Development and application of time-lapse ultrasonic tomography

Tudisco, Erika; Hall, Stephen; Roux, Philippe; Viggiani, Giulia M.B; Viggiani, Gioacchino

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Development and application of time-lapse ultrasonic tomography for laboratory characterisation of localised deformation in hard soils/soft rocks

E. Tudisco[1], S.A. Hall[1,2], P. Roux[3], G.M.B. Viggiani[4] and G. Viggiani[5]

[1] *Division of Solid Mechanics, Lund University, Lund, Sweden*
[2] *European Spallation Source AB, Lund Sweden*
[3] *ISTerre, Grenoble, France*
[4] *Università degli Studi di Roma "Tor Vergata", Italy*
[5] *Grenoble-INP/UJF-Grenoble 1/CNRS UMR 5521, Laboratoire 3SR, 38041, Grenoble, France*

1. INTRODUCTION

As with many materials, strain localisation processes are key to the deformation behaviour of rocks and soils, because, for example, localised deformation is often precursor to material failure. Therefore the understanding of the processes leading to localised deformation, and thus to failure, in geomaterials is critical to the success of many geotechnical engineering projects.
This work focuses on the analysis of localised deformation in hard soils, soft rocks and, more generally, cemented granular materials. For such materials localized deformation, in the form of localized strain, *i.e.*, shear and compaction bands, is often associated with damage, *i.e.*, inter and intra-granular fractures and cracks, de–bonding and breakage of particles (grain crushing). Furthermore, macrofractures are commonly surrounded by meso and micro cracks and a process zone of microfracturing precedes their propagation. To study localised phenomena such as strain and damage localisation, some kind of non-destructive, full–field measurement has to be used. Well-known techniques in geomechanics include x-ray tomography, to study material structure at the micro scale, and Digital Image Correlation (DIC) of 2D or 3D (volume) images, to measure the evolution of strain fields in a deforming specimen. DIC has proven to be a very powerful tool in the study of heterogeneous phenomena, but provides only data on kinematics and strain and not on associated property changes (*e.g.*, elastic properties). In this work another tool, ultrasonic tomography, is suggested as a full-field measurement of the elastic property variations in test specimens through mapping of ultrasonic wave propagation velocities. Ultrasonic tomography, as complementary technique to DIC and other full-field measurements, can thus provide new insight into the deformation processes.

2. EXPERIMENTAL WORK

In rock and soil mechanics, acoustic and ultrasonic methods have long been used to measure the elastic properties of test materials, including during mechanical testing. However, such measurements have generally been limited to only a few measurement paths (usually just one) for a whole sample, thus restricting the study of heterogeneity. Ultrasonic tomography can overcome this limitation since is based on multiple measurements across a test sample, which are mathematically reconstructed to provide the potential to map heterogeneous elastic properties inside the sample. The main contributions of this work are the development of ultrasonic tomography analysis for laboratory geomechanics (both in terms of the experimental method and subsequent data analysis) and its application to analyse material deformation and, in particular, material evolution during loading (time-lapse ultrasonic tomography). A key contribution is the implementation of the Double Beam Forming technique, for the particular case of laboratory test on geomaterials, to provide improved quality data and thus extraction of more precise information.
The developed ultrasonic tomography approach has been applied to investigate geomaterial behaviour in laboratory tests. In this context, experimental campaigns have been carried out on different materials, where the ultrasonic tomography has been complemented by comparisons with displacement and strain fields from 2D and 3D DIC plus structural analysis by x-ray tomography.
To determine the spatial and temporal resolution of the timelapse ultrasonic tomography in a simplified situation, tests have been carried out on rock samples containing a layer of cemented soil between two blocks of rock. This particular geometry was chosen with the objective to know *a priori* the region of the sample where most of the damage will occur because of the stiffness contrast between the layer and the rock. The comparison between a model-based ultrasonic tomography and an x-ray tomography of the intact sample (Figure 1 (a) and (b)) proved that the 5 mm layer of cemented soil can be well resolved and thus the resolution of the ultrasonic inversion respects the expectation. The timelapse ultrasonic tomography analysis (Figure 1 (c-e)) successfully revealed that the inclined layer is stiffer than the surrounding rock and that the latter experiences damage during the loading. DIC shows, to the contrary, a concentration of strain inside the layer while the two blocks of rock show only minor deformation (Figure 2). Moreover, the

volumetric strain, measured by DIC, displays compaction at the boundaries between the cemented soil and the rock with

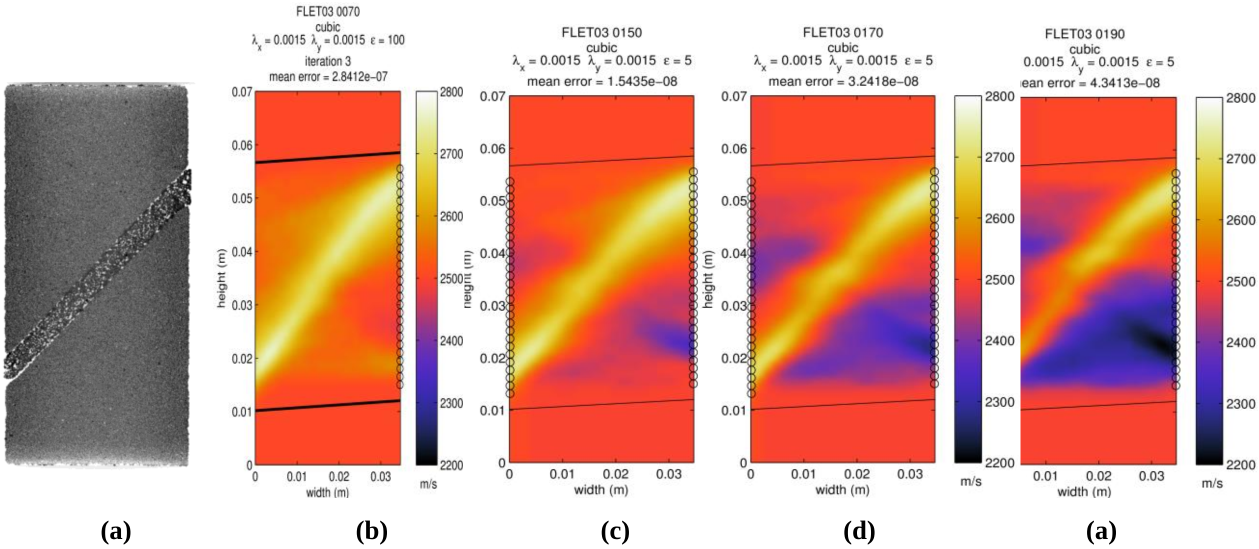

Figure 1 Vertical slice of the X-ray tomography before the test (a); ultrasonic tomography at the beginning of the test (b) and for subsequent step of loading (c-e)

dilation inside the layer. The ultrasonic tomography is not able to resolve such structure, as its spatial resolution is below the involved dimensions. The ultrasonic tomography does, however, provide information about the different mechanisms occurring inside the layer and in the rock. The fact that the deformation induces only a small effect on the velocities in the layer suggests that these deformations are mainly elastic and do not damage the material. On the contrary the surrounding rock is damaged despite only experiencing small strains. A possible explanation of this behaviour is the rupture of the natural cement that causes debonding of the grains whereas the cement between the

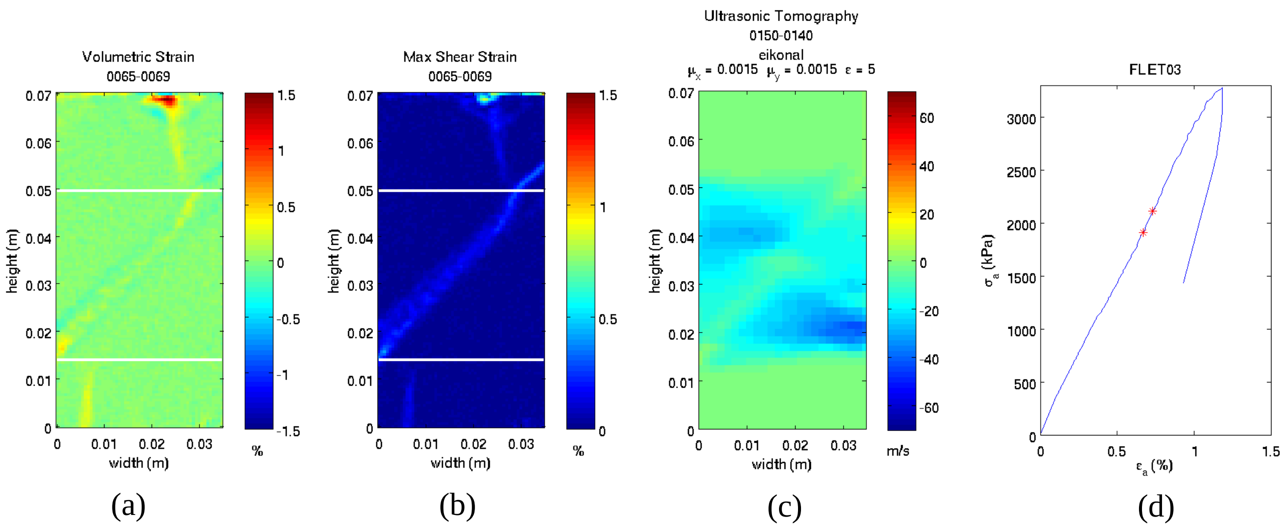

Figure 2 Comparison between DIC in terms of volumetric strain, where positive values represent compaction and negative values represent dilation (a), shear strain (b) and ultrasonic tomography (c) for one step of loading.

grains in the layer is stronger and does not experience any damage.

3. CONCLUSION

The different full-field techniques employed in this work have been found to provide different and complementary information. The x-ray tomography, which gives a 3D map of the density, is helpful in the study of the internal structure of the sample; the DIC, applied to the X-ray tomography images (volumes) pre- and post-mortem or to the photos taken during the test, provides important information on the kinematics while the velocity fields recovered by the ultrasonic tomography are linked to the elastic properties of the material and can, therefore, be used to investigate damage processes. Furthermore, it is shown that better understanding of the mechanical behaviour of geomaterials can be gained