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Segregation in heaps and silos: Comparison between experiment, simulation and continuum model

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ABSTRACT

Segregation is a very common phenomenon in industrial processes wherever granular materials are handled. It can occur at different stages in an industrial process and it is usually undesired. To support the industrial design, it is necessary to understand the mechanisms of segregation and to develop a tool which is able to predict the propensity of segregation depending on product and process properties.

The underlying mechanisms of segregation during filling and discharge of silos are discussed in detail. To study the effects for different configurations of silos (flat bottom vs. inclined hopper; with and without belt conveyor) a bimodal mixture of differently sized particles is employed. A useful tool to support the analysis of segregation processes is the discrete element method (DEM). A calibrated and validated DEM simulation has been used to simulate a pilot scale silo with a belt conveyor at the outlet. In this context, the influence of some common procedures in DEM, which are used to reduce the computational effort (way of filling, upscaling, periodic boundary condition) as well as their effect on the measured segregation is presented.

Moreover, a continuum approach is presented which fits the segregation effects using a simplified model to experimental data. This approach is useful in a first stage to predict the segregation behaviour based on a convective/diffusive model.

1. Introduction

Segregation is a common phenomenon when handling granular material and occurs always when granular mixtures are in motion, for example when granular mixtures are conveyed, transported or dispensed.

The possibility of modelling the particles of bulk solids in a discrete manner makes discrete element methods very useful in the field of segregation and mixing of granular matter. As an applied research in DEM, hopper flow has been extensively studied because of its high importance in industrial activities. Experimental studies focusing on flow of bulk solids in hoppers have been performed for several decades [1,2]. The simple geometry of a hopper but still complex flow behaviour makes it of great interest in many studies. Nowadays, many researchers have studied this process on a particle level experimentally and with the help of DEM simulations [3]. These studies were performed first in 2D [4], in more recent studies in 3D [5,6] and have been focused mainly on discharge rates [7], discharge profiles [8], wall pressures [9], particle interaction forces and particle velocities [10]. The various studies cover diverse geometries as flat bottom [8] and inclined hoppers [11], the position of inserts inside the silo as well as the facilitation of flow by aeration [12].

DEM has been extensively used to study the effect of process and product matters on segregation. The investigated process parameters include the geometry of the silos ([11,13,14]) and product parameters include: size [14,15], density [16,17], shape [18], surface roughness or friction [19], inelasticity [20,21] and cohesion [22]. The difference in particle size between the species has been found to be the main parameter affecting the extent of segregation [23]. In the present work, the behaviour of a binary mixture of a relatively large size ratio was studied during filling and discharging a silo.

DEM parameters should be appropriately determined in order to obtain quantitative prediction of segregation and reliable equipment design. Therefore, a calibration of the model input parameters, such as coefficients of friction and coefficient of restitution, is necessary. Once these coefficients are obtained, an experimental validation of the model is required. A procedure on how to perform the calibration of the parameters is presented in [23].

One of the main goals in particle technology is to identify the relationship between the microscopic parameters of the particles and the macroscopic behaviour of the bulk. Thanks to DEM, a relationship can be established between these two scales based on particle and interparticle properties. However, usually discrete element method can only be applied to relative small processes where a small quantity of particles is

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Table 1
Material property summary.

	Provider	x_{50} (mm)	Sphericity (−)	ρ_b (kg/m^3)	ρ_{part} (kg/m^3)
SA-03	Sand Samore GmbH	0.26	0.85	1400	2659
SA-16	Sand Rinderohr	1.6	0.82	1450	2655

involved. Researchers have become aware about this constraint and follow mainly two approaches: from the discrete element method obtain the physics to establish a continuum model [24] and, secondly, an upscaling of the particle size (i.e., enhance the particle size but reproducing still the behaviour of the bulk) [25]. This approach has also been used by several authors for different processes including die filling [26], pneumatic conveying [27], uniaxial test [28], and rotary drum [29].

The rate and propensity of segregation of a specific mixture can be studied by establishing a continuum model and, therefore, studying the intrinsic causes of segregation [10,15,30–36]. Savage and Lun [37] presented a model for slow flows which describes two main mechanisms for the motion between layers of the particles: sieving (gravity, size and void dependent) and 'squeeze expulsion' due to imbalances in contact forces. In this work, a diffusive/convective model, the Fokker–Planck equation, has been used. Two terms have to be differentiated: a random movement causing mixing (dispersion/diffusion) and a convective term (Eq. (1), (2)) as presented by Gray [15,36]:

$$\frac{df_1}{dt} = -\nabla\cdot\left(\overrightarrow{u_{bulk}}f_1\right)) + \nabla\cdot(D_1\nabla f_1) - \nabla\cdot\overrightarrow{u_{seg1}}f_1(1-f_1) \tag{1}$$

$$\frac{df_2}{dt} = -\nabla\cdot\left(\overrightarrow{u_{bulk}}f_2\right)) + \nabla\cdot(D_2\nabla f_2) + \nabla\cdot\overrightarrow{u_{seg2}}f_2(1-f_2) \tag{2}$$

f_1 and f_2 are the volume fractions of the components 1 and 2 respectively, D_1 and D_2 are the diffusion coefficients, $\overrightarrow{u_{bulk}}$ the velocity of the bulk and $\overrightarrow{u_{seg1}}, \overrightarrow{u_{seg2}}$ are the velocities of the species 1 and 2. Their sum is one for a binary mixture:

$$f_1 + f_2 = 1. \tag{3}$$

The dispersion term depends on the location of the particles in the studied system. The residence time for the type of particles with a smaller coefficient of diffusion in a certain region is longer since the dispersion term is related to the mobility of the particles and this causes segregation [15,31,32,34,35]. The convection and the dispersion mechanism can act against each other causing segregation or helping each other causing remixing of the bulk solids. The segregation rate depends also on the gradient of concentration in the region [34].

Additional terms are usually added to the standard convection/dispersion equation to add specific mechanisms apart to that of the random motion established by the dispersion term [38]. The relative velocity between the species 1 $\overrightarrow{u_{seg1}}$ and the bulk $\overrightarrow{u_{bulk}}$ is called velocity of segregation. This velocity of segregation can be split into the different mechanisms taking place in our system, Eq. (4). The mechanisms taking place will be described below.

$$\overrightarrow{u_{seg1}} = \overrightarrow{u_{S1}} + \overrightarrow{u_{P1}} \tag{4}$$

where $\overrightarrow{u_{S1}}$ is the drift velocity of the ith component due to shear-induced segregation also called kinetic sieving (the flow of coarser particles in the mixture across gradients of bulk velocity) and $\overrightarrow{u_{P1}}$ is the drift velocity due to gravity-driven spontaneous percolation of the fines through the coarse phase.

By the mechanism of kinetic sieving coarser particles (principally) migrate to regions of high local strain rate. Percolation occurs if two fractions of particles with two different sizes or densities are present in the mixture and an external movement is applied. In this case smaller particles pass spontaneously through the interstices. This mechanism can be explained with a net velocity in the direction of gravity for some of the species, while the rest will be forced to move in the opposite direction, similar to the two mechanisms proposed by Savage and Lun [39].

2. Methods and materials

2.1. Materials

The mixture used is composed of two kinds of sand (SA-03 and SA-16). The properties are given in Table 1, the particle size distribution of the components in Fig. 1 and the sphericity distribution in Fig. 2.

The main parameters influencing segregation, the shape and size ratios, are shown in Table 2 for the mixture studied. The particle size ratio

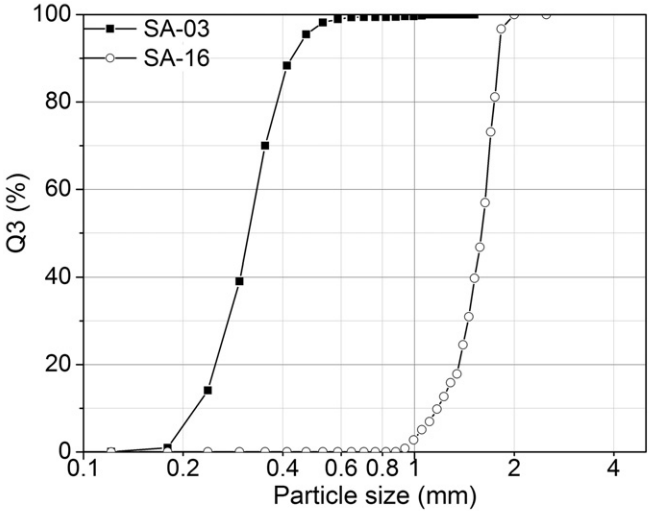

Fig. 1. Particle size distribution for SA-03 and SA SA-16.

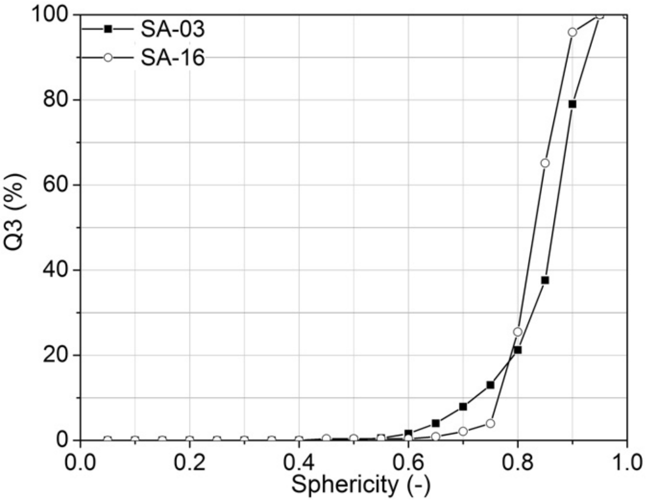

Fig. 2. Sphericity distribution for SA-03 and SA SA-16.