Measuring intergranular force in granular media

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Summary: A new method is proposed to measure intergranular forces in granular geomaterial from time-lapse high-resolution X-ray computed tomography imaging using a grain tracking approach and discrete element method.

1. INTRODUCTION

Understanding the complex compaction behavior of granular materials has always been a challenging topic and sandstone as a typical granular geomaterial is no exception. Sandstone compaction has been studied for decades, mainly because of the link to hydrocarbon resources. Production from sandstone reservoirs results in pore pressure reduction and compaction, which may lead to subsidence, induced seismicity and changing the production rate and recovery. Mechanical, physical and morphological properties of grains and their interactions play a major role in large-scale mechanical behavior of granular media [1,2]. High-resolution X-ray computed tomography (micro-CT) imaging and improving image and data analysis methods helped to precisely measure physical properties of grains. However, finding intergranular forces is still problematic, because the forces cannot be measured directly, and should be inferred from grain deformations or displacements. During the last decade, only a limited number of methods were proposed to measure grain interaction forces in granular media from time-lapse CT-imaging. However, either the proposed methods were limited to a pack of frictionless or soft grains, which are not a good representation for geomaterials, or 3D x-ray diffraction imaging was also needed along with CT-imaging, which limits them to crystalline material [3,4].

This work proposes a new method for the calculation of intergranular forces in granular geomaterials. We use the discrete element method (DEM) to bridge external forces which are continuously recorded during a compaction experiment and grain displacements which are measured through a grain tracking approach based on the time-lapse CT-imaging. Unlike in the LS-DEM [5] method, grains are not only used at the beginning of the experiments to generate them in a DEM software. In the proposed method, the numerical model has a recurrence relationship with the CT-images. In this research the particle flow code (PFC) package is chosen for numerical modeling [6].

2. EXPERIMENTAL METHOD

A small-scale uniaxial compression test was performed on glass beads, allowing for high resolution time-lapse imaging using the Environmental Micro-CT scanner (EMCT) [7] at Ghent University Center for X-ray Tomography (UGCT), Belgium. This scanner is specifically designed for in-situ imaging of materials. The X-ray source and detector rotate around the sample, while the sample itself stays stationary. This allows dynamic imaging for full 4D monitoring of changes in the interior of samples and facilitates the use of add-on devices to condition geological samples.

202 glass beads with the diameter range from 355 to 400 microns were placed in a small-scale uniaxial compression vessel ($2\times2\times3$ mm³). Scans (5 minutes each) were taken with a voxel resolution of 4.522 microns. First, low axial stress ($\approx$ 1.25 MPa) was applied on the glass beads. The displacement of the loading pistons was stopped, and a first scan was taken. Then, the axial stress was increased to 5 MPa with the displacement rate of 100 micrometers per minute. At the axial stress of 5 MPa, the sample was scanned for the second time while the loading piston was fixed. Since grain movements reduce the scan quality, the sample was left to relax for an extra 1.5 minutes before scanning, to make sure particles are not moving during the scan. This process of loading and scanning continued with the interval of 5 MPa up to 30 MPa.

Grain surfaces were generated from the first scan (Fig. 1a) and the translation velocity for each grain was measured from one scan to the next one. This measurement makes it possible to find inter-grain forces at each stage if a proper contact model for grain interactions is chosen: the grain surfaces are imported in the PFC package (Fig. 1b) and the measured translational velocity is imposed on each grain from one scan to the next. In this method external forces are not applied on the sample. However, they can be obtained by measuring the

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unbalanced forces on circumferential particles. At each stage the unbalanced force on each non-circumferential grain should be zero. However, due to the image resolution limitation this requirement is not always met. To solve this issue, the circumferential particles of the model are fixed after the particles have been translated in the first step. Meanwhile the other particles (in the middle of the model) can rearrange based on Newton's laws to resolve their unbalanced forces. If particle displacements in this step (at the end of rearrangement phase) are lower than the spatial resolution of the CT-images, and the unbalanced forces acting on circumferential particles are close to the applied external forces, then it can be concluded that this approach works properly, and the chosen contact model is suitable.

3. RESULTS

Choosing an appropriate contact model plays an important role to increase the accuracy of this method. Therefore, this model can also help to find the best contact model applicable between grains. In this work, the Hertzian contact model for glass was chosen. Fig. 1c shows the intergranular forces at the uniaxial stress level of 10 MPa, after imposing the measured particle velocities from the scan at uniaxial compressive stress from 5 MPa to 10 MPa. In this figure the unbalanced forces on the non-circumferential particles (in the middle of the model) are not zero. However, these unbalanced forces vanished in Fig. 1d when the circumferential particles were fixed, and the other particles could move freely in all directions.

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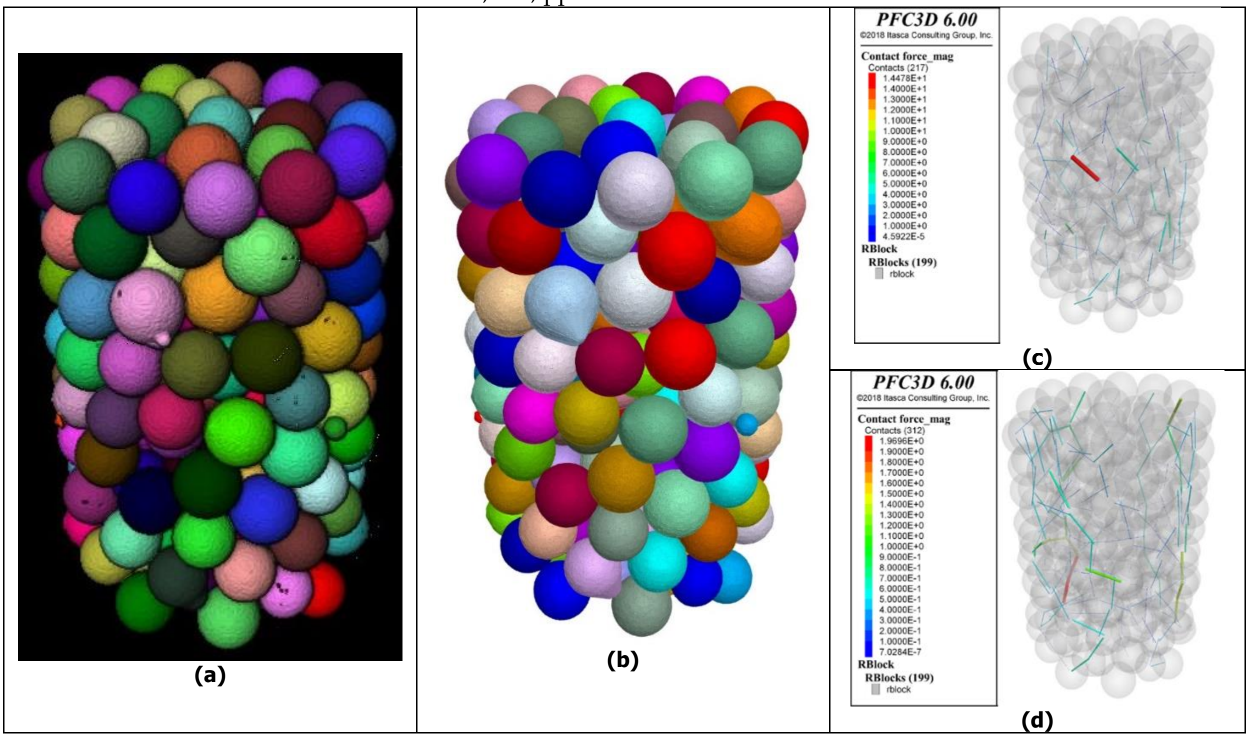

Figure 1: (a) Generated grain surfaces of the sample, (b) Generated particles in PFC from the grain surfaces, (c) Intergranular force after imposing particle displacements based on the measured particle velocities from the scan at uniaxial compressive stress of 5MPa to 10MPa, (d) Intergranular force after non-circumferential particle rearrangement due to the unbalanced forces