were adjusted to four different moistures 10.20%, 12.46%, 14.05% and 15.96% w. b. The common range of moisture content of wheat was from 10% to 16% w. b. The sample were stored in plastic bags at approximately 4 °C. The moisture content of wheat was determined by using a standard oven-drying method to dry 10 g samples at 130 °C for 19 h in triplicate (ASAE Standards, 2001).

2.2. Model selection

To simulate bulk density of wheat in silos, this article firstly assumed the wheat with four moisture levels above was stored in a model silo, and then an appropriate elastoplastic constitutive model was used for describing the relationship of stress-strain of these grains. Finally, this selected model was applied to calculate the bulk density and the stress distribution of wheat at different moisture contents by using ABAQUS.

The selection of the elastoplastic constitutive model was the most important part of the bulk density simulations of this article. In the elastoplastic mechanics, researchers have considered several constitutive models (Zhang et al., 1986), such as Mohr-Coulomb, Drucker Prager, Lade Duncan and Modified Cam-Clay model. The Modified Cam-Clay model is a basic elastoplastic model which is widely used by engineers and researchers (Tripodi et al., 1994; Suebsuk et al., 2010). The model has only five parameters which are easily determined by conventional triaxial tests. Considering the large volume compression of grain under stress, the volume compression of wheat is more prominent in the process of compression. In the above cases, the modified Cam-Clay model is more suitable for studying the stress-strain relationship of wheat in storage.

2.2.1. The Modified Cam-Clay model

In the Modified Cam-Clay model, the total strain increment $d\varepsilon$due to a stress is divided into two components: the volume strain increment $d\varepsilon_v$and the shear strain increment$d\varepsilon_s$, as follows:

$$d\varepsilon = d\varepsilon_v + d\varepsilon_s \tag{1}$$

The volume strain increment $d\varepsilon_v$ and the shear strain increment can be written in the following form:

$$d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p \tag{2}$$

$$d\varepsilon_s = d\varepsilon_s^e + d\varepsilon_s^p \tag{3}$$

Where, $d\varepsilon_v^e$is the elastic volumetric strain increment; $d\varepsilon_s^e$is the elastic shear strain increment; $d\varepsilon_v^p$is the plastic volumetric strain increment; $d\varepsilon_s^p$is the plastic shear strain increment.

In the Modified Cam-Clay model, the generalized shearing force q and the mean principal stress p can be represented as follows:

$$q = \sigma_1 - \sigma_3 \tag{4}$$

$$p = (\sigma_1 + 2\sigma_3)/3 \tag{5}$$

2.2.1.1. Elastic stress-strain relationship.

The elastic strain increment is calculated using generalized three dimensional Hooke's law. So the elastic strain increment can be expressed as follows:

$$d\varepsilon_v^e = \frac{3(1-2\nu)}{E}dp \tag{6}$$

$$d\varepsilon_s^e = \frac{2(1+\nu)}{3E}\mathrm{d}q \tag{7}$$

$$E = \frac{3(1-2\nu)(1+e)}{\kappa}p \tag{8}$$

Bring formula (8) into formula (6) and (7), get the following equations:

$$d\varepsilon_v^e = \frac{\kappa}{1+e}\frac{dp}{p} \tag{9}$$

$$d\varepsilon_s^e = \frac{2}{9}\frac{1+\nu}{1-2\nu}\frac{\kappa}{1+e}\frac{dq}{p} \tag{10}$$

Where, ν is the Poisson's ratio, dimensionless; κ is the isotropic swelling index, dimensionless; e is the void ratio, dimensionless; E is the elastic modulus, kPa.