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Three-dimensional quantification of the morphology and intragranular void ratio of a shelly carbonate sand

Joana FONSECA^{a,1} Constantino Carlos REYES-ALDASORO^a, Laure WILS^b

^a*City University London, London, United Kingdom*

^b*Ghent University, Ghent, Belgium*

Abstract. Shelly carbonate sands represent an extreme soil type in terms of their mechanical behavior which derives from the bioclastic nature of the constituent grains. In their uncemented form, these deposits exhibit very high compressibility, which has posed a number of geotechnical engineering problems; in most cases related to the reduction in the bearing capacities of both shallow and deep foundations. Remarkable features of these carbonate sands include the complex shape and the structural weakness of the grains and the high inter and intra granular porosity. Previous studies, have quoted the interlocking of the angular shelly particles to be at the origin of their high friction angles and high initial void ratio, however, up until now, no scientific micro-scale examination has been carried out. This paper presents a non-invasive image based investigation into the grain morphology of a carbonate sand from the Persian Gulf. This sand has a median grain size of 570 μm and a high CaCO_3 content in the form of aragonite and calcite. Three-dimensional images from x-ray computed tomography (3DXRCT) with a size of 6 μm were used. The presence of various skeletal bodies such as shells of small organisms with distinct densities and composition poses real challenges for an accurate segmentation. Image processing algorithms were developed in order to identify the individual sand grains and quantify their properties. Earlier work on silica sands has highlighted the importance of 3D non-invasive techniques in providing an accurate distribution of the grain sizes when compared to more traditional techniques such as sieving analysis and 2D microscopy. The methodology here proposed allows an accurate quantification of grain shape and size and the assessment of grain damage following mechanical deformation. This study, contributes towards improving our understanding of the engineering properties of carbonate sands and thus, predicting their response under loading.

Keywords. 3D imaging, carbonate sand, microstructure, shape, particle breakage

1. Introduction

Shelly carbonate sands are widely spread throughout the ocean's seabed and have represented a major challenge for geotechnical engineering since the late 60s. In particular, major interest on this material has developed from problems encountered during offshore platform installation. Numerous cases have been reported of bearing capacities in shelly carbonate sands being much less than predicted using conventional

¹ Corresponding Author: City University London, London EC1V 0HB, UK. E-mail: Joana.Fonseca.1@city.ac.uk

theories essentially based on Quartz sand behavior [1, 2]. There is a general recognition that carbonate sands warrant special consideration and their behavior remains an 'engineering enigma' [3].

Shelly carbonate sands are bioclastic origin deposits comprising essentially the remains of marine organisms, such as shell and skeletal materials and therefore, possess very distinct characteristics and mechanical behavior when compared to more common terrigenous soils. Outstanding features of the shelly grains include the predominance of plate-like and angular shapes, structurally weak and thin-walled bodies and the presence of intragranular voids. Shelly carbonate sands tend to form loose soil packing, void ratio greater than 1 are commonly measured and this is believed to be a result of the interlocking of the angular grains. Moreover, the high compressibility of this sand is likely to derive from the collapsible nature of the soil fabric also exacerbated by the relative softness of the grains (calcite has half the hardness of quartz in the Mohs scale).

The loose internal structure developed in these sands results in few inter particle contact points, which according to previous studies [4] leads to high inter granular stresses at relatively low applied stress and hence, lower mean stress at which crushing occurs. Semple suggested that this behavior approaches that of 'quick' sands and clays [5]. The contribution of the structure of the individual grains on the physico-mechanical characteristics of the soil has also been highlighted by Levacher in [6]. In particular, the author has pointed out i) an intragranular porosity as high as 20%, ii) a high compressibility leading to a collapsible fabric and iii) the change in granulometry due to crushing which affects the mechanical behavior of the soil.

Despite the recognition of the effect of the micro scale properties on the engineering properties of these sands, previous studies have been essentially qualitative and based on two dimensional (2D) image analysis of thin sections. With the increase of offshore activity in temperate and tropical regions of the world where shelly carbonate sands proliferate, a more scientific explanation for the mechanical behavior accounting for their microstructure is needed. This paper presents a methodology developed to quantitatively describe the overall grain morphology and intragranular porosity of the grains of a shelly carbonate sand using three dimensional tomographic images.

2. Grain shape and the mechanical response

The influence of grain shape on the engineering properties of sand is widely reported in the literature. Previous studies, mainly on quartz sands, have shown that the maximum void ratio and minimum void ratio are closely related to the shape of the soil particles. The range of void ratios ($e_{\max} - e_{\min}$) tends to decrease with increasing sphericity and roundness, e.g. [7]. When bulky particles are mixed with platy ones, the effect is a significant increase in the void ratio accompanied by an increase in compressibility and reduced shear strength, e.g. [8]. Therefore, given the diversity in biogenic detritus forming shelly carbonate sands, it is suggested that as important as particle size distribution, particle shape distribution constitutes a fundamental characteristic of this soil. A key characteristic of shelly carbonate sands is the friable nature of the grains that tend to break and get damaged more easily when compared to silica rich sands. Mesri in [9] has defined three levels of particle damage including i) abrasion or polishing of particle surface asperities, ii) chipping, breaking or crushing of particle

surface protrusions and sharp particle corners and iii) fracturing or splitting of particles. The relative softness of the carbonate grains together with the angular nature of the grains makes polishing of surface asperities and crushing of sharp corners particularly significant. Experimental evaluation of grain fracture is generally obtained in post-test analyses by investigating the change in grain size distribution using sieve analysis. However, as highlighted by [10], sieving analysis presents major limitations when compared to non-invasive analysis such as 3D-XRCT. While these findings were related to silica sands, it is suggested here that for shelly carbonate, sieving limitations will be aggravated. In fact, the predominance of plate-shaped grains with $c \ll a, b$ (for a , b and c defining the length of the major, intermediate and minor axes of the grain, respectively) and needle-shaped grains with $a \gg b, c$; sieve analysis cannot capture grain splitting since a given grain with an initial major axis length of a_0 and after splitting $a_f = a_0/2$ with no change of the minor axis length, i.e. $c_0 = c_f$, is likely to fall through the same sieve aperture [11]. Moreover, subtle grain damage can only be captured by a detailed 3D description of the grain shape pre and post testing.

3. Soil description and image acquisition

The primary material used for this study is an uncemented shelly carbonate sand from the Persian Gulf, termed S2 sand with a high CaCO_3 content in the form of aragonite and calcite. This sand is a well graded material with a median grain size of $570\mu\text{m}$ and the coefficient of uniformity of approximately 3.67. Additional physical properties of this sand include an $e_{\min} = 0.832$ and $e_{\max} = 1.382$. Recent oedometer and triaxial shearing tests on S2 sand have shown that the stress-strain and strength characteristics of this sand are significantly affected by the presence of water. During 1D compression the wet sand tends to compress more than the dry material, as shown in Figure 1. Moreover, during shearing, saturated samples tend to exhibit less dilation and a lower shear strength is reached when compared to the dry samples. As presented in [12], granulometry analysis obtained from sieving has indicated a clear shift in the PSD following oedometer compression, but resulted of limited use to clearly identify changes in grading between wet and dry samples. The methodology proposed in this paper will provide a more scientific approach to assess the damage mechanism, including breakage, caused by the effect of water on shelly carbonate sands.

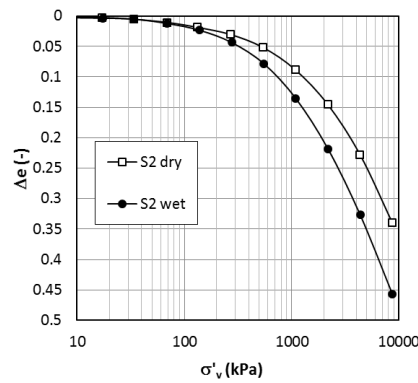


Figure 1. Void ratio changes for wet and dry samples of S2 sand.

3.1. Image acquisition

Three dimensional images of the internal structure of S2 sand were obtained using high resolution, x-ray computed tomography (XRCT). X-ray micro-CT is a non-destructive, 3D high resolution imaging method that allows for the internal structure of objects to be investigated (Figure 2). The sand was scanned with a *nanotom m* (phoenix|x-ray, GE) and the images obtained have a spatial resolution of 6 μm . Micro-CT scans generate 3D images that map the variation of x-ray attenuation within objects, represented by the intensity value (I) of each voxel in the image. This attenuation, resulting from the x-ray interaction with matter, is a function of the composition and density of the object and the beam energy. Dense materials (i.e., materials with high atomic numbers) attenuate more the x-ray beam energy than less dense materials and this difference in attenuation provides the contrast that forms the image. The capacity of x-rays to penetrate an object is, therefore, highly material dependent. The presence of various skeletal bodies such as shells of small organisms with distinct densities and composition leads to images with a wide range of I values, which poses real challenges for an accurate segmentation, as discussed in the following Section.

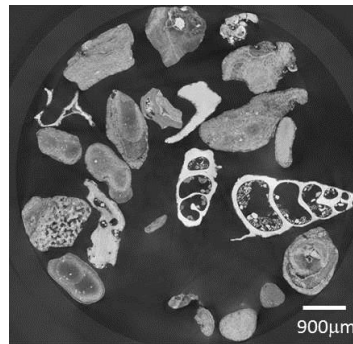


Figure 2. Slice through a 3D tomographic image of the shelly carbonate sand investigated in this study.

4. Methodology

4.1. Image processing

Tomographic images are rich in information. A key step required prior to extract measurements from an image is the segmentation process where the voxels in the image are classified into features of interest, in this case, the individual grains and the void space. The image segmentation in this study was performed using an in-house built algorithm based on Matlab® (The Mathworks). The algorithm exploited the fact that the grains exhibit a significant difference in the intensity values compared with the background or void space. This allowed using an intensity-based algorithm to separate the two phases, i.e. solid grains and void space. However, the significant difference of intensity levels exhibited by the grains, as shown in Figures 3a, 3b, 3c and discussed previously, introduces major challenges when it comes to identify the individual grains within the solid phase. A simple binarisation with one threshold value followed by a

watershed segmentation technique, to separate grains touching [13, 14] would imply that in some cases, dark objects could be losing some of their detail whilst bright objects could be merged. Therefore, a multilevel intensity segmentation was implemented. Multilevel intensity segmentation has proved to be successful at segmenting complex shapes with varied intensity levels such as fluorescently-labelled immune cells observed in biological experiments [15]. This intensity-based approach was followed by the application of morphological operators (closing and opening) with small structural element to enhance the result. Once the individual particles were segmented, the data were stored as three-dimensional arrays, where each voxel in the three-dimensional image was mapped to an array cell. Each particle-phase voxel was assigned an integer identification number (*id*) to associate it with a specific grain.

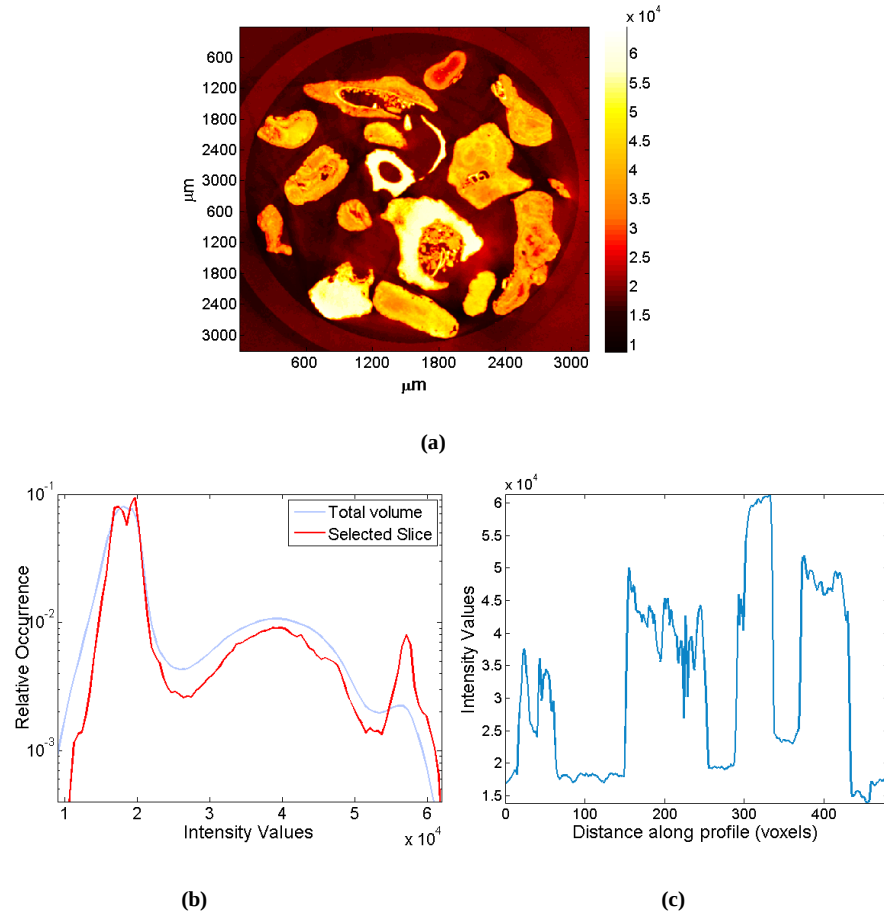


Figure 3. (a) Slice through a 3D image with the different intensity levels (i.e. brightness) of the grains highlighted. (b) Histograms describing the total 3D tomographic data set (blue dashed line) and the histogram of the slice shown in (a). Notice how some peaks that correspond to different regions are apparent in the selected slice as compared with the total data set. (c) One profile line in which particles of three distinctive intensity levels can be distinguished from the background.

4.2. Morphology and intra granular void ratio characterization

Having the 3D microstructure stored in MATLAB matrices where each grain is defined by a cloud of points or elements with coordinates (x, y, z, I) , it is possible to obtain various metrics related to the morphology of the grains. The grain size is one example, as shown in Figure 4, the grain size can be described using the global volume of the grain, i.e. by counting the total number of voxels with a specific id . In addition, the size can be described by the major, intermediate and minor dimensions of the particle. This involves using Principal Component Analysis to obtain the principal axis orientations and applying an orthogonal rotation to the voxel coordinates so that its principal axes of inertia are parallel to the Cartesian axes, more details can be found in [10].

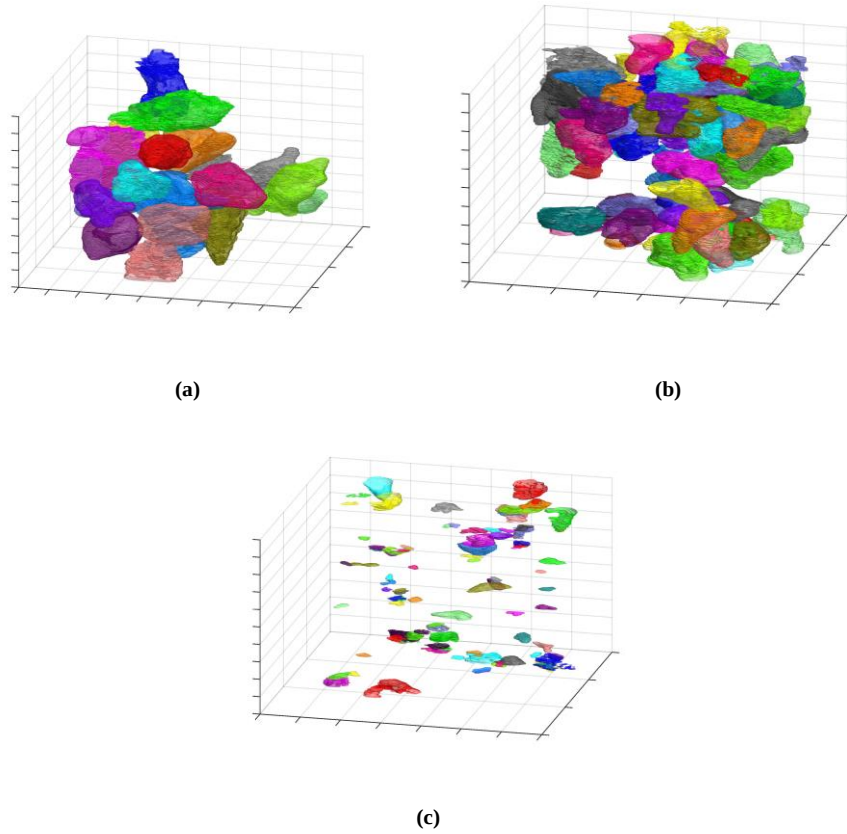


Figure 4. Segmented grains of S2 sand, grain's id identified by color and grouped by size: (a) large grains, (b) medium grains and (c) small grains.

The overall shape characterization for bulky-shaped grains has been done primarily in terms of sphericity, convexity, and the aspect ratios elongation and flatness, e.g. [10]. Characterizing the shape of biogenic sediments is of utmost importance as it allows obtaining the distribution of these shapes. In particular, the predominance of plate-like or bulky-like shapes using the flatness index defined as the ratio between the minimum and the maximum principal axes lengths. Convexity and sphericity indices are more

relevant for bulky-shaped grains. These indices are however of limited use to describe the intricate internal structures commonly found in some shells and often associated to intra granular porosity. The quantification of the complex morphologies can help evaluating the susceptibility of the grain to crush. To this end, the identification of structural weaknesses such as thin walls, as illustrated in Figure 6, and measurement of their thicknesses and orientation in relation to major principal stress, can provide valuable information. Also important is the measurement of the intragranular void ratio, which can be obtained by segmenting the void space contained in the overall volume as depicted in Figures 5b and 6b. This investigation has shown that intra granular voids can be internally as well as externally connected, the latter is commonly found for the grain type shown in Figure 5. For bulky-type grains, most of the internal voids are likely to be unconnected as illustrated in Figure 6. Aside from enhancing the potential of grain to crush, the intricate internal topology of the grains and their connected/unconnected internal voids is also responsible for difficulties in achieving a desired B value during sample saturation, as reported by Coop in [16].

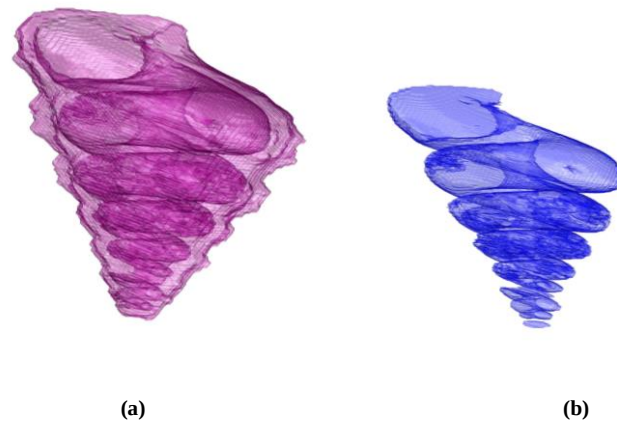


Figure 5. (a) Individual grain showing intra granular voids and thin walls. (b) Segmented interconnected intra granular voids.

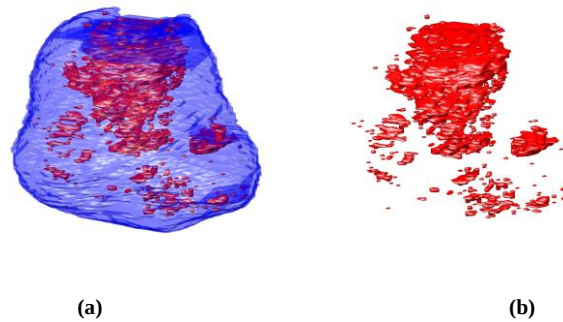


Figure 6. (a) Intra granular voids on a bulky-shaped grain. (b) Segmented intra granular voids.

5. Conclusions

This paper presents a significant first step towards the full characterization of the microstructure of uncemented shelly carbonate sands. While the distribution of particle sizes and the grain shapes are fundamental characteristics of any soil, traditional experimental techniques such as sieving or thin section analysis fails to provide adequate quantification in the case of the complex shapes with intricate internal structures. Of particular interest is the need to obtain the distribution of plate-like and bulky-type grains, for which a full 3D analysis is required. The methodology here proposed enables a more scientific quantification of the overall grain morphology and of the internal topology found in many shelly grains. Complex internal topologies are associated with the presence of intragranular voids and can be directly linked to the structural weakness of the grain and its susceptibility to crush. In addition, when applied prior and after loading, this grain scale approach can provide a more precise assessment of grain damage, including breakage, following mechanical deformation.

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