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How does strain localise in standard triaxial tests on sand: Revisiting the mechanism 20 years on

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ABSTRACT

In this paper we present results from the first experiment on Hostsun HN31 sand using a newly-developed, standard size triaxial cell which allows x-ray tomography during loading. Results are consistent to previous work, however new measurement techniques including improved spatial resolution and Digital Volume Correlation, allow incremental strain fields to be measured. Incremental strain fields after failure reveal a complex structure of localised strain, whose beginnings are found far before the stress peak. This opens some fundamental questions on how to best interpret these fundamental deformation mechanisms in sand from a modelling perspective.

1. Introduction

"Triaxial tests" – whereby a cylindrical specimen in a flexible membrane with hard circular end platens is subjected to some confining pressure and an additional stress on the circular platens, is an industry standard in geotechnical engineering practice as well as in soil mechanics research. A triaxial test is generally considered to be a unit test, meaning that it is utterly representative of the material's "constitutive" mechanical behaviour, and is large enough to be free of any scale effects. This means that the mechanical response of the specimen obtained during a triaxial test can be described by a simple relationship between the changes of a single stress tensor and the changes of a single strain tensor that describe the entire specimen.

Unfortunately in reality, it appears that things are not so simple: studies using laboratory full-field measurements by our group in the 1990s, studying triaxial tests in sand using x-ray tomography as offered by a medical scanner, reveal that strain localisation is unavoidable and is ineluctable and omnipresent when sand is sheared. Even when taking all possible precautions to perform the "cleanest" (*i.e.*, most mechanically perfect) triaxial tests, which appear to have no external sign of strain localisation, the ability to look inside deforming specimens revealed complex structures of localised changes of porosity whose integrated kinematics appear externally as a uniform deformation – see [6] and [3].

This appeared not to bode well for the triaxial test in general, however the upshot of these experiments is that "critical state soil mechanics" – a theory that predicts the mechanical behaviour of materials under large, monotonic shearing – is particularly well-verified inside the observed localised band of deformation, rather than the average of a complex strain field.

In this paper we revisit these experiments 20 years later, using a newly-developed triaxial cell for our lab x-ray scanner (which itself is not far from its 10th birthday!). 20 years of technological progress means that spatial resolution has significantly improved, and the ability to perform experiments directly inside the (specifically-designed) x-ray scanner allow small steps in strain to be applied between scans, meaning that progressive mechanisms can be followed much more finely than before. In this short communication, the results of the first experiment of a relatively large campaign are discussed.

2. Material and methods

We study the Hostun HN31 sand, of which the Hostun RF studied in [6] is a practically-identical ancestor. It is a standard material in soil mechanics research, and is composed of angular quartz grains of mean grain size $D_{50} = 338$ µm and coefficient of uniformity $C_u \approx 1.5$. The triaxial tests are performed on cylindrical specimens 70 mm diameter and 140 mm high. These are prepared inside a latex membrane of thickness 0.41 mm stretched in a mould. The confining pressure is applied by pressurised air. The specimen is shortened under displacement control, and the mechanics of the system are such that the two platens cannot rotate or displace in the plane normal to the application of the stress (*i.e.*, they are al-

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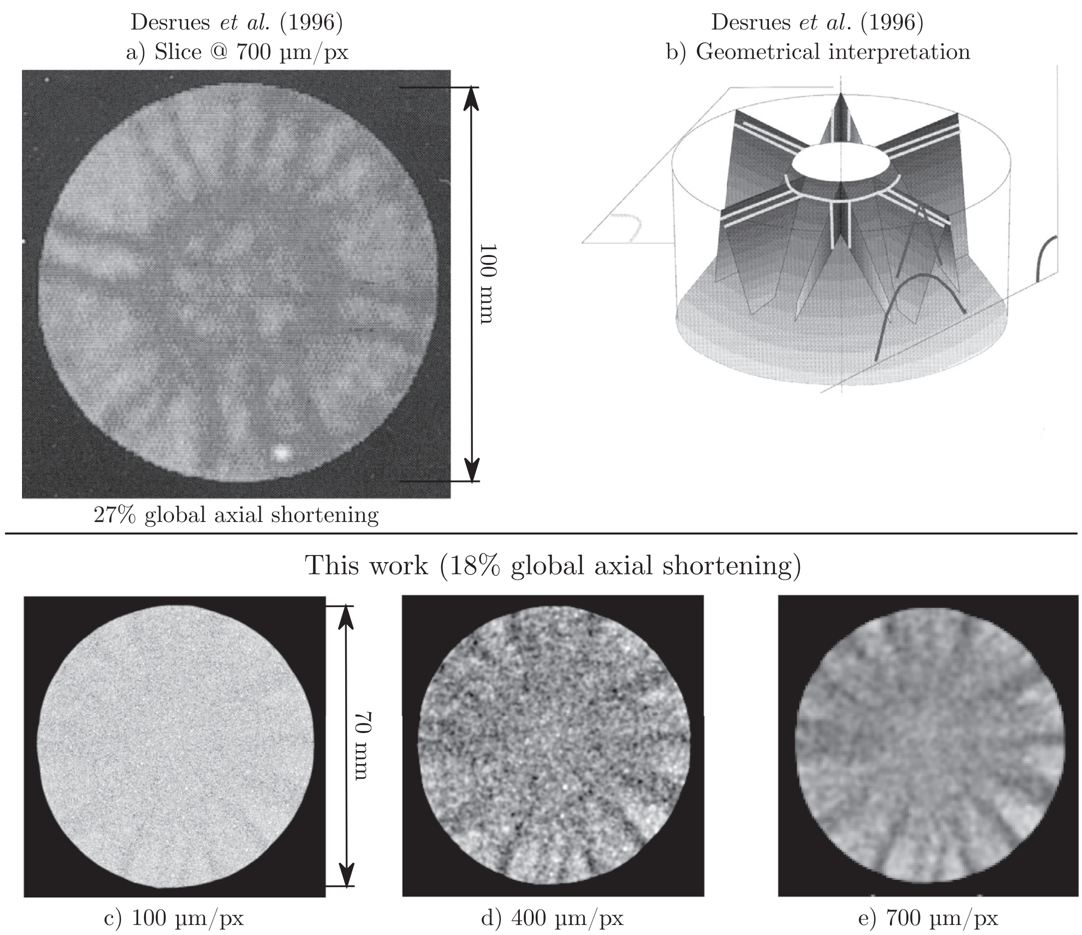

Fig. 1. Comparison of x-ray tomography slices from the 1990s and now. (a) Horizontal slice from [6] – Fig. 14. (b) Geometric interpretation of the dilative, localised bands visible from [6] – Fig. 16. (c) Horizontal slice through our specimen at 100 µm/px. Colourmap shows greylevels from 16-44k (d) and (e) Same horizontal slice with artificially degraded resolution to 400 and 700 µm/px. Colourmap shows 35-40k.

ways parallel and co-axial). Please note that in the tests analysed in [6], rotations of the upper platen were permitted. In this first test the loading platens are not lubricated.

The x-ray tomography setup combines a micro-focus x-ray source with an amorphous silicon flat-panel detector – see [15] for more details. An x-ray compatible triaxial apparatus is used, first presented in [5], whose plastic pressure vessel also takes the return force from the axial compression of the specimen. In order to keep the large specimens studied in the field of view, the pixel size is 100 µm/px.

This is a substantial increase in spatial “resolution” since the medical scans in the 1990s, and is close to being able to resolve the approximately 27 million grains of sand in the specimens. Comparing Fig. 1(a) and (c) the gain in spatial resolution is appreciable, however given the granular texture that can be resolved, such gain in resolution hides “the trees from the forest”, in the sense that the clearly dilatant bands visible in (a) are hard to make out. However, if the pixel size of the images is artificially reduced to the same level as the 1996 paper[1] (so that voxels include multiple grains in such a way that the x-ray attenuation field measured is a good proxy for mesoscopic density) as shown in (e) a strikingly similar shear band pattern is visible in our specimen.

3. First compression test

The triaxial compression test studied here has been performed at a cell pressure of 100 kPa. The specimen’s initial relative density is 96% ($e_{\min}$ and $e_{\max}$ from [7]).

In 28 different points during the test, the loading is stopped, and during about two hours an x-ray tomography scan is performed, with 1120 radiographs being acquired as the entire triaxial apparatus is rotated through 360°. Fig. 2 shows the mechanical response of the specimen as the stress deviator ($q = \sigma_1 - \sigma_3$) against the axial shortening (ϵ_a) applied. The points at which a scan is performed are easily seen in the q vs ϵ_a graph as stress relaxations. Please note that the path from 01 to 02 is not standard triaxial compression, since 01 is at 50 kPa isotropic stress and 02 is at $\sigma_3 = 100$ kPa and $\sigma_1 = 200$ kPa ($\frac{\delta q}{\delta p} = 1.2$ instead of 3).

The insets of Fig. 2 show vertical slices through the reconstructed x-ray attenuation fields for three key points in the test (prior to shearing, peak axial stress, end of test), although it is important to note that 28 such images exist. A further inset shows that a clear granular texture is visible within the specimens, even though individual grains are difficult to make out. The three vertical slices in Fig. 2 reveal a specimen which is initially relatively homogeneous; at the peak a loosening of the middle part of the specimen starts to become visible, and by the end of the test a significantly loosened zone in the middle is clear, and two dense friction-cones top and bottom (due to lack of lubrication) are also visible.

[1] Using a gaussian pyramid approach – see [1].