Laboratoire
Sols Solides Structures Risques

Centre National
de la Recherche
Scientifique
UMR 5521

Institut polytechnique
de Grenoble

Université Joseph
Fourier
Grenoble - 1

Interactive visualization of 3D time lapse data of deforming granular media

Abstract

Geomechanics studies the behavior of granular materials (materials consisting of many small grains) when stress is applied, with the objective of creating models useful to civil engineering. In situations where a granular medium is over-stressed and fails, strains inside the material have been observed to localize (typically in a shear band). This means that there is no longer homogeneous deformation - this causes problems both in the modeling of such phenomena (classical continuum models have trouble handling this) as well as the experiments to investigate such phenomena (which typically make measurement at the boundary). The experimental challenge has been overcome with the advent of non-destructive 3D imaging techniques such as x-ray tomography. Recent advances allow the measurement of 3D displacements and rotations of all the grains in a typical geomechanics test. Data coming from these experiments needs to be studied in order to better understand the causes and mechanisms of localized deformation (to allow subsequent integration into richer models, such a double scale models). For this study and understanding to be possible, the evolution in time of these complex mechanisms needs to be visualized.

This PhD project will investigate such visualizations for time-dependent datasets of approx. 100,000 grains in approx. 20 different states for which the initial positions and the 3D displacements and rotations are known. The PhD project will investigate the application of interactive 3D visualization techniques from scientific visualization to this problem to enable material scientists to get a deeper understanding of the material's behavior. In particular, the amount and type of displacement needs to be visualized, specific grains should be more or less visible depending on the type of exploration, and it should be possible to depict similarities within local neighborhoods. The contacts between the grains which carry the applied stress have been found to be important and visualizations taking these into account will consequently be of great use. It is particularly important to be able to focus on the changes in the shear band since the remainder of the sample typically does not undergo further strain. It is also essential to allow the study of the precursors of the shear band. The project will therefore concentrate on applying abstraction techniques to the three-dimensional dataset to allow the viewer to focus on the behavior of the grains in the shear band.

Phenomena under Study: Localisation in Geomaterials

This particular theme of our research has been central in the lab – and more specifically in Equipe GDR – as long as anyone can remember. **Localisation (of strain)** refers to the phenomenon of the loss of homogeneity of an initially sample – for example in Figure 1 there is a sample of sand (inside a membrane – which allows us to apply all-around pressure on the sand) that was initially cylindrical, and it is clear that is has not deformed in a homogeneous manner – a **Shear Band** is evident, crossing the sample from bottom left to top right. Shear bands are very localised phenomena, 5 to 15 grains thick (a few millimetres). They are profoundly related to the failure of the material, and what happens in the shear band controls the post-failure behaviour of the whole material.

Since the "classic" global measurements of force and displacement are of limited use when studying these local phenomena, non-destructive 3D characterisation of the material was embarked upon, first using a medical scanner in 1996 (Desrues et al. 1996) – see Figure 2.

Figure 1: A **Localised** sample of sand inside a membrane, after axial (vertical) deformation.

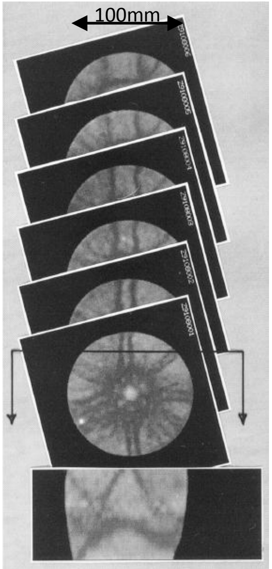

Figure 2: First x-ray scans of a deformed, sand sample, with complex patterns of localisation

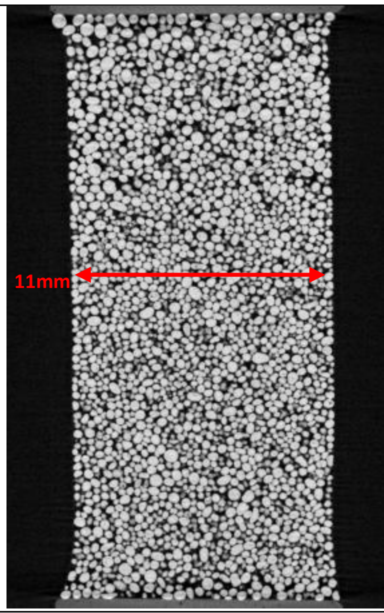

Figure 3: Current x-ray imaging capabilities, on a **small** sample, allowing **each grain** to be imaged.

This first result (Figure 2) was very important – showing that even if there was no localisation visible on the outside of the sample, there complex patterns were seen inside the material, which could be investigated with non-destructive techniques such as x-ray tomography.

Since then we have done experiments in the ESRF (Synchrotron here in Grenoble), and more recently acquired our own x-ray tomograph, allowing us to take many different 3D images while we deform our granular materials. We have capabilities to **image all grains** in a sand sample in around 20 steps per test. This avalanche of new data is great, but we need to use it to answer some mechanical questions. We use both 3D Digital Image Correlation (Hall et al. 2010) to follow small sub-volumes of the 3D-images of a test as well as a grain-based particle tracking technique (called ID-Track – Andò et al. 2012) – and it is on this discrete grain-based data that we'd like to collaborate. Both techniques are in development, and give us the evolution of the material during a test. To summarise, the output of the particle-tracking technique is:

- **"labelled" images of 50,000 to 100,000 grains**
- **Initial position of the grains**
- **3D displacements and rotations of each grain through all the steps of a test**

Of particular importance as well is the behaviour of **contacts** between the grains, the orientation and movement of which defines how stress is transmitted through the granular system. These data are also available.

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Visualisation of Data so far...

Currently, the output of the grain tracking code (used to track particles between loading increments, giving their displacements and rotations) is used to colour grains by displacement or rotation in different steps of a test (Figures 4 and 5).

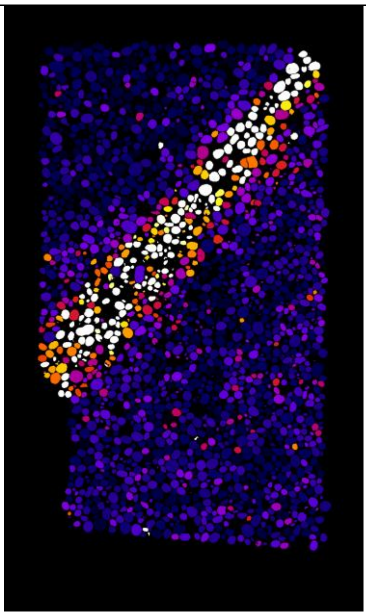

Figure 4: An example slice, with grains coloured by their rotation

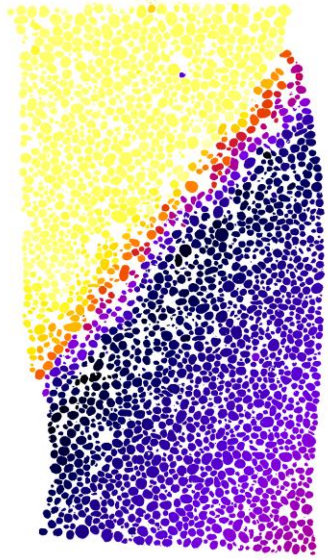

Figure 5: An example slice, with grains coloured by their displacement

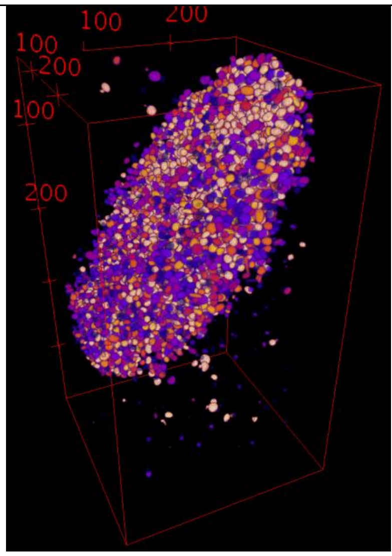

Figure 6: Less frequent, 3D-visualisation of the rotation data (very slow and difficult to use)

Some 3D visualisation of the "raw" 3D x-ray attenuation volumes is performed during the reconstruction phase, and although this interface supports a cutting plane, because of the presence of all the grains, it is difficult to see the arrangement of the granular skeleton. A 3D-visualisation of the rotation data has been attempted with success, but since this was a hardcoded 3D-volume creation and rendering is very slow (Figure 6). We mostly remain in a slice-based view of our samples, which seems like a pity...

What we'd like to see...

Theory and simulation and imagination give us some indication of micro-mechanical phenomena that we'd like to investigate. We consider visualisation to be of primary importance for the **understanding** of our data, and then subsequently of use for making measurements. Since the data we want to visualise is discrete (measurements based on either grains or contacts) this should help us simplify the visualisation.

I am imagining, but perhaps this is not the best approach, a 3D visualisation which allows control of time, and allows different properties (x, y, z, total displacement, displacement different from neighbourhood displacement, rotation, rotation axis...) to be overlayed on the objects being shown (a bit like Figure 6). In order for this to be useful, we need to have a good way to hide or simplify the bulky volumetric grain data. All this on-the-fly.

Global – Discrete Selections

One first thing that would be good to do is to allow a certain amount of discrete objects (grains or contacts) to be removed or faded out "live" from a visualisation, for example in figures 4 and 6, all the grains under a certain threshold of rotation could be hidden. Some clever way of selecting grains by a combination of volume (selecting all objects within certain pixel boundaries) selection and

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perhaps flood filling objects either by similar properties (de-select all close objects within 10% of a given object), or through a given number of links (select this objects and its N rings of neighbours) could be quite exciting, and would allow us to explore the data.

Local – Neighbourhoods

Another nice thing would be to be able to look at local similarities, for example be able to (a bit like described above in fact) select one object and proportionally fade out all object different to it.

Another important mechanical fact is that of the evolution of contacts between grains: contacts can form, disappear, slide, rotate or just stay put. A visualisation able to show how these states evolve in time would be essential to our understanding. A sliding contact could, for example be shown as a different local colouring on the two grains that are sliding.

Global – Data Abstraction

One of the things that attracted us a lot about your work with molecules is the ability to control structural abstraction. This is particularly good from the contacts perspective, where the grains in contact could simplify in order to allow an easier view of the mechanics.

Bibliography (available on demand)

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