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Effective elastic properties and pressure distribution in bidisperse granular packings: DEM simulations and experiment

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ABSTRACT

The effective elastic properties and pressure distribution in granular mixtures depend on both, material and geometric properties of particles. Using the discrete element method, the effect of geometric and statistical factors on the mechanical response of binary packings of steel beads under uniaxial confined compression was studied. The ratio of the diameter of small and large spheres in bidisperse mixtures was chosen to prevent small particles from percolating through bedding. The study addressed lateral-to-vertical pressure ratio and effective elastic modulus of particulate beds. The bimodality of mixtures was found to have a strong effect on the packing density of samples with the ratio between large and small particles larger than 1.3; however, no effect of particle size ratio and contribution of particle size fractions on the distribution of pressure and elasticity of bidisperse packings was observed. Regardless on the composition of mixtures, the lateral-to-vertical pressure ratio followed the same paths with increasing contribution of small particles in mixtures. The effective elastic modulus of granular packings increased with increasing compressive load and was slightly affected by geometric and statistical factors. The experimental data followed the same trend of the DEM predictions; however, only qualitative agreement between numerical and experimental results was obtained. The discrete element method generated packings with smaller density and overpredicted pressure ratios and elastic parameters of mixtures.

1. Introduction

Granular materials play an important role in chemical engineering and many processes dealing with chemical powders and granules. The large-scale application and processing of these materials in many branches of industry requires advanced research into the properties of granular matter. The mechanical properties of particulate media are important in many applications, which makes them the subject of intensive research. Up to date, a number of experimental [1–5] and theoretical [6–8] studies have been conducted to examine mechanical response of particulate beds under shearing or compressive loads. As the bulk

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response of granular material undergoing deformation is determined by the interactions between discrete grains, the grain-scale numerical simulations have also found a wide application in the analysis of mechanical processes dealing with particulate beds [8–10]. The mechanical properties of grain bedding depend on material and geometrical properties of individual grains, interparticle contact geometry and load history [11]. Design of an efficient technological equipment requires determination of parameters, such as packing density ρ, angle of internal friction φ, friction coefficient between grain and construction material $\mu_{s,\,pw}$, effective modulus of elasticity E and pressure ratio k. Nowadays, several silo design codes including standardization of methods for determination of mechanical properties of granular materials are available [12,13]. The mechanical parameters are recommended to be determined under loading conditions similar to the operating load conditions. The most common methods for measuring mechanical properties of grain bedding are shear tests (Jenike tester or triaxial compression test) and uniaxial compression test.

The effective modulus of elasticity and pressure ratio are the most important parameters characterizing granular bed. While the former parameter characterizes elastic deformation of material, the latter one provides information about distribution of pressure in grain assembly. The European Standard [12] recommends determination of values of parameters during loading or unloading of the sample in uniaxial compression test.

The values of parameters were found to be dependent on porosity of assembly which is strongly determined by material [5] and geometrical properties of grains [14,15]. Liu [16] reported a strong influence of grain size, porosity and moisture content of material on mechanical properties of sand samples subjected to the dynamic triaxial test. The authors observed large differences between elasticity of samples with varying moisture contents and porosities. Numerical and experimental studies on the effect of moisture content of rapeseed on elastic properties and pressure distribution in grain assembly, conducted by Wiącek and Molenda [5] have shown a decrease in an effective elastic modulus and lateral-to-vertical pressure ratio with increasing moisture content of grains. These authors have also observed an increase in stiffness of granular packings with decrease in its porosity [14]. The study on the effect of a particle shape on effective elastic modulus of samples has shown larger stiffness of samples composed of oblong particles as compared to ones composed of spheres. In turn, an increase in an aspect ratio of grains resulted in decrease in lateral-to-vertical pressure ratio. The numerical investigation of the role of particle size heterogeneity on macromechanical properties of assemblies of spherical particles subjected to confined uniaxial compression test, conducted by Wiącek and Molenda [17] have shown an increase in stiffness of grain assemblies and decrease in pressure ratio with increasing compressive loads. Nevertheless, both parameters were found to be independent on degree of particle size heterogeneity.

Although a number of experiments have been conducted over last few decades in order to determine elastic parameters and pressure ratios of various materials, many phenomena related to incomprehensive behavior of granular assemblies still remain unexplained. Therefore, the investigation of the effect of various factors on mechanical properties of granular media is still needed to better understanding and more accurate and reliable prediction of mechanical response of materials during storage, handling and processing.

Most particle packings involved in industrial and natural processes consist of the common property of polydispersity, which may influence structural and mechanical properties of granular beds. *Granular packings may be composed of one, two, three or more particle size fractions. Binary mixtures represent the simplest case of polydisperse granular materials which* exhibit interesting *behavior*. In close-packed binary mixtures, two basic types of particle arrangement are produced: tetrahedral and octahedral [18]. When the ratio of the diameter of large and small spheres is not smaller than 4.44, small spheres may be trapped in the tetrahedron made with four large contacting spheres, which increases the density of the sample without a change in its volume. In the case of octahedron made by six identical spheres, a smaller sphere is trapped when the diameter of the large particle is not smaller than 2.42 of the diameter of the small sphere. For particle size ratio larger than 2.42, small particles percolate under gravity through the bedding.

The experimental and numerical studies conducted for binary particulate beds have shown that their microstructural and micromechanical properties were sensitive to geometric and statistical factors, such as particle size ratio [19–21] and contribution of *particle size fractions in grain assembly* [19,21,22]. Experimental studies conducted by McGeary [19] and Rassously [22] for binary mixtures with various particle size ratios have shown increase in packing density of mixtures with volumetric contribution of small particles in samples increasing up to 60%. A further increase in contribution of small particles in mixture resulted in decrease in packing density of samples. The rate of change of packing density with increasing contribution of smaller grains in samples decreased as the *particle diameter ratio* of *large to small* spheres increased. The geometric and statistical factors were found to affect also the distribution of stress between grains within the sample [23,24]. A numerical study conducted by Shire et al. [24] for bimodal sphere packings have shown that, regardless of particle size ratio, small grains contributed approximately equally to stress transfer in packings with volume fraction of small particles not lower than 30%. In samples comprising lower number of small grains, smaller contribution of small spheres to stress transfer was observed, which decreased with increasing particle size ratio.

Since the macromechanical properties of granular packings are determined by microstructural and micromechanical properties of materials, it may be expected that the factors affecting the latter ones affect also the mechanical response of material subjected to loading conditions. Although a number of study on distribution of pressure and stiffness of granular packings under different conditions has been hitherto conducted, the knowledge on effect of contribution of particle size fractions on mechanical properties of binary mixtures with various particle size ratio is still scarce. Therefore, in the reported project, the relationship between the lateral-to-vertical pressure ratio and the effective elastic modulus, which are the key parameters to silos' design, and contribution