IV International Workshop on Modern Trends in Geomechanics
G. Viggiani, D. Salciarini, F. Silvestri, C. Tamagnini, G.M.B. Viggiani
(Eds) Assisi, May 16--18, 2016

MEASUREMENT OF FORCE AND STRAIN DISTRIBUTION IN GRANULAR MATERIALS

Stephen A. Hall[1], Stefanos D. Athanasopoulos[1], Ryan C. Hurley[2], Jonathan Wright[3] and Joe Kelleher[4]

[1]Division of Solid Mechanics, Lund University, Sweden
e-mail: stephen.hall@solid.lth.se; stefanos.athanasopoulos@solid.lth.se

[2]Computational Geosciences Group, Lawrence Livermore National Laboratory, USA
e-mail: hurley10@llnl.gov

[3]European Synchrotron Radiation Facility, France
e-mail: wright@esrf.fr

[4]ISIS Pulsed Neutron & Muon Source, UK
e-mail: joe.kelleher@stfc.ac.uk

Keywords: Experimental Granular Mechanics, neutron diffraction, x-ray diffraction, x-ray tomography.

Summary. New experimental approaches enabling in-depth study of granular mechanics using based neutron and x-ray based measurements of deformation and force transfer mechanisms at continuum- and grain-scales are presented.

1. MEASUREMENT OF DEFORMATION AND FORCE TRANSFER IN GRANULAR MATERIALS

In recent years, significant progress has been made in the experimental characterisation of deformation mechanisms in granular materials through the use of techniques such as photoelasticity, x-ray tomography and digital image correlation (in 2 and 3 dimensions). The former can be highly insightful to understand mechanisms of force transfer and, in conjunction with image analysis, grain kinematics and contact distributions (e.g., [1]). However, photoelastcity experiments, in general, consider idealised, 2D materials. Recent works using X-ray tomography combined with digital image analysis have enabled quantitative characterisation of deformation and structural evolution (e.g. grain contacts, strain fields and grain kinematics) in granular assemblies (e.g. [2][3][4]). Earlier work on plane-strain tests (e.g., [5][6]) revealed similar insights by 2D imaging. Unfortunately, no real information on force transmission is available from such methods.

Recent work has demonstrated that neutron and X-ray diffraction measurements can be used to measure the strains in the crystal structures of sand grains (quartz crystals) during loading of granular assemblies. Since the sand grains behave elastically until brittle failure, the crystal strains can be related to force transfer through the elasticity of the grains. With such measurements, each grain essentially acts as a local 3D strain or force gauge. This, in conjunction with imaging of structural evolution, opens the door to new studies where both deformation and force-transfer can be measured in real granular materials. Herein, two experimental approaches exploiting these methods are described.

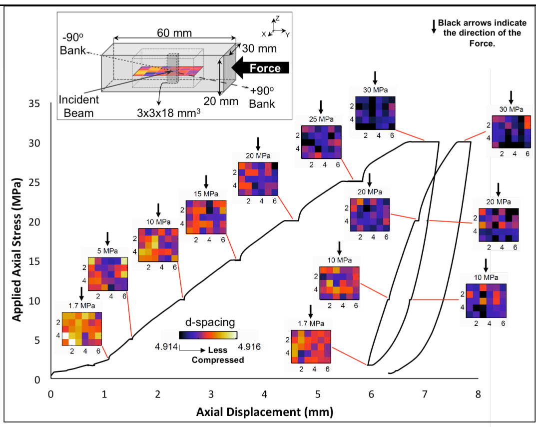

Fig. 1: Maps of the axial crystallographic ("d") spacing of a sample of quartz sand measured by neutron scanning diffraction with a gauge volume of 3x3x18 mm^3. (Darker colours indicate smaller d-spacing (more compression) and structures of darker pixels can be seen to form in the axial direction at high loads).

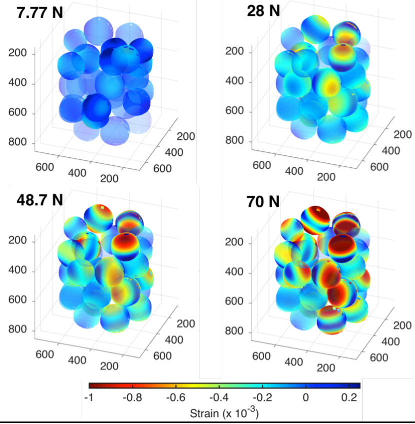

Fig. 2: Strain tensor data for each of the grains, in a sample of quartz grains (sample width is about 1.5 mm), presented as a 3D rendering of the strain ellipsoids onto the 3D grain surfaces from x-ray tomography (in the initial configuration) at different axial loads; see [7] for more details.

2. EXPERIMENTAL RESULTS

The first method considers a sample of a very large number of sand grains and uses spatial mapping of crystal strains by neutron diffraction based "gauge-volume" measurements, which gives maps of "grain strains" averaged over small volumes of, in this case, 3x3x18 mm^3, during loading. Fig. 1 shows results from a proof-of-concept experiment of a sample of sand (D_{50} = 210 microns) confined in a parallelepipedic box with soft side-walls (performed at ENGIN-X at ISIS Pulsed Neutron and Muon Source, UK). Based on this proof-of-concept further experiments are underway with a plane-strain device with pressure boundary conditions and viewing windows to enable digital image correlation based full-field strain measurements. The second approach, based on 3D x-ray diffraction and tomography, provides quantification of the full strain tensor for individual sand grains in samples of up to about 1000 grains, in addition to the evolution of the granular/contact structure. Fig. 2 shows example results of the grain configuration, from x-ray tomography, and the tensor crystallographic strains, from diffraction, for each grain in a sample of a small number of grains; the experiment was performed at ID11 at the European Synchrotron Radiation Facility (see [7]). Inverse analysis of these data has also been performed to provide quantification of the contact force network evolution.

References

[1] T.S. Majmudar & R.P. Behringer. Contact force measurements and stress-induced anisotropy in granular materials. *Nature* 435, 1079–1082, 2005.
[2] F. Forsberg & C. Sivour. 3D deformation and strain analysis in compacted sugar using x-ray microtomography and digital volume correlation. *Measmt Sci. Technol*., 20, 095703, 2009.
[3] S.A. Hall, M. Bornert, J. Desrues, Y. Pannier, N. Lenoir, G. Viggiani & P. Bésuelle,. Discrete and continuum analysis of localised deformation in sand using X-ray μCT and volumetric digital image correlation. *Géotechnique* 60, 315–322, 2010.
[4] Z. Hu, Y. Du, H. Luo, B. Zhong H. & Lu. Internal deformation measurement and force chain characterization of Mason sand under confined compression using incremental digital volume correlation, *Expl. Mech*. 54, 1575–1586, 2014.
[5] J. Desrues & G. Viggiani. Strain localization in sand: an overview of the experimental results obtained in Grenoble using stereophotogrammetry, *Int. J. Numer. Anal. Meth. Geomech*., 28, 279–321, 2004.
[6] S.A. Hall, D Muir Wood, E. Ibraim & G. Viggiani. Localised deformation patterning in 2D granular materials revealed by digital image correlation, *Granular Matter*, 12, 1-14, 2014.
[7] S.A. Hall & J. Wright. Three-dimensional experimental granular mechanics, *Géotechnique Letters*, 5, 236–242, 2015.