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Full field measurements and identification in Solid Mechanics

Experimental characterisation of (localised) deformation phenomena in granular geomaterials from sample down to inter- and intra-grain scales

Stephen A. Hall[a*], Jacques Desrues[b], Gioacchino Viggiani[b], Pierre Bésuelle[b], Edward Andò[b]

[a]*Division of Solid Mechanics, Lund University, Lund, Sweden and European Spallation Source AB, Lund, Sweden*
[b]*CNRS/UJF/INPG, Laboratoire 3SR, Grenoble, France*
**stephen.hall@solid.lth.se*

Abstract

This paper outlines some recent advances in the full-field experimental characterisation of the mechanics of granular geomaterials (in particular, sands) using a range of methods that provide characterisation at different scales, from the sample-scale down to the inter- and intra-grain scale. The techniques used are "full-field" approaches involving in-situ x-ray micro-tomography, 3D-volumetric digital image analysis/correlation and grain ID-tracking, in-situ 3D x-ray diffraction and in-situ, spatially-resolved neutron diffraction. These methods provide new data on the mechanics of sand at different scales, including continuum measures of strain, porosity, and fabric plus discrete measures of particle kinematics and force transmission. The results of such measurements might be used to advance higher-order continuum theories, and provide the necessary input parameters, or to calibrate discrete grain-scale simulations of sand behaviour to explore loading paths that are inaccessible in the laboratory.

keywords: Full field characterisation; x-ray tomography; 3D image analysis; digital volume correlation; x-ray & neutron diffraction

1. Main text

Granular materials exhibit multi-scale behaviour associated with the interactions of the individual grains across their contacts. This structure leads to complex, pressure-dependent mechanical responses

* Corresponding author. Tel.: +46 46 222 45 89.
E-mail address: stephen.hall@solid.lth.se.

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and inhomogeneous, often localised, deformation phenomena. Various modelling approaches exist to describe the mechanics of these materials, including: higher-order continuum approaches to characterise, for example, strain localisation; multi-scale approaches involving homogenisation of explicitly modelled micro-scale (granular) mechanics; discrete element models that attempt to model granular systems from the grain-scale upwards. However, such models require experimental results, at the appropriate scales, to identify and characterise the important mechanisms controlling the material responses, to provide ground-truth and to identify model input parameters. Unfortunately, traditional experimental methods fall short of providing the necessary data for these ambitious modelling approaches, as they provide information relating to the macro-scale, "averaged" response and no details on internal structure evolution and deformation mechanisms, e.g., shear-band development, individual grain kinematics and force-transmitting contact distributions.

In this paper, different experimental analyses are presented that provide extended insight into the mechanics of granular media (specifically natural sand) over a range of scales; from the sample-scale down to that of the grains and grain-contacts and further down to the internal deformation of the grains themselves. The techniques used are "full-field" approaches involving in-situ x-ray micro-tomography, 3D-volumetric digital image analysis/correlation and grain ID-tracking, in-situ 3D x-ray diffraction and in-situ, spatially-resolved neutron diffraction. Phenomena including dilation, grain rotation and grain-contact evolution associated with strain localisation are quantitatively characterised as well as evidence of inter-granular force transfer. Whilst the focus is the mechanics of sand, a natural granular material, the insight provided and techniques used have wider implications for granular mechanics in general.

The paper consists largely of a review of recent work, but starts with the historical context from the first innovative uses of full-field measurements in soil mechanics carried out in Cambridge, UK, in the 1960's, up to the 3D imaging made possible after the advent of x-ray tomography. The advances in such technology have provided vast improvements in the 3D image resolution such that it is now possible to image the grain-scale detail of sand samples under load. The subsequent sections of the paper follow from this point where the analysis of sand mechanics is investigated from a scale, where sand might be considered as a continuum, to imaging allowing grain-scale analysis of "discrete" mechanics. Finally, some very recent, on-going advances aiming towards analysis of intra-granular mechanics and force transfer mechanisms are discussed. The presentation of the different methods is followed by a short discussion of their relevance in the context of the simulation of sand deformation, before some conclusions.

2. Historical context

The importance of inhomogeneous deformation in soils, in particular strain localisation, has been appreciated for some time and has been well studied through laboratory testing. However, if deformation is inhomogeneous (which is the rule rather than the exception in geomaterials, e.g., when strains are localised or the material has pre-existing heterogeneity), standard (traditional) boundary measurements of loads and displacements have only nominal, or conventional, meaning. To study such inhomogeneous behaviour requires full-field measurements, i.e., measurements of a field of properties as opposed to point-wise measurements, for which a number of techniques are available (e.g., [1]).

The importance of x-ray tomography as a full-field imaging tool in geomechanics is evident in the increasing number of publications and international meetings e.g., the GeoX series of conferences ([2-4]). However, the first soil mechanics measurements using x-rays were carried out in the 1960's in Cambridge, UK, when Roscoe and co-workers (e.g., [5][6]) used x-ray radiography to image 2D (plane-strain) tests on structural sand models. From the early 1980s x-ray tomography was used by Desrues and co-workers ([7-9]) and later by [10]; see [11] for a review. These studies provided new 3D observations of localisation patterning in sand. Importantly, in some work the analysis was taken beyond the idea of just obtaining a 3D image to use of x-ray tomography as a quantitative tool; e.g., the measurement of void

ratio evolution inside a shear band and its relation to critical state by [9]. Some work was also carried out with triaxial tests "in-situ" (i.e., the loading is carried out within the x-ray tomograph) to provide 4D (three dimensions in space and one in time), e.g., [9][10][12].

Due to the image resolution possible in the studies cited above, sands had to be considered as continua in both the imaging sense – grains are not seen individually and a volume average of grains and porosity is given at each voxel (the 3D version of pixels) – and the mechanics sense – any discrete or strongly-discontinuous deformation is blurred out by the spatial resolution. Such approaches provide good insight into emergent structures associated with deformation, e.g., localisation patterns (if they are accompanied by a sufficient density change), but not into the mechanisms. However, x-ray tomography has advanced steadily, since its advent in the 1970's, such that now micro-tomography and sub-micron tomography is possible using both synchrotron facilities and laboratory "scanners". Some scanners even permit imaging resolution down to tens of nano-metres; however high resolution is only possible with small samples. For sands, whose grain-sizes are in the range of 100's microns (and bigger), sub-micron imaging has not yet seen much interest. However, micro-tomography with resolutions of microns to 10's microns now allows sand to be studied as a discrete material, i.e., one made up of individual, discrete particles. For example, [13] presented micro tomography images of sand grains inside a shear band, showing organised structures that had only previously been observed in 2D thin sections ([14]). More recently, [15][16] used synchrotron x-ray micro-tomography with in-situ tests to produce 4D images in which individual sand grains could be identified and tracked (however the tracking, at this time was limited to 2D for a section through the specimen and the authors noted that the problem required full 3D analysis).

In the remainder of this paper a number of methods for full-field analysis of sand deformation, building on the historical foundations outlined above, are discussed.

3. Experimental methods and data analysis

Three different experimental set-ups and techniques will be presented. These techniques provide different information about deformation mechanisms and at different spatial resolutions.

3.1. In-situ X-ray micro-tomography

As discussed above, in-situ (i.e., during-test) x-ray tomography imaging for loading tests on sands has been carried out using industrial/medical scanners to provide impressive 3D images of dilatant localisation structures, which lead to improved understanding of the mechanics at a meso-scale between the sample and grain scales (e.g, [9]; [10]). However, it is clear that the mechanisms of deformation that lead to meso-scale localised deformation features are acting at the grain-scale. X-ray *micro*-tomography imaging, first only possible with synchrotron sources, but now available using laboratory scanners, provides imaging of samples with grain-scale detail, albeit with smaller test samples. In the following, the in-situ micro-tomography experiments and data of [17] are briefly presented before a discussion of the 3D image analysis and correlation techniques used to extract quantitative measures of deformation phenomena. Note that these experimental data were the first such data leading to such detailed analyses, but subsequent, on-going work is yielding an increasing suite of data on different sands under different loading conditions (PhD thesis of E. Andò, Laboratoire 3SR, Grenoble, expected in 2012).

[17] presented experimental results from a triaxial compression test performed on a dry specimen of S28 Hostun sand (quartz sand with a mean grain size (D_{50}) of about 300 μm), under a confining pressure of 100 kPa, carried out in-situ at the European Synchrotron Radiation Facility (ESRF) in Grenoble on beamline ID15A (see [17],[18] for details of the in-situ loading system). The sample was 11 mm in diameter and 22 mm high, comprising roughly 50000 grains. Figure 1b shows the sample stress-strain response. Relaxations can be seen at the moments at which x-ray tomography scans were carried out,

these drops occurred rapidly after the loading was stopped then the axial force remained quite constant. Figure 1c presents vertical slices through the 3D x-ray tomography volumes acquired through the test. These images have a voxel size of 14 x 14 x 14 μm^3; such dimensions were chosen to provide sufficient voxels per grain (about 5500 voxels on average with about 21 voxels across their diameters), which allowed clear identification of individual grains.

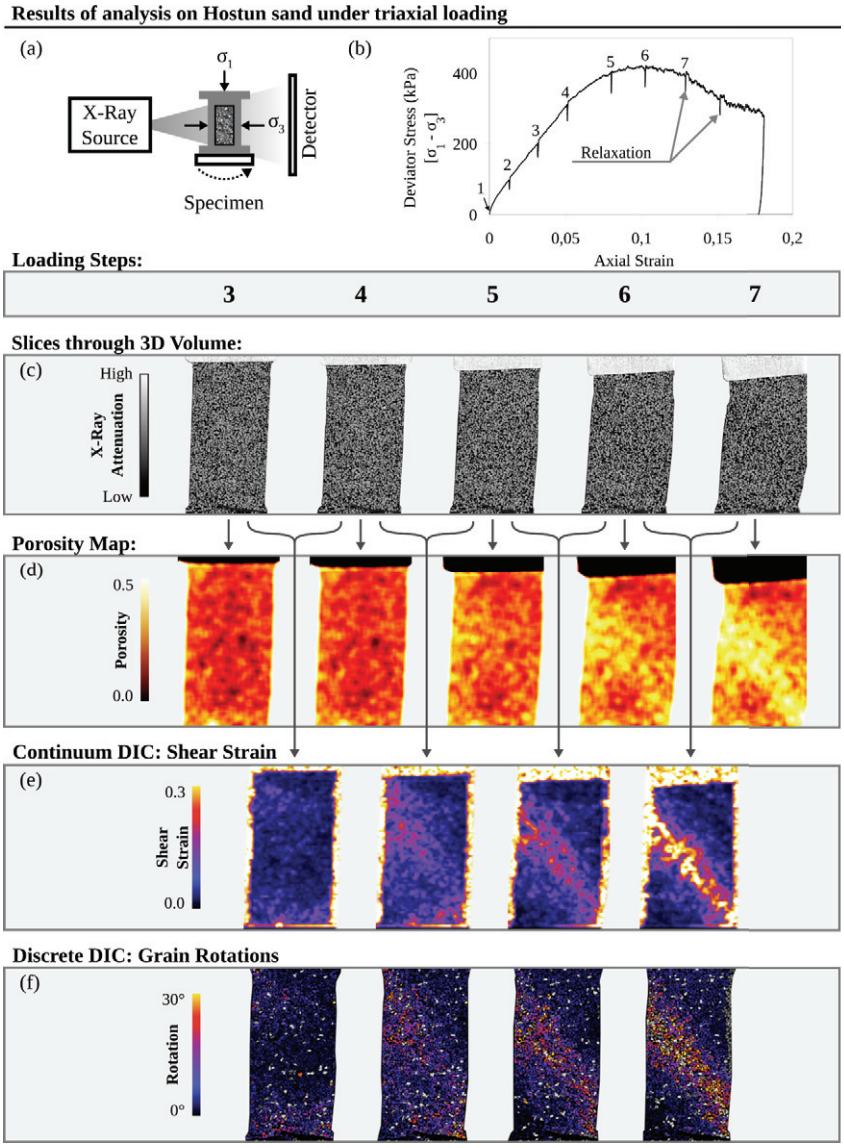

Fig. 1. (a) Data acquisition; (b) stress-strain curve indicating also the image acquisition times; (c)-(f) vertical slices through the image volumes of x-ray tomography, porosity, shear strain and individual grain rotations (Note that the grains in the final image are represented in their initial configuration)

3.2. 3D image analysis – continuum and discrete grain-scale measurements

The images produced through in-situ x-ray tomography are impressive, but remain just images and to extract information about the mechanisms at play requires further, quantitative data analysis. The first and most straight-forward quantification of these images involves determining the 3D porosity field evolution through the test. The porosity fields for the test of [17] are presented in Figure 1d. This calculation was based on a binarisation of the x-ray tomography image volumes into "grain" and "pore" voxels (i.e., a threshold grey-scale value has been defined such that voxels with a grey-scale value above this threshold are considered to be within a grain and those below the threshold, pore space). Porosities are given for overlapping cubic windows of side 61 voxels (854 μm, about 3 x D_{50}) throughout the sample volume. The window size used is a compromise between a good representative elementary volume size and the need for spatial resolution. The derived values represent the accumulated porosity from the start of the test.

Once binarised into grains and pores, the x-ray tomography images can also be "segmented" to identify and label individual grains. This has been performed using the 3D watershed algorithm from the image-processing package VISILOG (©Noesis, http://www.noesisvision.com/). The output from this procedure is an image volume in which each grain is assigned a unique label (number) such that they can subsequently be identified and characterised to give their geometrical characteristics (this information can also be used to recognise grains from one step to the next, as discussed later). In addition, once the grains are separated and labelled, contacts between grains can be identified as described by [19] to give binary or labelled volumes of contacts. Quantification of contact statistics and geometries can thus be carried out, e.g., in terms of orientation distribution functions, contact density fields and grain coordination numbers.

3.3. 4D Analysis, 3D-volumetric continuum DIC, discrete DIC and grain tracking

Porosity and grain or grain-contact characterisation in 4D can provide good insight into the structural evolution and consequences of deformation, which could be used in enriched modelling approaches. However, it is also of interest to quantify the actual deformation, either in terms of strain fields or particle kinematics. Such analysis is possible through digital image correlation (DIC). DIC was pioneered in the 1980s (e.g. [20]) for surface full-field deformation measurement. The extension of 2D-surface DIC to 3D-volume DIC to measure 3D displacement and strain fields within a volume, e.g., using 3D images acquired by X-ray tomography, is relatively straightforward, but is quite recent (e.g. [21-23]; also see [24] for a review).

DIC (whether in 2D or 3D) can be simply considered as a mathematical tool to define the best full-field mapping of one image into another, either by a field of rigid body translations or by some more general transformation functions. Implementations of DIC usually involve local evaluations of the transformation over cubic (for the volume case) subsets that are regularly distributed over the reference image. The evaluation requires solving an optimisation problem for each subset, in which some measure of the similarity of the considered subsets in the two images is maximised over a parametric set of transformations. As a digital image is a discrete representation of grey levels, some interpolation is necessary to evaluate the transformation with subvoxel accuracy.

It should be noted that standard implementations of DIC assume a continuous displacement field, at least within each subset. When deriving strain from the displacements of separate subsets, continuity between adjacent subsets is assumed. For this reason, such DIC analysis might be referred to as 'continuum DIC' (or in this case piece-wise continuous). The details of the continuum DIC procedure used to produce the results presented later are provided in [17] [25]. An alternative DIC approach for granular materials that recognises the granular character both of the images and the mechanical response was proposed by M. Bornert (Institut Navier) and presented in [17][26]. This approach is a 'discrete DIC' procedure with the specific aspect that the regularly shaped and spaced subsets are replaced by subsets

centred on individual grains, with a shape following the actual shape of the grain. If the grains are assumed to be rigid, then the transformation of each subset is a rigid motion involving a three-component translation vector plus a three-component rotation.

Tracking of individual grains through a series of in-situ 3D tomography images based on their geometrical characteristics is an alternative to the discrete DIC approach discussed above. This concept was originally proposed by [27], but has only been fully implemented recently see [28]. This method performs comparably with the discrete-DIC approach (yielding the same information), but is less computer intensive and thus faster; it is, however, perhaps less general and grain rotations are less well determined.

3.4. Selected results

This section presents a selection of results from the analysis of the data of [17]. First, Figure 1d shows vertical slices through the 3D porosity fields. These images indicate the evolution of an inclined zone of localised porosity increase (dilation) through the test, plus there are indications of structure in the band in the form of high and low porosity zones conjugate to the main band orientation.

Continuum 3D-volumetric DIC carried out on consecutive pairs of the 3D x-ray tomography image volumes provided 3D displacement and strain fields for each increment. Figure 1e shows vertical slices through DIC-derived “shear strain” volumes (the second invariant of the strain tensor); as in the previous images, these vertical slices are cut roughly perpendicular to the “plane” of localisation that developed during the test. These strain images clearly show the evolution of a localised band that traverses the sample diagonally from top-left to bottom-right, corresponding to the observed band of porosity increase. This localisation appears to initiate in the increment 4-5, i.e., well before the peak load. Furthermore it can be seen that the band starts as a broad zone and converges towards a narrow band of localisation in step 6-7 (the zone is around 5 mm, about 17 D_{50}, at this stage) with a narrower, high strain core. Note that localisation is visible in these maps before it becomes clear in the porosity images. At this stage, the general picture is of a localisation of shear strain then dilatancy, which starts as a broad zone and slowly reduces in width. The DIC results also show that the localised band is not uniform and contains structure, including aligned zones of either reduced or elevated strains at angles "conjugate" to the main band direction. The orientations of these zones are similar to those of “columns” of aligned grains identified by [13] in a shear band in sand. Therefore, the shear-strain structures might indicate the presence of columnar structures in the grain assemblage and motivate the use of discrete image analyses.

Discrete DIC was applied to provide incremental analysis of the kinematics of each grain (3D displacements and rotations). Grain displacements agree with the continuum DIC results with relatively continuous fields of displacements, even in the presence of strain localisation, which explains why continuum DIC performed well. However, locally (between grains) the kinematics can be discontinuous. Figure 1f presents the magnitude of rotation for each grain about its rotation axis (which is specific for each grain). These results indicate that grain rotations become progressively more intense into a zone that roughly corresponds to where shear strain localises, showing that the shear strain is due, at least in part, to grain rotations at the micro-scale.

Contact density distributions for tomography images 1 and 7 have also been derived in [19]. This analysis showed that the zone of localised shear strain is associated with a lower density of contacts (and is populated with lower coordination number grains), which is consistent with the observed increase in porosity in this zone. The orientations of the contacts in a sub-volume within the shear-band at step 7 were also analysed, which indicated that contacts seem to be aligned with the localisation feature.

3.5. Intra-granular measurements: Coherent elastic neutron and X-ray diffraction

The understanding of mechanics in granular materials could be aided by measures of force distribution, in addition to the grain kinematics and structural evolution. Unfortunately, forces cannot be measured, however they might be inferred from strains in the supporting grains. To this end [29] presented first results of neutron and x-ray diffraction measurements of changes in crystallographic lattices of sand grains (which are quartz crystals) in samples of many grains under load. These approaches exploit the concept of coherent elastic scattering, which is the interaction of x-rays with the electron cloud around an atom, or of a neutron with the nucleus of an atom, leading to diffraction. Constructive and destructive interference of the diffracted x-rays or neutrons leads to patterns of 'Bragg peaks' that are characteristic of the arrangement of atoms in the scattering crystals and, in particular, the spacing between the atomic planes (the "d-spacing"). The diffraction angle (2θ) of the Bragg peaks can change if the d-spacings between crystallographic planes change. Measurement of changes in Bragg peak positions can thus be used to determine strains in different directions in the diffracting crystals such that each grain can act as a local 3D strain gauge or, for elastic deformations, a force gauge. Two spatially resolved diffraction techniques, with different space and strain resolutions, are described below.

3.5.1. In-situ Neutron diffraction

The monochromatic neutron diffraction instrument SALSA, at the Institut Laue-Langevin, France ([30) allows very precise measures of crystal strains over small gauge volumes on the assumption that, within the volume, there is a continuous orientation distribution function of crystals (an assumption of "powder" diffraction). [29] presented results of neutron diffraction measurements using SALSA for sand under 1D (œdometric) compression (using an aluminium œdometer of internal diameter 30 mm). Loading was carried out in-situ, i.e., whilst mounted in the diffraction set-up, over a load-unload-load cycle of $0 \rightarrow 35 \rightarrow 1 \rightarrow 35$ kN. At each 1 kN loading step the force was held whilst a diffraction measurement was performed for a gauge volume of 4 x 4 x15 mm^3 in the centre of the sample (average sand grain diameters were about 250 μm); the large gauge volume produced stronger scattering thus allowing faster measurements over a range of loads, at the expense of spatial resolution. A Bragg peak at $2\theta \approx 86.8°$ (λ = 1.64 Å) was measured with a Q-vector (strain measurement direction) along the sample axis.

Figure 2 shows the loading-piston displacement (indicating macro-strain) and the axial 2θ values (indicating grain-strain averages over the gauge-volume) as functions of the applied axial force. Globally, the grain-strain follows a remarkably similar trend to the macro-strain. However, the grain-strain at first increases more slowly, than the macro-strain, until about 10 kN, after which the gradient increases; this appears to correspond to a reduction in the macro-curve gradient (i.e., a stiffer response). These trends perhaps indicate a change in the general deformation mechanism from porosity reduction to grain strain. There is a significant non-recovered macro-strain as would be expected due to porosity reduction, but there is also a significant residual grain-strain. This suggests that the grains remain confined between themselves ("locked") after removal of the load. The significant variation of the grain-strain variations around the trend is not thought to be just noise, but rather might indicate the occurrence of load transfer in and out of this volume; this hypothesis is being tested with 3D mapping and smaller gauge volumes.

3.5.2. In-situ 3DXRD

The measurements presented above using neutron diffraction are measures of crystallographic strain averaged over a volume. Whilst the technique is being extended to use smaller gauge volumes and 3D mapping, it will remain a "continuum" intra-granular measure. Similar gauge-volume techniques exist for x-rays, but with the fine focussing possible at synchrotron facilities other, more refined, approaches can be considered. 3DXRD (3D x-ray diffraction) is a technique that can provide grain-by-grain measures of 3D grain-strains, albeit for reduced numbers of grains; this has mostly been applied for metals, see [31]. However 3DXRD for sands has been presented by [29]. Measurements were carried out at the European

Synchrotron Radiation Facility using beamline ID11 where grain-strain resolution of about 10^{-4} can be expected. This was the first such application to geomaterials and involved 1D compression in-situ in the 3DXRD setup using quartz-glass œdometers (internal diameter 10 mm) and sand grains of average diameters of about 720 μm. The early results presented in [29] demonstrated that diffraction patterns could be measured and assigned to individual grains. Furthermore, there were good indications that quantitative measures of individual grain-strains plus grain and sub-grain kinematics (rotations and intra-granular crack opening) could be made. The analysis of these data is on-going and individual grain strains over a range of loads are now being determined.

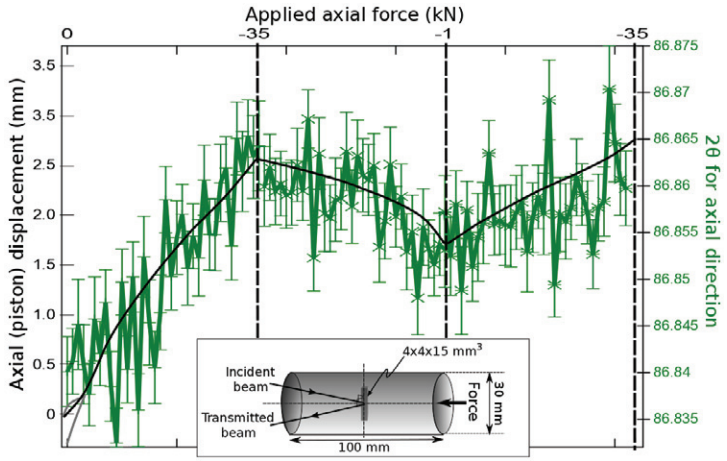

Fig. 2. Neutron diffraction results: macroscopic axial displacement and change in 2θ, indicating grain-strain in the axial direction (average over the gauge volume see in-set), as functions of the applied axia force. Inset: measurement and loading set-up

4. Discussion

A range of different experimental techniques have been presented that elucidate the mechanics of sand at a range of different scales. However it is important to highlight where, in terms of advancing the simulation of sand deformation, these measures can be useful. An initial example is the demonstration by [9] that the critical state concept, whereby a soil will reach a certain (critical) degree of porosity with loading, is valid, but only applies to the localisation zone and not globally; this was postulated in 1938 by Casagrande & Watson ([33] as quoted in [9]), but only with modern experimental tools could this keystone of soil mechanics be verified. The results of [9] were achieved with low-resolution in-situ tomography calibrated to yield porosity measures. A similar analysis could be carried out with the data presented in Figure 1d to provide further insight into the applicability of this concept (is critical state reached through a localisation zone or is it only applicable in certain areas?). The lower-resolution imaging, or indeed the continuum analysis (porosity or DIC) of higher resolution imaging, can answer questions on the development of patterning and length-scales in the material. For example in the case of larger samples with multiple localisation features, what is the juxtaposition of the different features (patterning), what are the key length scales (width of the band, but also band spacing) that should be accounted for in continuum models where length-scales are taken into account (the so-called generalised, enriched or micromorphic continua)? Such aspects were discussed for a 2D granular material in [33]. These different length-scales are key parameters revealed by full-field methods and important further insight can be gained by the comparison of the different measures. For example, the porosity

representation of the shear-band in Figure 1d is wider than that in the shear-strain field (Figure 1e); this in part stems from the total versus incremental analysis, but also (and most importantly) indicates the interrelationship between shear and dilation, which is a key ingredient of any continuum theory of inelastic deformation of geomaterials. The width of the localisation features is also possibly different when grain-rotation and grain-displacement are considered; [28] showed two examples, one for the rounded Ottawa sand and the other for the angular Hostun sand, in which shear bands in triaxial tests were slightly wider for rotation than displacement in the former, but significantly wider for rotation in the latter. This probably indicates the role of some "cog" effect between the angular Hostun grains.

The analysis of contact distributions, in 2D experiments or numerical simulations has in the past been used to understand the origins of anisotropy in mechanical properties. The type of imaging described herein allows this to be extended to 3D and for real sands, also the evolution can be assessed. Furthermore, combination of the grain kinematics analysis with contact recognition could also permit characterisation of "contact kinematics", which might be revealed as being important aspects to the mechanics and, in particular, the differences between the ways by which different sands transmit load.

The described observations and measurements at the grain-scale clearly allow the underlying mechanisms of deformation to be better understood and thus better described in modelling; such insight might be used as a guide to develop (standard or generalised) continuum models, but can also be used to calibrate micro-scale, discrete simulations for a given loading path. The, thus calibrated, simulation approach might then be used to investigate other loading paths, including those inaccessible in laboratory experiments; this could lead to further improved understanding for continuum models.

The possibility of inferring forces at different scales provides another new dimension to the experimental analysis and thus new understanding for modelling. One might imagine eventually being able to access all aspects of the mechanical behaviour of granular materials, i.e., kinematics (displacements, strain) and statics (forces, stress). Such measures will also improve the understanding of the mechanisms, e.g., how are the forces transmitted, do just a few grains support the load and, if so, what is the configuration of the load-carrying grains and what are the characteristic distances? Additionally, what are the processes that lead to failure? If force-chain buckling is key to failure, as has been suggested (e.g., [13]), one must be able to measure this experimentally, which requires some experimental determination of force (rather than just relying on geometrical considerations) – the diffraction measures discussed, might well permit this in the future for real sands (as opposed to numerical experiments or idealised experiments on photoelastic materials). The example given above using neutron diffraction also highlights key issues relating to the partitioning of strain in the granular material – whilst at low strain it is the porosity reduction that is important, at higher (but not so high) strain, the grains themselves do deform (this result will clearly depend on packing). These results can also illuminate issues relating to the phenomenon of granular locking.

5. Conclusions and perspectives

Granular materials exhibit multi-scale behaviour associated with the interactions of the individual grains across their contacts. This structure leads to complex, pressure-dependent mechanical responses and inhomogeneous, often localised, deformation phenomena. The quest for improved predictive models of these materials requires greater understanding of the mechanisms at the scale of the grains that control the macroscopic mechanical behaviour. This paper has outlined some recent advances in the full-field experimental characterisation of the mechanics of sand using a range of methods providing characterisation at different scales from the sample scale down to the inter- and intra-grain scale.

X-ray tomography can now provide impressive 3D images of a specimen in which the individual grains can be identified and distinguished, but value can only be truly gained through quantitative measures. Such measures, which include porosity, grain and grain contact geometries and distributions,

might be continuous or discrete. However, to understand the mechanics, the evolution of a specimen and its properties should be followed in 3D as a function of loading, which requires in-situ testing with 4D (3D plus time) imaging coupled with quantitative analyses. In addition, 3D-volumetric DIC can be employed with such 4D images for quantification of strain fields and, for example, the evaluation of strain localisation phenomena (in this case shear-bands) in terms of geometry (width, orientation) and internal structure (e.g., the observed conjugate features within the band). Access to the underlying grain-scale mechanisms that give rise to these meso-scale structures is now possible with discrete DIC or grain ID-tracking, and grain rotation has been shown to play a significant role; although further analysis of other tests, including different grain shapes and loading conditions, is needed and is underway. Furthermore, the kinematic analysis is being extended to characterise the kinematics across grain contacts. Finally, new insight might be gained using in-situ 3DXRD and spatially-resolved neutron diffraction to provide data on force transmission in granular assemblies; the first steps have been made in this direction. Simultaneous diffraction measurements and tomographic imaging will be the next step.

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