# Development of Image Analysis Tools to Evaluate In-Situ Evolution of the Grain Size Distribution in Sand Subjected to Breakage

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**Abstract** Grain crushing is a phenomenon of pivotal importance in the inelastic deformation of granular materials. The progressive evolution of the grain size distribution is known to play a major role in a number of geotechnical engineering problems. There is, however, a lack of experimental work tackling the quantification of the three dimensional evolution of the grain size distribution of materials undergoing grain crushing. The technological advancements in X-ray computed tomography now allow in situ, 4 dimensional (3D + time) images of geomaterials to be obtained as they evolve. While recent investigations of the kinematics of persistent grains have allowed a deeper experimental understanding of some inelastic micro-mechanisms to be obtained, a further effort is required when interpreting tomographic images in which grains are not persistent (i.e., they can break). In this contribution, a novel image-analysis technique under development is proposed to quantify the evolution of the grain size distribution as grain crushing proceeds in an experiment. This technique is applied to the analysis of 3D tomographic images of sand sheared at high confinement.

## 1 Introduction

New micro-mechanics based models have started integrating our understanding of how micro (e.g., grain scale in the case of sand) processes affect the macro (REV scale) behaviour. Some micro-mechanics based models explore the possibility

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of predicting the evolution of the micro-structure (e.g., de-bonding of cemented grains, or grain breakage, (see Einav 2007a, b), with clear practical implications for geotechnical engineering (e.g., permeability evolution in oil production). The need for information regarding micro-mechanical processes pushes experimental mechanics to strive for a more quantitative understanding of the observed processes to assess the predictions of these models.

X-ray tomography is proving to be a very powerful tool for the experimental investigation into the mechanics of granular media—allowing a range of scales to be imaged non-destructively. Recent work in Grenoble (Ando et al. 2012a, b) has used X-ray tomography to image the shearing of small cylindrical specimens (22 mm height by 11 mm diameter) of different types of sand in triaxial compression. Analysis of the acquired images allows most of the 50,000 grains of a specimen to be identified and followed during a test, allowing in turn the identification of some grain-scale processes responsible for the different specimen-scale responses of these materials.

In an even more recent experimental campaign using the same specimens and imaging techniques, triaxial compression tests were carried out at relatively high confining pressures for sand (in a range from 100 to 7,000 kPa, see Alikarami et al. 2015). In the high confinement tests, x-ray imaging reveals that grain crushing occurs during the shearing of the specimen (as suggested in Ando et al. 2013, whose final figure is reproduced here as Fig. 1), since pores can clearly be seen to fill with fragments
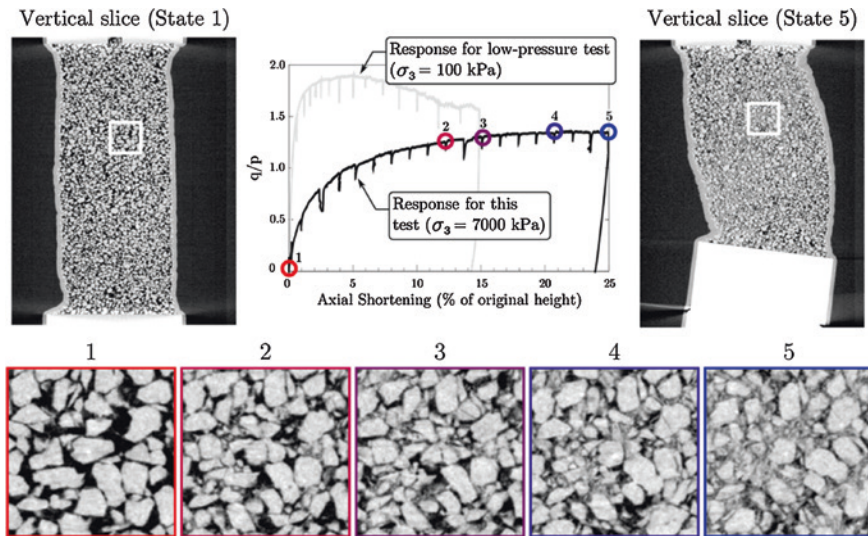


**Fig. 1** Figure showing the production of fines during a triaxial compression test on Hostun sand at a relatively elevated confining pressure of 7,000 kPa. *Top left* and *right*: *vertical slices* through the 3D images of the specimen after isotropic compression and at the end of deviatoric loading, respectively. *Top, middle* q/p *versus* axial shortening for a test on Hostun sand at 7,000 kPa (*black*) and at 100 kPa cell pressure (*grey*). *Bottom*: Following the neighbourhood around a grain which breaks, for 5 different imaged states (noted on the graph). Entire Figure adapted from Ando et al. (2013)

of grains. The quantification of the grain crushing occurring in these time-resolved images is a key step in the dialogue between experiments and theory of breakage.

The objective of this paper, therefore, is to obtain a grain size distribution from images of a breaking granular medium, by image analysis.

## 2 Image Analysis

Figures 1 (top and bottom, left) show vertical cross sections of 3D x-ray tomography images of a sand specimen before shearing. In such an image it is clear that this is a two-phase system (pores and grains). If these two phases can be clearly identified and separated (the simplest way being with a threshold value of x-ray attenuation), grains can then be identified and counted in what amounts to a virtual sieving process. If, under shear, this system evolves without grains crushing, the techniques presented in Ando et al. (2012a, b) can be used to measure grain kinematics since grains are permanent objects.

However, the series of five vertical sections shown at the bottom of Fig. 1 (each centered on the same grain, and taken from X-ray images acquired at different points during shearing) tell a clear story: as the specimen is sheared, grains break and these fragments of grains fill the pores. The system remains a two-phase system even after crushing (pores and potentially broken grains). However, from an image analysis point of view, some grain fragments become smaller than, or around the size of one voxel (a 3D pixel) in the x-ray tomography (a voxel in the case of these images measures $15.6 \times 15.6 \times 15.6\ \mu m^3$); their partial occupancy of the voxel means that they appear to have an x-ray attenuation value between the value for pores (i.e., air in this case) and the sand grains (quartz). Although these "partial volume" voxels are also necessarily present along the grain-pore interfaces in the images before shear, their number grows as grains reduce in size, giving what appears to be a three phase system by the end of the test.

Recalling that the objective of the analysis is to obtain a grain size distribution, it is clear that this information will necessarily be partial when grains start to become smaller than the resolution at which the images are acquired. As a first concrete step in the analysis of this type of image, the technique presented herein attempts to identify the coarsest grains (those bigger than a few voxels) in order to reconstruct the coarser part of the grain size distribution using digital sieving of individual grains. The technique, which for the moment requires a manual selection of global threshold values, starts from a very conservative initial threshold in order to capture the voxels with the highest x-ray attenuation values. The voxels thus selected should in principle be inside grains sufficiently large to have at least one non-partial-volume voxel. Since some noise is inherent in these images, some voxels within the grains are not captured by this first threshold; a dilate procedure is put in place to locally expand and therefore join the voxels selected by this first threshold. The dilation operation (which is far from shape-preserving) is combined with information of the highest local greyscale variance in the image

in order to have better-resolved edges. The result of the procedure at this stage is a series of markers—zones that the technique considers to be certainly within grains. Observation of these markers shows that they select the insides of the grains with a fair reliability; however they fall short of selecting the edges of these grains. This information is recovered by going back to the original data with the markers subtracted and making a second thresholding operation on the remaining data; this selects some additional material, which is added to the markers, and which describes the coarse grains. Further technical details of this technique can be found in Gkiousas-Kapnisis (2013). Currently the different thresholds are operator-chosen, which can cause a certain amount of subjectivity in the results.

Figure 2 shows that when grain crushing has occurred in a test, the technique described above allows the coarse grains to be extracted with a good degree of success. These coarse grains are then separated from each other with a commercial watershed code, which in turn (after due labelling of each grain) allows access to the volume of each grain. This is converted into the diameter of a sphere of equal volume. These discrete data can then be shown with a normalised, cumulative histogram (normalising with respect to the mass or volume of grains, and not the *number* of grains), also known as a grain size distribution.

Figure 3 shows the evolution of the sample-wide grain size distributions obtained by the digital sieving of a few of the images of the test presented in
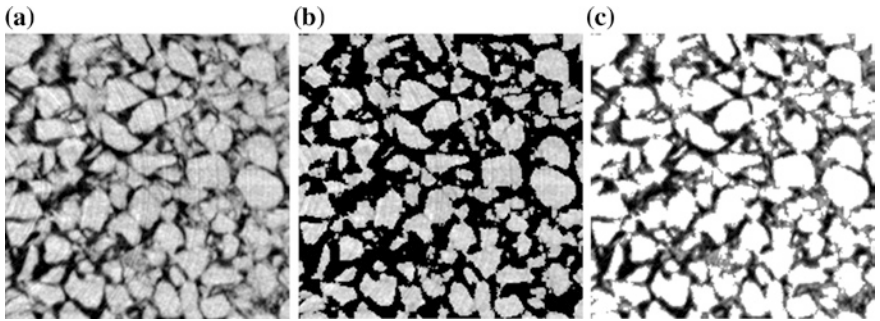


**Fig. 2** *Horizontal* sections of an x-ray tomography image showing a zone with grain crushing. **a** raw data, **b** voxels identified as the coarse grain phase, **c** a–b, the remaining two phases, with the coarse grain phase replaced by *white*



**Fig. 3** Specimen-wide grain size distributions obtained by the digital sieving of all of the identified coarse grains in several images acquired during progressive shearing of specimen of Hostun sand at 7,000 kPa cell pressure
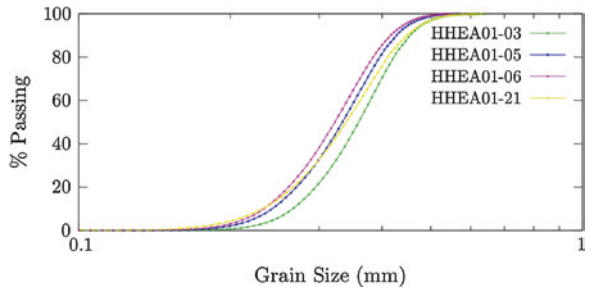
Fig. 1. We recall that a voxel is 0.016 mm wide in these images. The technique is clearly able to pick up the evolution of the grain size distribution to some extent, although the final state presented (HHEA01-21) appears to have a grain-size distribution describing larger grains than previous steps, which is considered to be physically impossible and is almost certainly due to the subjective choice of threshold values.

## 3 Conclusion

This paper has presented the work in progress on an image analysis technique able to extract grain-scale information from x-ray tomography images of a granular system which is experiencing crushing. Although at the moment the technique requires manual intervention (particularly in the choice of thresholds, which are manually chosen for each image) the first results using only the coarse grains seem promising.

There is a limit—the image's spatial resolution—to the amount of quantitative information that can be obtained about the smallest grains from such an image. However, it is likely that some information about the distribution of grain sizes can be obtained from the "crushed grains" phase. Over and above the considerations of the preservation of mass, further information about the expected distribution could be built into the technique as an *a-priori*.

This *a-priori* is the sort of information that can come from a rich dialogue with micro-mechanical models of breakage, see Tengattini et al. (2014).

Once a more complete image-analysis measurement technique is put in place, and duly verified, one clear path for investigation of these images is the assessment of the distribution (diffuse or localised) of breakage within a specimen. Once obtained, this field of grain breakage can be understood in comparison with other maps, incremental shear/volumetric strain or porosity for example.

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