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Image based simulation of one-dimensional compression tests on carbonate sand

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Abstract High factors of safety and conservative methods are commonly used on foundation design on shelly carbonate soils. A better understanding of the behavior of this material is, thus, critical for more sustainable approaches for the design of a number of offshore structures and submarine pipelines. In particular, understanding the physical phenomena taking place at the microscale has the potential to spur the development of robust computational methods. In this study, a series of one-dimensional compression tests were performed inside an X-ray scanner to obtain 3D images of the evolving internal structure of a shelly carbonate sand. A preliminary inspection of the images through five loading increments has shown that the grains rearrange under loading and in some cases cracks develop at the contacts. In order to replicate of the experiments in the numerical domain, the 3D image of the soil prior to loading was imported into a micro Finite Element (μFE) framework. This image-based modelling tool enables measurements of the contact force and stress map inside the grains while making use of the real microstructure of the soil. The potential of the μFE model to contribute insights into yield initiation within the grain is demonstrated here. This is of particular interest to better understand the breakage of shelly grains underpinning their highly compressive behavior

Introduction

Carbonate soils cover over 40% of the world's seabed, where offshore structures, pipelines, artificial islands and other marine structures are founded. For the most part, carbonate soils are of biogenic origin comprising skeleton bodies and shells of small organisms, the shelly carbonate sands [1,2,3]. These soils are a complex and poorly understood material, in particular the high compressibility of the material is not well predicted using current modelling techniques. As a consequence, shelly sands have been placed into a niche classification of "problematic soils" in most design guides [4,5]. While failures are now relatively rare, conservative methods and high factors of safety are commonly used. Understanding the behavior of shelly carbonate sand is critical for the design of foundations for offshore structures. In particular, understanding the physical phenomena taking place at the

microscale has the potential to spur the development of robust computational methods.

This study makes use of a recent developed micro Finite Element (μFE) model [6] The model takes as input the geometrical grain scale data obtained from micro tomography (μCT) to model the individual grains and their interactions in the framework of combined discrete-finite-element method. The soil fabric is therefore virtualized by meshing the constituent grains and allowing them to interact and deform according to appropriate constitutive model and frictional contact conditions. The contact response results from the deformation of contacting bodies, which accounts for the specificities of each contact surface. This simulation technique presents exciting avenues to model complex morphologies numerically

Experiments

One dimensional compression tests were performed under dry conditions inside an x-ray scanner. The system used was a Nikon XTH 225 ST located at the Research Centre at Harwell (RCaH), Oxfordshire (UK). The soil investigated was a shelly carbonate sand from the Persian Gulf with a median grain size of 2 mm. The experimental set-up consisted of a load cell, a vertical piston a micrometer and a small oedometer as shown in Fig.1. The set-up was designed for this particular scanner and was mounted on the rotating table of the scanner. The size of the specimen was 13.5 mm in diameter with an aspect ratio (height/diameter) between 1.0 and 1.1. The force was exerted by a micrometer with 450N axial loading capacity [7]. The sample container was made of Perspex with 2mm thickness which has less than 3 μm deflection under the maximum applied force. The lateral friction has been minimized by considering a 1 mm gap between the container and the x-ray window. The exerted force was monitored by a low profile 'pancake type' load cell with a 500 N capacity.

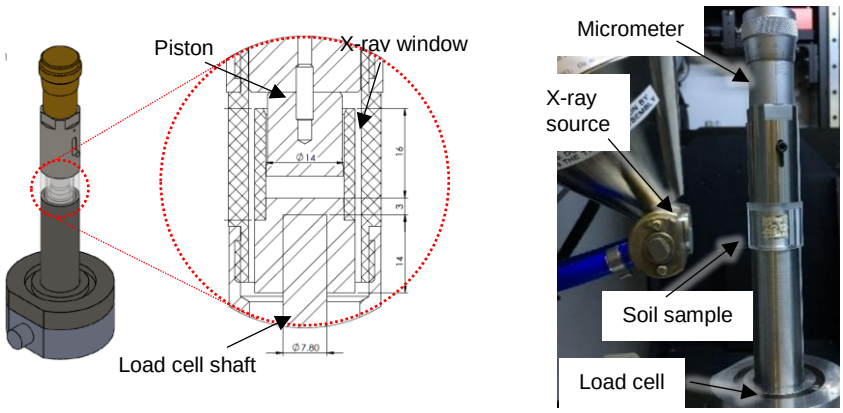


Fig. 1. Schematic of the apparatus to perform one dimensional compression tests inside a μCT scanner

The x-ray tomography data was acquired at an accelerating voltage of 90 keV. A total of 3142 projections were collected per scan, with an exposure of 500 ms per projection. The 3D images acquired had a resolution of 9.5 μm (length of voxel edge). The tests were performed at five loading stages up to a maximum 10% axial strain. In-house imaging processing codes were employed to segment the images in order to identify the individual grains. This includes firstly to binarise the images using Otsu's thresholding and subsequently apply an iterative watershed algorithm to overcome the challenges posed by the large diversity and complexity of the shapes associated with the bioclastic nature of shelly sands. The codes are fully described in [8].

Numerical Meshing

An important requirement of the meshing process is to obtain a good finite-element representation of irregular shaped grains which in shelly grains is particularly relevant. The surface mesh extraction technique used here was a refinement of the constrained Delaunay triangulation implemented using a developed Matlab (Mathworks, 2015) script to generate the image-based mesh. [6]. Triangular iso-surfaces were extracted from the 3D image with pre-set values for density, which controls the size and number of triangles representing the surface of each grain.

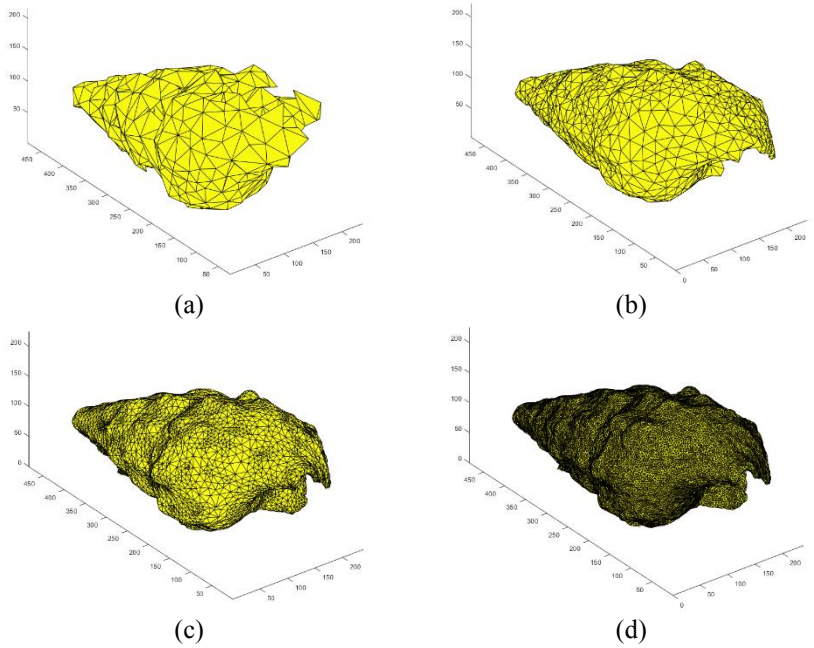
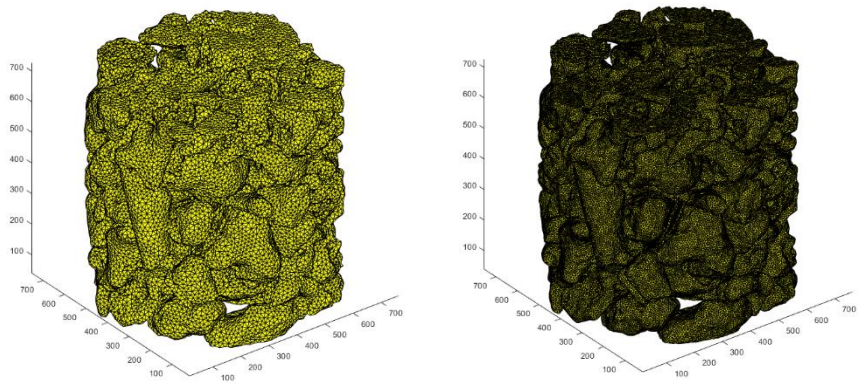


Fig. 2. A single shelly grain meshed with different mesh sizes (a) coarse mesh, (b) intermediate size mesh, (c) fine mesh and (d) super fine mesh

Fig. 2 shows a single grain meshed with different mesh sizes. The mesh size and quality is controlled by four parameters, which includes the minimum angle of the triangles, the maximum volume of an element, the maximum surface element size and the maximum distance between the center of surface bounding circle and the center of the element bounding sphere. Fig. 2a shows a coarse mesh with parameter values of 40°, 30, 30 and 10, respectively. It can be observed that this mesh size cannot capture well the irregular features of the shelly grain. The mesh was progressively refined in the three examples presented in Figs. 2b, 2c and 2d, a minimum angle of 40° was used in all cases due to efficiency issues. The four parameters used in these cases were: 40°, 20, 30 and 5 (Fig. 2b), 40°, 30, 30 and 1 (Fig. 2c) and 40°, 3, 3 and 1 (Fig. 2d). It was found that the mesh presented in Fig. 2c (termed here fine mesh) is able to capture well grain shape while avoiding the more expensive computation cost of using a highly refined mesh in Fig. 2d (super fine mesh). Thus, the fine mesh was chosen for the simulation.
Figs. 3a and 3b show the virtualized assembly with coarse and fine mesh, respectively. The main drawback of using a coarse mesh is that contact interactions cannot be accurately simulated. The fine mesh used here corresponds to an element mesh size that is 5 times the voxel size of the images.



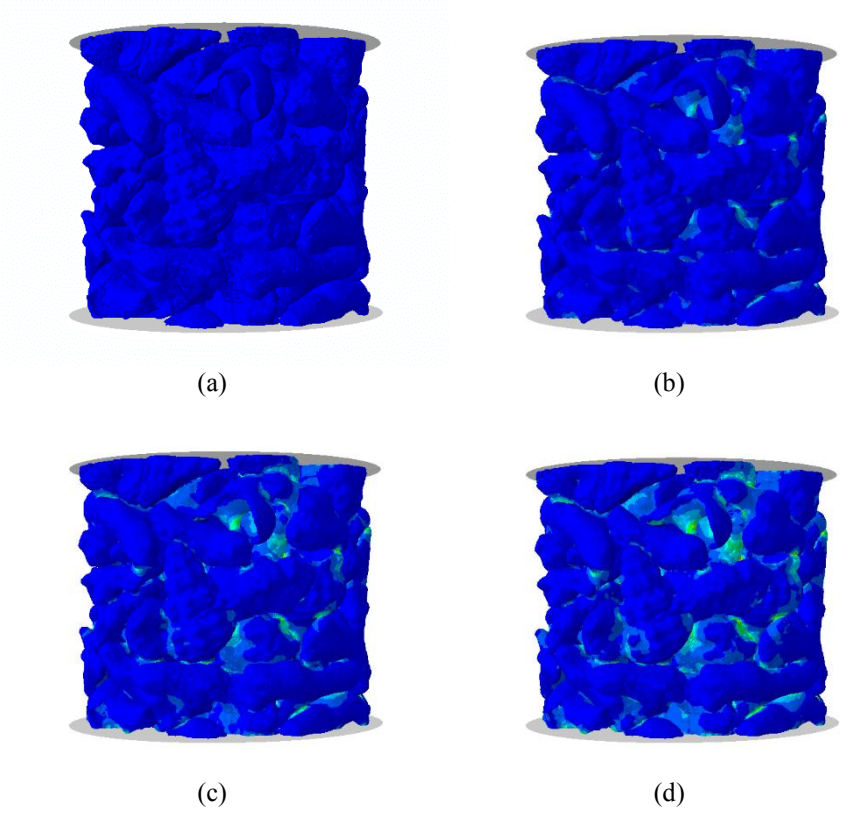
(a) (b)

Fig. 3. Numerical mesh generated for the full assembly using a (a) coarse mesh, (b) fine mesh.

Simulations

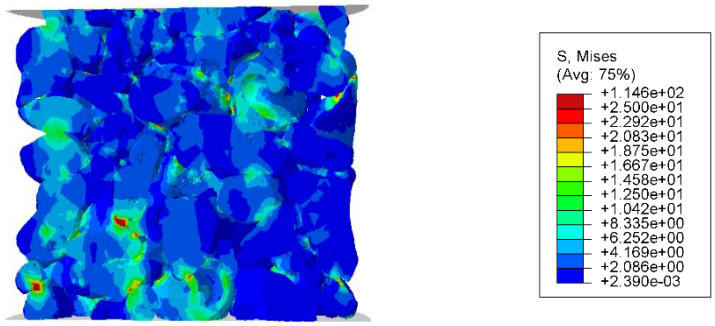
The numerical mesh was imported into the μFE model that runs in the Abaqus finite-element package (Dassault Systèmes, 2014). The sample was confined laterally using a rigid cylinder and the displacement was applied at the top of the sample.
Fig. 4 shows the stress distribution in the full assembly at four stages of loading, using the von Mises criterion. The stages include: stage 0 at no applied loading (ε_a = 0%), stage 1 for ε_a = 5%, stage 2 for ε_a = 7.5% and stage 3 for ε_a = 10%. It can

be seen that at the initial stage, since the sample is not loaded yet, all grains have a stress field constant and equal to zero (Fig. 4a). At stage 1 the stress concentration starts at the grain contacts and propagates through the grains before being transmitted to other neighboring grains, again by way of their contacts (Fig. 4b). At stages 2 and 3 (Fig. 4c and 4d), the assembly becomes more heavily loaded and this is shown by the larger internal stress values exhibited at the grains. The stress at the contacts can be better visualized in the vertical cut through the sample presented in Fig. 4e. These data enable the identification of the stress-transmitting particles and the investigation of the micro-mechanisms that lead to the breakage initiation within the grain.



(a) (b)

(c) (d)



(e)

Fig. 4. Stress distribution in the full sample at (a) 0% strain, (b) 5% strain, (c) 7.5% strain, (d) 10% strain and (e) vertical cut through the sample at 10% strain

Conclusions

This paper presents a preliminary investigation into the numerical simulation of shelly carbonate sands that takes into account the detailed representation of grain shape. We have demonstrated here the capability of the model to measure the stress concentration at the contacts and its propagation throughout the grain skeleton for materials with complex grain morphology.

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