Pressure distribution in bulk of seeds in a shallow model silo. Experiments and DEM simulations

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Abstract

Contribution concerns Discrete Element Method simulations and experimental verification of radial distribution of pressures in bulk of seeds in a shallow bin, typical storage structures for agricultural grain. The effect of the grain size, aspect ratio and coefficient of particle-to-particle rolling friction on pressure distribution was studied. The DEM simulations provided qualitative agreement of the radial distribution of the vertical pressure on the floor of a shallow model silo and the radial distribution of the shear stress within the material with experimental data. Clusters of two or three spheres modeling ellipsoidal shape of particles improved fitting of experimental data of the shear stress distribution.

Keywords: Distinct Element Method, granular solids, pressure distribution, storage silo

1. Introduction

Granular solids exhibit complex nonlinear behavior resulting from elastic and frictional interactions between particles. As the frictional force in particles contact is defined by an inequality, the mobilization of friction (ratio tangent to normal force divided by friction coefficient) is undefined in static conditions. For a contact in a static equilibrium the mobilization of friction may range from −1 to 1. Elastic and frictional interactions between particles affect pressures exerted on silo structures.

Discrete Element Method (DEM), considering equation of movement of each particle in the system, provides new possibilities of deeper insight into the micro-scale behaviour of bulk solids, which are not available with traditional or even modern approach of continuum mechanics where gradients of displacement and stress are extremely high [7]. The rapid development of computer calculation techniques permitted the simulations of a variety of processes in granular materials, such as: dynamic effects in silos, mixing and segregation.

For small depths the silo wall pressure recommended to be calculated as hydrostatic pressure [1]. It is commonly assumed that the vertical pressure is uniform across the radius of a silo. The experimental research demonstrated that the vertical pressure at the silo bottom during storage undergoes some variations [9]. The general tendency is decreasing pressure with increasing radial distance from the silo centre, but near the wall, a local maximum of pressure was observed.

The objective of this study was to determine the effect of the grain size, aspect ratio and coefficient of particle-to-particle rolling friction on the radial distribution of the vertical pressure on the floor of a shallow model silo and the radial distribution of the shear stress within the material.

2. DEM simulations

The DEM simulations were performed with spherical particles or near ellipsoidal shape clusters of 2 or 3 spheres reflecting aspect ratio of horse bean (α=1.48) and field pea (α=1.22) seeds. Equivalent particle diameters were normally distributed ranging from 8 mm to 8.4 mm for horse-bean and from 6 mm to 6.24 mm for field pea seeds. Assemble consisted of 40 to 116 thousands particles. The Hertz–Mindlin theory of elastic frictional collisions between particles and particle–wall was used for the simulations. Young's modulus (E=526 MPa), Poisson's ratio (ν=0.26), coefficient of restitution (e=0.6), coefficient of particle-to-particle sliding ($\mu_{p\text{-}p}$=0.4) and rolling (m_r=0; 0.1) friction, and coefficient particle-to-wall friction ($\mu_{p\text{-}w}$=0.35) were selected as adopted for DEM simulations for similar seeds (bean, pea) by several researchers as cited in Horabik and Molenda [4]. Numerical simulations were carried out for a cylindrical model silo of 0.305 m in diameter and 0.305 m high (DEM/experiment scale ratio of 1:2).

The macroscopic stress tensor σ_{ij} in the system of particles averaged over all the contacts in the volume V was determined as the dyadic product between the contact force f_j^c vector at contact c and the branch vector l_i^c connecting two contacting particles [2,8]. The stress tensor components in cylindrical coordinates (r, ϕ, z) were calculated as described in [6]:

$$\sigma_{ij} = \frac{1}{V}\sum_{c=1}^{N_c} l_i^c f_j^c \quad (i, j = r, \phi, z). \tag{1}$$

Shape of the representative volume element (RVE) of particles used for the stress components calculations was assumed to be a ring of height Δh=0.057 m (approximately 7 average particle diameters) and radius increment Δr=0.02 m. To obtain stress component profile along the bin radius the inner and outer radius of the RVE ring was increased in step of 1.3 mm. The total number of contacts in the RVE in range from 600 to 8000 provided smooth profile of averaged quantities. The EDEM software package [3] was used for the numerical simulations.

3. Comparison with experiment

Comparison of the results of DEM simulations with the experimental data indicated qualitative agreement of the vertical pressure on the silo bottom and the radial distribution of the shear stress in bulk of seeds (Fig. 1). Slow decrease of the bottom pressure with the radial location was obtained in the case of field pea while radial variation of the bottom pressure near the wall was reproduced by DEM in the case of horse bean

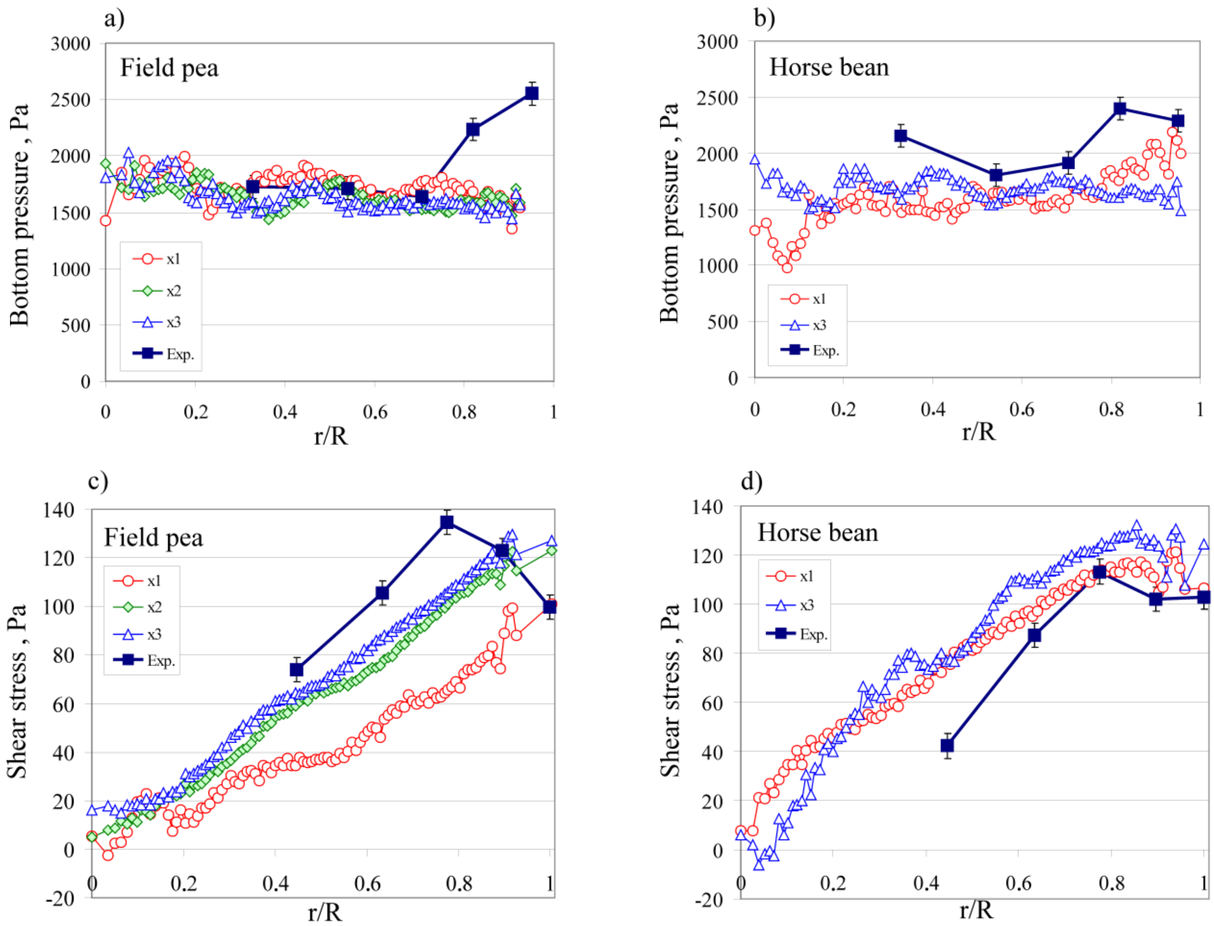

Figure 1: Radial profile of the bottom normal pressure of (a) field pea and (b) horse bean seeds, and the shear stress in bulk of (c) field pea and (d) horse bean seeds. Particles in DEM modelling: x1 – spheres, x2 – clusters of 2 spheres, x3 – clusters of spheres, m_r=0. Experimental data after Horabik and Molenda [5].

modelled by spheres. Approximately 20% lower the solid fraction of the simulated bed of particles as compared to the experimental data caused difference in mean values of the bottom pressure between simulation and experiment. Ellipsoidal shape of particles (clusters of spheres) improved fitting of experimental data of the shear stress distribution. To improve consistency with experiment shapes of particles used in simulations should go beyond limits of simple cluster of spheres to reflect better shape irregularities of agricultural grains.

4. Conclusions

1. DEM predictions of radial distribution of vertical pressure on the silo bottom qualitatively agree with experimental data.
2. The best fitting of the shear stress profile along the radial location was obtained for horse bean seed modelled by clusters of three spheres.

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