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Research Article

Micro Model of Grain Shearing During Silo Discharge

Changnu Zeng
School of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou, 450001, China

Abstract: In order to solve the current difficulties of modeling for designing grain silo considering silo shear during discharge. A new numerical model based on Discrete Element Method (DEM) is proposed from the micro levels. A DEM model based on triaxial test results is to examine the grain shear during silo discharge. Micro parameters comprise of the contact, material and mechanical models. The relationships between macro and micro mechanical parameters are built. Based on the results, this study proposed new methods of analyzing silo discharge, which provides cost effective and simple techniques to determine suitable input parameters for models of discrete element method and finite element method. Finally, the parameters given from numerical and experimental results have shown efficiency and rationality of this modeling method.

Keywords: Macro parameters, micro parameters, PFC3D, triaxial tests

INTRODUCTION

Silo is usually used for the storage of granular material such as grain, cements, sand *et al*. The mechanism of lateral wall pressure during silo discharge is still a challenge. The traditional method of Janssen's theory (1895) commonly suitable for static conditions is difficult to obtain exact dynamic lateral stress during discharge. It is very difficult to explain how the lateral pressure produced during discharge. The amount of lateral wall pressure recommended by the code all over the world do not very exactly reflect the real condition during silo discharge. One of the main reasons is that the mechanical character during discharge is still not well-understood. The shear character during silo discharge is very similar to the triaxial tests used for soils.

It is well-known that the stored granular material will shear during discharge by theory and test evidence. Many researchers studied the silo discharge using finite element method to study the key problem of lateral pressure. However the large deformation induced by discharge limited the use of FEM. The Discrete Element Method (DEM) is a very realistic tool for granular material (Cundall and Strack, 1979). DEM can capture particle behavior at the microscopic scale better than FEM method especially for silo discharge (Chen and Liang, 2008; Vidal *et al*., 2006; Haussler and Eibl, 1984; Więckowski, 2000). The modeling of triaxial tests using PFC3D is very popular for soils but the micro parameter of grain obtained from PFC3D is very rare in the literature. Analogy to sand, the determination of micro-parameters were the key parameter for the chosen of macro-behavior (Kozicki and Tejchman, 2011; Zheng *et al*., 2014). The 3D DEM modeling provides a realistic stress state (Lu and Frost, 2010; Zhao *et al*., 2011).

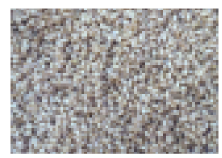

Fig. 1: Grain size

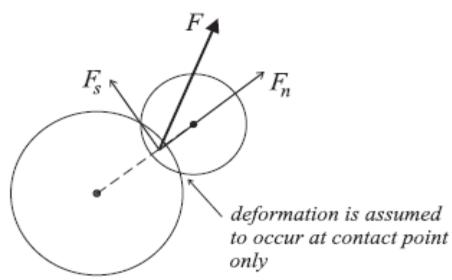

Fig. 2: Contact logic

In this study the particle interaction was modeled using PFC^{3D} to deduce the macro parameters. The parameters obtained from DEM method is obtained from a series of numerical modeling comparing with physical experiment results. From the comparison micro parameters as well as macro parameters are deduced for further analysis in the study.

MATERIALS AND METHODS

Materials: The grain material used for investigations was a winter wheat, grown in Henan, China. The average major and minor axes of the grain are 6.2 and 2.8 mm as shown in Fig. 1. The equilibrium moisture content of the wheat in the laboratory was 11.5%.

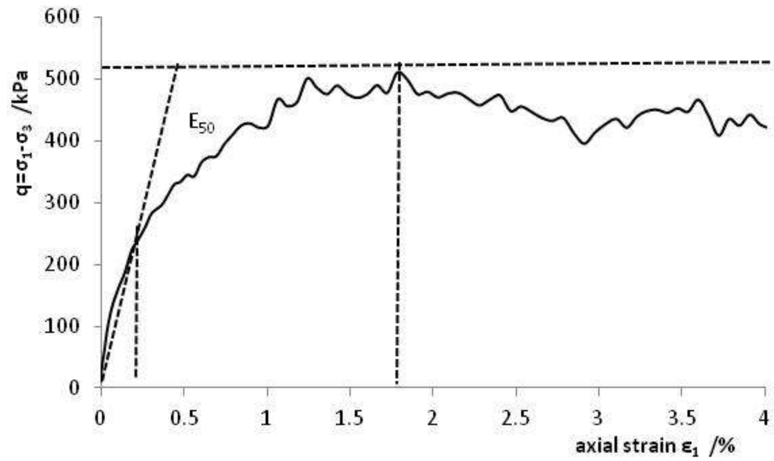

Fig. 3: Deviatoric stress vs. axial strain

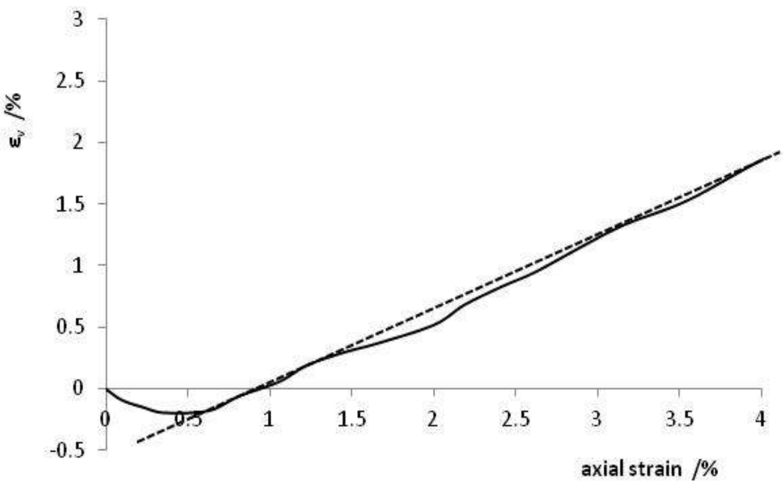

Fig. 4: Volumetric change vs. axial strain

Triaxial test model: The triaxial tests of wheat were conducted in triaxial tests using confining pressure of 100 kPa.

The macro parameters resulting from triaxial test simulation will be compared to the results from an triaxial test in lab. For a triaxial test $\sigma_3 = \sigma_2 =$ constant and it follows (1):

$$E = \frac{\dot{\sigma}_1}{\dot{\varepsilon}_1} \tag{1}$$

For plasticity the flow function become active at the same time resulting in an angle of internal friction according to the peak stress:

$$\left(\frac{\sigma_1}{\sigma_3}\right)_{\max} = \frac{1+\sin\varphi}{1-\sin\varphi} \tag{2}$$

During plastic flow, using the flow rule, the volumetric strain is the sum of the strains in all three directions. This results in:

$$\frac{\dot{\varepsilon}_{vol}}{\dot{\varepsilon}_1} = \frac{-2\sin\psi}{1-\sin\psi} \tag{3}$$

The simulations of triaxial tests are made with certain values for the micro parameters. The macroscopic quantities that the result from the test are the stresses of $\sigma_1, \sigma_2 = \sigma_3$ and the strains ε_1, $\varepsilon_2 = \varepsilon_3$. When the micro parameters are adjusted, the effect on the macro scale is measured by observing these quantities.

From these quantities, the macro parameters are determined using the Eq. (1) to (3). Two plots as shown in Fig. 1 and 2 were made of the result, the deviator stress $q = \sigma_1 - \sigma_3$ versus the axial strain and the negative volumetric strain versus the axial strain. The calculation is given in Fig. 3 and 4. The behavior looks more like that of triaxial test results with real materials having a stiffness decreasing slowly until a peak stress is reached. For this reason, it has been chosen to determine the elastic parameters E_{50} and υ_{50} like in triaxial tests.

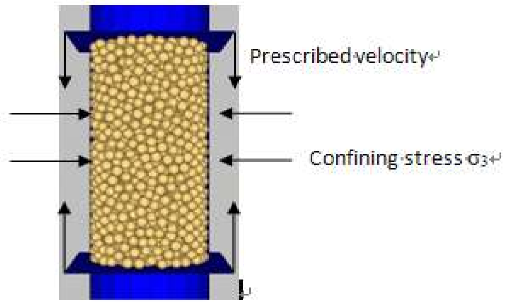

Fig. 5: PFC3D model

PFC^{3D} model: For every time step of the computation, interaction forces between particles and consequently resulting forces acting on each of them, are deduced from spheres positions through the interaction law. Newton's second law is then integrated through an explicit second order finite difference scheme to compute the new spheres positions. The dry intergranular interaction law (Fig. 2) is described by a relation of proportionality (elasticity) between the contact force and the relative displacement of the two spheres involved in the contact. In the direction normal to the tangent contact plane the relation of proportionality is characterized by a stiffness coefficient denoted kn. In the direction included in the tangent contact plane the stiffness coefficient is denoted ks. In addition, the tangential contact force obeys the Coulomb friction law characterized by the friction angle φ and no tensile normal contact force is allowed.

The contact stiffnesses relate the contact forces and relative displacements in the normal and shear directions via Eq. (4) and (5), which are shown in Fig. 1. The normal stiffness is a secant stiffness since it relates the total normal force to the total normal displacement:

$$F_i^n = K^n U^n n_i \tag{4}$$

The shear stiffness is a tangent stiffness since it relates the increment of shear force to the increment of shear displacement:

$$\Delta F_i^s = k^s \Delta U_i^s \tag{5}$$

The contact stiffnesses used in the above equations are assigned different values depending upon the contact-stiffness model employed. In this study the contact-stiffness model employed here is a linear model as shown in Fig. 4.

Three stages were employed for the numerical specimen tests:

- Specimen preparation
- Consolidation
- Specimen shearing

First a specimen has to be created as Fig. 5. The granular particle may not form a tightly-packed assembly with the target porosity. A FISH function will automate the process and ensure that the target porosity is obtained. The radius expansion method was used to general the particles. The minimum particle radius was $r_{min} = 0.09$ mm and the maximum radius/the minimum radius is 4:3. With this the size of the cell is known. The cylinder diameter was 4 mm and the height was 2 mm.

During the consolidation stage the isotropic stress of a particle assembly is defined as the mean of the direct stresses. A numerical servo-mechanism is applied iteratively to arrive at the radius expansion necessary to achieve the required mean stress.

Finally the shear process was loaded while the confining stress is kept constant by adjusting the radial wall velocity using a numerical servo-mechanism. The upper and lower walls of the sample are given a prescribed velocity in vertical direction to achieve compression of the sample while the stress on the left and right walls is kept constant at the initial value.

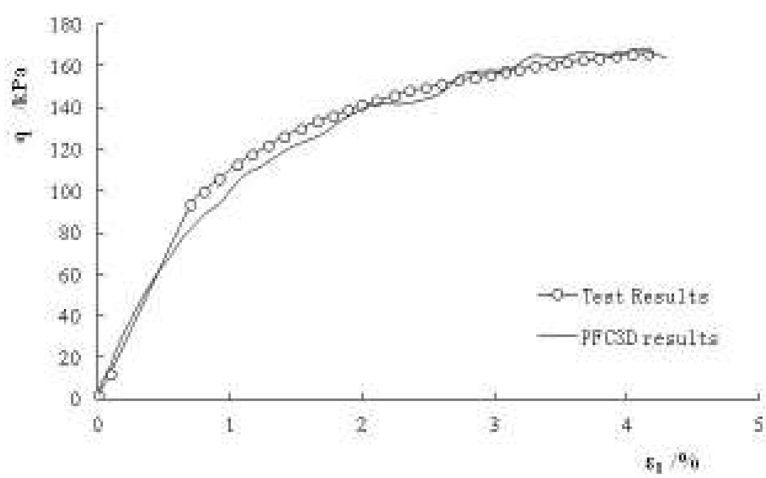

Fig. 6: Comparison of experiment and DEM

Table 1: Micro parameters used in DEM

Specimen height/mm	40
Specimen width/mm	20
Particle radii range/mm	0.9-1
Initial void ratio	0.4
Particle normal stiffness kn/N/m	3e6
Particle shear stiffness ks/N/m	3e6
Particle friction coefficient	0.8
Wall stiffness/N/m	3e5

Table 2: Parameters from DEM

Parameter	Value
Young's modulus E_{50}/MPa	11.00
Poisson's ratio	0.18
Friction angle/°	27.00
Angle of dilatancy /°	13.20

RESULTS AND DISCUSSION

Micro and marco parameters: The triaxial test was conducted at the confining pressure of 100 kPa. The shear stress-strain plot is shown in Fig. 6. The grain parameters resulting from the simulation using the above equations were given in Table 1.

The triaxial test simulations were made with 1000 particles and a porosity of 0.40. The cell height was 2.0 times the cell diameter and the maximum radius/the minimum radius is 4:3. With this the size of the cell is known. Calculations were made using the linear contact model. During the tests the micro parameters were adjusted to match the experimental result. The initial stress-state was created setting the internal friction fric = 0.05. Then for the actual test the friction was set to different values.

The experiment curve was fitted with DEM simulation result shown in Fig. 5. The Young's modulus and friction angle corresponding with the maximum deviator stress is calculated from Fig. 5. These parameters are given in Table 2. The Young's modulus is a bit larger than that from experiments. And friction angle correspond well with that from the triaxial test. Poisson's ratio of 0.18 is also a common value for wheat granular. The angle of dilatancy is a little higher than that from the tests but not very far off.

CONCLUSION

This paper discussed the new method to describe the grain shear during silo discharge. The DEM model was set up to examine the micro and macro parameters used for silo discharge. Conclusions were presented as follows:

- The proposed method using PFC^{3D} to examine the shear properties during silo discharge is a very economic and rationality method.
- The mechanism of discharge is modeled using the concept of triaxial test considering stress path. The shear produces the trend of dilatancy during discharge, which induces the overpressure of wall pressure.
- The comparison of results from DEM model and experiments produce the good relationship between macroscopic and microscopic parameters.

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