In-situ study of deformation mechanisms of soft clay using X-ray Computed Tomography and Digital Volumetric Correlation

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Summary: Construction projects increasingly come up against the challenge of soft clay deposits. Nevertheless, experimental data on deformation mechanisms in natural clays is scarce (until recently limited to 2D observations). Here initial results from in-situ mechanical testing combined with tomographic imaging and subsequent Digital Volume Correlation provide insight on the 3D structural changes during mechanical compression.

1. INTRODUCTION

Soft sensitive clays, fine grained material where the pores are filled with water, are characterised by their sensitivity for shear strain perturbation (in quick clays leading to a phase transition through liquefaction) and big volumetric changes under the influence of mechanical loading. An additional yet important aspect of their mechanical behaviour is rate dependence, due to the role of water flow through the pore system. However,the presence of water through all structural scales, from sub-particle to pore space, makes it a challenging task to distinguish the specific effect of water on each scale. The bulk soil, comprising the clay minerals, can be imaged using X-ray imaging as the main requirement is a sufficient density contrast field. The material studied in this test series are natural samples of sensitive silty clay (depth 6 m, water content 73%) from the Utby test site in Gothenburg, Sweden [1]. The fraction of silt particles works effectively as the necessary speckle pattern for Digital Volume Correlation (DVC). Furthermore, the phase transition that soil experiences at high strain levels can be observed at the continuum structural level with the spatial resolution X-ray Computed Tomography (XCT) offers. Applications of X-ray tomography have already been established for coarse geomaterials [2] and rock. To the best of the authors knowledge no previous in-situ XCT have been conducted for natural soft clays.

2. EXPERIMENTAL METHOD

The experiment was performed at the 4D Imaging Lab of the Division of Solid Mechanics in the Faculty of Engineering at Lund University. A high resolution laboratory 3D X-ray microscope (tomograph) Zeiss Xradia XRM520 was used to obtain 3D images of the sample at different stress levels. Signal attenuation, drainage time and sampling procedure were factors which defined the final sample size. A bespoke set up was created to be compatible to the tomograph's hutch environment (Figure 1a). The selected experiment was a laterally confined stepwise one dimensional compression test. The loading cell was formed by a capillary tube with inner diameter of 4.05 mm and a wall thickness of 0.05 mm. Fluid pressure was applied through a high precision Syringe Pump from Cetoni GmbH on a one side drained sample. The acquisition time at the end of each loading step was approximately 40 minutes for 1601 radiographic projections. Radiographic projections were also used to track top sample-displacements during the loading steps.

Soft clays have a time dependent mechanical response, *i.e* pore pressure dissipation and creep prevent instant deformation in the clay sample. This creates additional challenges to obtain accurate reconstructions from the

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raw radiographs. Therefore, during the acquisition the sample should ideally be kept stable without additional deformations. To achieve this, a scheme of drained conditions during loading and undrained conditions (preventing water outflow from the sample) during imaging was adopted. The acquisition settings were designed such that the necessary acquisition time was sufficiently short so that pore pressure dissipation would not affect reconstruction quality. Images were acquired for axial pressure levels of 20, 40, 60 and 80 kPa. Each loading increment was gradually applied with a rate of 1.16 kPa/min. Gradual loading causes smoother excess pore pressure reaction. The selection of stress increments was made with the consideration of detecting structural changes before and after the material's yield point. The achieved voxel width was $10\mu m$.

3. RESULTS

TomoWarp2 [3] was used for Digital Volume Correlation, which is based on the earlier TomoWarp code [2]. The 3D displacement fields were used for the calculation of volumetric and maximum shear strain fields. In Figure 1b the volumetric and the maximum shear strain fields of the vertical central slice are presented for four different stress levels (20 – 80 kPa). The contribution of the silt grains in initiating shear localisation is investigated. Differential local stiffness in the direction of loading, as well as longer flow paths around the big grains (silt) could trigger shear distortions which would not be expected for a one dimensional confined test. In this way, around large grains localisation patterns are formed and evolve through loading steps. An interesting observation is that shear localisation evolves as a discontinuity after the 40 kPa loading step. In order to interpret the final fabric collapse in a fully saturated soil sample, shear localisation could be linked to excess pore pressure evolution.

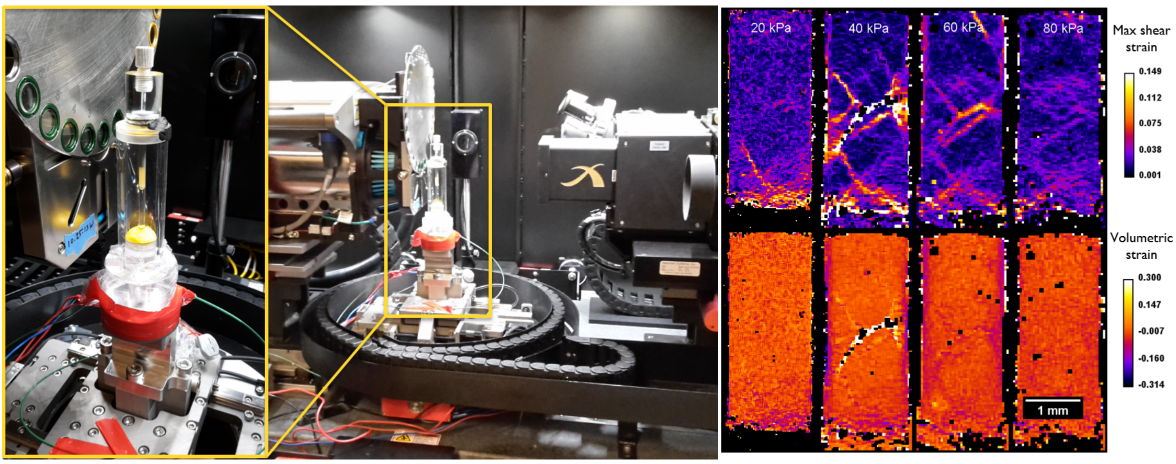
In conclusion, the results of this experimental approach provide insight into progressive structural changes and image the evolution of soft soil deformation mechanisms under various hydro-mechanical loading conditions. It is demonstrated that X-ray tomography is a valuable tool in strengthening and improving the existing constitutive models for different types of soft soils, which currently are only based on boundary measurements.

References

[1] M. Karlsson, A. Emdal & J. Dijkstra. Consequences of sample disturbance when predicting long-term settlements in soft clay. *Canadian Geotechnical Journal*, 53(12), 1965–1977, 2016

[2] S. Hall, N. Lenoir, G. Viggiani, J. Desrues & P. Bésuelle. Strain localisation in sand under triaxial loading: characterisation by x-ray micro tomography and 3d digital image correlation, *Proceedings of the 1st Int. On Computational Geomechanics (ComGeo 1) Symp.*, 239–247, 2009.

[3] E. Tudisco, S. Hall, E. Charalampidou, N. Kardjilov, A. Hilger & H. Sone. Full-field measurements of strain localisation in sandstone by neutron tomography and 3D-volumetric digital image correlation. *Physics Procedia*, 69, 509–515, 2015.



(a) (b)

Figure 1: (a) Test configuration mounted in Zeiss Xradia XRM520 hutch and the products of Digital Volume Correlation (b): maximum shear and volumetric strain field for different loading steps (20–80 kPa).