X-ray tomography for granular materials
current trends and perspectives

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outline

• x-ray radiography, x-ray tomography
• x-ray tomography and image analysis
• trends, challenges, perspectives
  • individual grain kinematics
  • characterization of grain-to-grain contacts
  • production of fines by grain breakage
  • cemented granular materials (grain debonding)
  • partially saturated sand (menisci)
  • fine-grained geomaterials
x-rays

Hand with Ring: print of Wilhelm Röntgen's first "medical" x-ray, of his wife's hand, taken on 22 December 1895 and presented to Ludwig Zehnder of the University of Freiburg, on 1 January 1896

- discovery of x-rays by Wilhelm Röntgen
- first radiographies in 1895
- first ever Nobel prize in Physics in 1901

x-rays have been voted the discovery of the last 100 years

radiographs are maps in 2D of the attenuation of the x-rays as they travel through the object being imaged
Roscoe and coworkers, Cambridge 1960s
when things must be seen in 3D, then radiography is not sufficient

radiography (2D) → computed tomography (3D)

in order to get a 3D image with x-rays we need:

- many radiographs (acquired at different angular positions)
- some mathematics (Radon transform)

- tomography = "extension" of radiography
- original mathematical framework by Radon in 1917
- first x-ray CT scanner in 1972 by Hounsfield & Cormack
- Nobel prize in Medicine in 1979
Jacques Desrues: using a medical CT scanner to hunt for strain localization in 3D in sand
x-ray tomography as a quantitative tool

Void ratio evolution inside shear bands in triaxial sand specimens studied by computed tomography

in a geomechanics lab in Grenoble...
imaging the physics at the pertinent scale(s)
imaging lab-scale CPT

Priscilla Paniagua
NTNU Trondheim

Soil deformation around a penetrating cone in silt

P. PANIAGUA*, E. ANDÓ†, M. SILVA†, A. EMDAL*, S. NORDAL* and G. VIGGIANI†
imaging lab-scale CPT (again, but with visible grains)
low tech "CPT" in flat "sand"
bean seed growth in sand

Viggiani et al. (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils
bean seed growth in sand

Viggiani et al. (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils
even more exotic x-imaging (unleash your imagination!)

massive ice lensing in bentonite  
radial growth of ice lenses in kaolinite

Viggiani et al. (2014) - Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils
grain-scale imaging a sand specimen while it deforms under load
Caicos Ooid
Calcite, $D_{50} = 350\mu m$
very rounded

Ottawa 50/70 Sand
Quartz, $D_{50} = 250\mu m$
rounded

Hostun HN31 Sand
Quartz, $D_{50} = 338\mu m$
angular
individual grain kinematics

Hall et al., Géotechnique 2010
Andò PhD 2013
Andò et al. Géotechnique Letters 2012
Andò et al. Géotechnique Letters 2013
Grain-scale kinematics for test COEA01

Deviatoric Strain

Intensity of Rotations

Combining DIC and ID - Track - latest results
Grain-scale kinematics for test COEA01

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Grain-scale kinematics for test COEA01

Deviatoric Strain

Intensity of Rotations

Combining DIC and ID - latest results
don’t forget these are 3D data
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are we happy with what we can measure? Beyond grain kinematics

in-situ x-ray tomography combined with advanced image processing now allows **experimental micro-(geo)mechanics**

e.g., high-quality kinematical measurements are possible on all (say 50000) grains in a sand specimen deforming under load

**but, different scales of interest exist**

challenges arise when smaller-than-grain-scale measurements are required

- characterization of grain-to-grain contacts (orientations and evolution)
- production of fines by grain breakage
- cemented granular materials (grain debonding)
- partially saturated sand (menisci)
- ...

IS-Cambridge 2014
1 - 3 September 2014, Cambridge, UK.
grain-to-grain contacts: detection
grain-to-grain contacts: detection

Global Mean Coordination Number (COEA01)
Mean Coordination Number in Band (COEA01)
COEA01 ($\sigma_3 = 100$ kPa) Stress Ratio $R$

Axial shortening (%)
grain-to-grain contacts: orientation

A digital grain

Vlahinić et al., 2014, Granular Matter

a “grain” is in fact an assembly of voxels
grain-to-grain contacts: orientation

how well resolved is a contact between such voxelated objects?

Andò et al., 2013, Géotechnique Letters
grain-to-grain contacts: orientation

Pair of Mathematicians

Hugues Talbot

Clara Jaquet

⇒ Contact orientation algorithm

Jacquet et al., 2013, Proceedings ISMM
Viggiani et al., Powders and Grains 2013
evolution of contact network – why do we care?

→ measuring fabric and fabric evolution – talk to Yannis D.

Xia Li · Hai-Sui Yu

Fabric, force and strength anisotropies in granular materials: a micromechanical insight

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grain breakage – production of fines
triaxial compression tests on angular Hostun sand

Alikarami et al., Acta Geotechnica 2014 (submitted)
previous work

Colliat-Dangus et al., 1988, ASTM
Hostun sand (01) | Hostun sand (01)

\[ \sigma_3 = 100 \text{ kPa} \]

\[ \sigma_3 = 7000 \text{ kPa} \]
Hostun sand (02)

\[ \sigma_3 = 100 \text{ kPa} \]

Hostun sand (02)

\[ \sigma_3 = 7000 \text{ kPa} \]
Hostun sand (03)

$\sigma_3 = 100 \text{ kPa}$

Hostun sand (03)

$\sigma_3 = 7000 \text{ kPa}$
Hostun sand (05)

\[ \sigma_3 = 100 \text{ kPa} \]

Hostun sand (05)

\[ \sigma_3 = 7000 \text{ kPa} \]
Hostun sand (07)

$\sigma_3 = 100 \text{ kPa}$

Hostun sand (07)

$\sigma_3 = 7000 \text{ kPa}$
Hostun sand (09)

\[ \sigma_3 = 100 \text{ kPa} \]

Hostun sand (09)

\[ \sigma_3 = 7000 \text{ kPa} \]
So... what's happening?

Recent single-grain (d=3mm) uniaxial compression x-ray work from Hong Kong

B. Zhao, J. Wang, M. Coop
...at our scale...

Recent single-grain \((d=3\text{\,mm})\) uniaxial compression x-ray work from Hong Kong

B. Zhao, J. Wang, M. Coop
experimental observation of grain breakage mechanisms

Rock on Top of Another Rock by Fischli/Weiss (Serpentine Gallery, London – March 2013)

3D assessment of fracture of sand particles using discrete element method

M. B. CIL* and K. A. ALSHIBLI*
triaxial compression tests at high pressure ($s_3 = 7$ Mpa)
recent results from 1D compression of zeolite ($D_{50} = 1.2$ mm)
grain breakage: quantifying evolution of grainsize distribution

- grains do break
- fine material fills up the pore space
- coarser grains are visible but surrounded by finer material
- as it is, the final state image cannot be segmented

a challenge for image analysis – why do we care?

→ measuring evolution of breakage B – talk to Itai E.

Breakage Mechanics model by Einav (JMPS 2007a, 2007b)
cemented granular materials – both grains and bonds can break
TXC on “soft” and “stiff” Fontainebleau sandstone

grain cementation by quartz overgrowths

J. Fonseca, P. Bésuelle and G. Viggiani, Géotechnique Letters 2013
the quantitative grain-scale study of bonded granular materials is very challenging
grain-scale processes involve **grain rearrangement** + **debonding** + **grain breakage**

→ from natural materials to model materials

x-ray scan of calcite-cemented Glass Ballotini

(PhD Alessandro Tengattini)
A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part I—Theory

Alessandro Tengattini\textsuperscript{a,b}, Arghya Das\textsuperscript{a}, Giang D. Nguyen\textsuperscript{c}, Gioacchino Viggiani\textsuperscript{b}, Stephen A. Hall\textsuperscript{d}, Itai Einav\textsuperscript{a,b}

A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part II – Validation and localization analysis

Arghya Das\textsuperscript{a}, Alessandro Tengattini\textsuperscript{a,b}, Giang D. Nguyen\textsuperscript{c}, Gioacchino Viggiani\textsuperscript{b}, Stephen A. Hall\textsuperscript{d}, Itai Einav\textsuperscript{a,b}

Journal of the Mechanics and Physics of Solids
granular materials – more than two phases
partially saturated sand
characterizing water retention behavior at the grain scale
what about fine-grained geomaterials?
we would like to see the deforming micro structure!

how small is "small" for a clay?

BIB image of Boom Clay -- courtesy of J.L. Urai, Aachen University
the Jose Andrade’s question

So What?
micro vs. macro dialogue experiments – modeling

- micro AND macro \(\rightarrow\) multi scale
take-home message

1. observing, measuring (w/statistics), understanding the relevant physics at some appropriately small scale

2. injecting this physics into double-scale models or micro-inspired models (micro $\rightarrow$ macro)

the success of multi-scale approaches crucially depends on the quality of the physics one injects: ideally, this comes directly from experiments

there is still plenty of work (and fun) ahead of us!