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Citation: Kong, D. & Fonseca, J. (2019). On the kinematics of shelly carbonate sand using X-ray micro tomography. *Engineering Geology*, 261, 105268. doi: 10.1016/j.enggeo.2019.105268

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Link to published version: <https://doi.org/10.1016/j.enggeo.2019.105268>

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1 On the kinematics of shelly carbonate sand using X-ray micro tomography

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6 ABSTRACT

7 Shelly carbonate sands are highly compressible soils due to the susceptibility of their loose and
8 intricate fabric to collapse under loading. An accurate assessment of the physical phenomena taking
9 place at the grain-scale is critical for a better understanding and modelling the mechanical behaviour
10 of this material. This paper presents a study on the grain kinematics of shelly carbonate sand through
11 analysis of in-situ 4D X-ray tomography images acquired during oedometer compression. Two sands
12 from the Persian Gulf, with coarse and fine grading, were investigated. An adaptive watershed
13 segmentation technique is used here to identify the grains in the image(s) prior to loading and a digital
14 volume correlation (DVC) technique is employed to obtain the displacement field of each grain under
15 loading. The displacement fields are used to reconstruct the grains in their new positions and compute
16 the associated translation and rotation. An extensive statistical analysis was carried out to demonstrate
17 the effect of grain morphology and local fabric (coordination number) on grain kinematics. The new
18 findings presented here shed light on the mechanisms of grain rearrangement leading to the
19 compressible fabric of shelly carbonate sands and, are also critical, to better understand other weak
20 grained sands and/or silica sands with an open fabric.

21 **KEYWORDS:** Calcareous soils; Fabric/structure of soils; Offshore engineering; Particle-scale
22 behaviour; Grain kinematics; Compressibility

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26 **1. Introduction**

27 Shelly carbonate sands are of biogenic origin and comprise grains of low hardness and angular shapes
28 forming an interlocked open fabric (e.g. Semple, 1988; Golightly, 1989; Coop, 1990; Wang et al.,
29 2011; Fonseca et al., 2015). The high compressibility has been identified as one of the most important
30 factors affecting their mechanical behaviour (e.g. Yasufuku et al., 1995; Randolph et al., 2004;
31 Dijkstra et al., 2013; Shahnazari et al., 2013). When subjected to loading, the change in soil fabric is
32 achieved through grain rearrangement by means of slippage and rotation. However, for shelly sands
33 with interlocked internal structure and structurally weak grains, this process could also require prior
34 grain damage such as chipping of asperities as a means of ‘unlocking mechanism’ (Mesri and
35 Vardhanabhuti, 2008). These unlocking mechanisms associated with the large voids, are believed to
36 lead to a temporary loss of contacts and consequently to an abrupt fabric collapse. A more scientific
37 understanding of these grain-scale phenomena is critical for an accurate modelling of shelly soils and,
38 indeed, other weak grained sands or silica sands with an open fabric (Bolton, 2000).

39 The compressibility of granular soils can be modelled using two methods: discrete element modelling
40 and analytical approaches. A desirable characteristic for both methods is that they make use of
41 parameters with a physical meaning derived from the microstructure of the soil and their evolution
42 under loading. Meidani et al. (2017) proposed an analytical compression model based on the
43 contribution of micro-scale mechanics to the change of active and inactive voids. Discrete element
44 modelling techniques enable the simulation of granular interactions, however, the challenges in
45 defining soil fabric and realistic particle shapes limit their application to shelly carbonate sands.
46 Recent work by the authors (Nadimi and Fonseca, 2018) used the true representation of the soil fabric
47 and grain shapes obtained from three-dimensional (3D) images, to model the individual grains and
48 their interactions in a framework of combined discrete-finite-element method. In this model, the
49 shelly grains are allowed to interact and deform according to an appropriate constitutive model, as
50 well as, frictional contact conditions and the contact response results from the deformation of
51 contacting bodies. The development and validation of this approach requires the kinematical
52 behaviour of the soil grains obtained from experiments.

53 Imaging techniques such as X-ray computed tomography (μ CT) has been pivotal to contribute
54 insights into the deformation of the internal structure of soil under loading (e.g. Matsushima et al.,
55 2010; Fonseca et al 2013a; Cil and Alshibli, 2014; Mahbub and Haque, 2016). A key step in analysing
56 μ CT images of granular materials at a scale where grains can be identified is to separate the individual
57 grains using segmentation techniques based on watershed algorithms (Beucher and Lantuejoul, 1979;
58 Meyer 1994). The main challenge of watershed segmentation is the treatment of ill-segmentation, i.e.
59 when an individual grain is mistakenly segmented into several sub-grains, or, several grains are
60 combined as one. Ill-segmentation potentially affects all types of sand and has been effectively
61 alleviated in recently proposed watershed algorithms (e.g. Wählby et al., 2004; Fonseca, 2011; Shi
62 and Yan, 2015). This problem, however, can be more severe for shelly carbonate grains due to the
63 presence of highly irregular grain shapes and intra-granular voids, as discussed by Kong and Fonseca
64 (2018).

65 Once the individual grains are identified in the initial stage, a statistical analysis of various grain
66 indices, such as, size, shape and orientation can be carried out for the whole sample (e.g. Fonseca et
67 al., 2013a, 2013b) to characterise the material. To investigate grain kinematics, in terms of rotation
68 and translation of the grain, it is required to obtain the position of the grain in the subsequent loading
69 stages, in other words, in its deformed position. Existent techniques, previously developed for silica
70 sands, include the ID tracking method (e.g., Smit, 2010; Andò et al., 2012) that consists of attributing
71 an identity to each grain, using an analogy to an ID card that in this case contains the characteristics of
72 the grain that make it unique in relation to other grains in the sample (e.g., shape, size, etc.). The
73 effectiveness of this method is, however, largely susceptible to watershed segmentation discrepancies
74 and the occurrence of grain damage. Most importantly, since the essence of the ID-tracking method is
75 to identify a given grain in the target (deformed) image that has properties close to the grain in the
76 reference (undeformed) image, the occurrence of ill-matching (*i.e.* when a grain cannot be tracked due
77 to small changes in its outline and it is instead wrongly matched with a different grain) will result in
78 an erroneous measurement of grain displacement.

79 In this paper, an alternative to the ID tracking method is used, in which, the displaced position of a
80 grain is “reconstructed” based on its prior-to-loading position and the displacements of each voxel
81 (3D pixel) forming the grain. The displacements are obtained by correlating the intensity patterns of
82 the reference and the target images, using the digital volume correlation (DVC) technique originally
83 proposed by Bay *et al.* (1999). This is a powerful tool as evidenced by its increasing use for
84 biomechanics, material science and experimental mechanics studies (e.g. Liu and Morgan, 2007; Bay,
85 2008; Hall et al., 2010; Leclerc et al., 2011; Hussein et al., 2012). This DVC-based new method is
86 particularly suitable for shelly carbonate grains that are susceptible to surface damage by chipping of
87 asperities and ill-segmentation that potentially make grain tracking impractical.

88 This paper first describes the experiments, including the set-up of the one-dimensional compression
89 tests and the acquisition of the X-ray micro tomography images. The image analysis part investigates
90 the evolution of the grain morphology and coordination number. Following that, the DVC-based
91 technique is used to quantify grain rotation and translation. Finally, a discussion on the effect of grain
92 morphology and fabric on grain kinematics under one-dimensional compression is presented.

93 **2. One-dimensional tests and image acquisition**

94 Two uncemented carbonate sands from the Persian Gulf, a coarse and a fine sand, denoted CS and FS
95 respectively hereafter, were investigated. The median grain sizes of CS and FS are approximately 1.9
96 mm and 0.4 mm, respectively. *In-situ* one-dimensional compression tests were carried out using a
97 mini-oedometer placed inside a Nikon XTH 225 ST scanner (Fig. 1), at the Research Complex at
98 Harwell (UK). Three-dimensional (3D) X-ray tomography images were acquired with a spatial
99 resolution of 9.57 μm at various stages throughout loading, as shown in Table 1. The accelerating
100 voltage of the scanner was set to be 90 kV for the CS and 110 kV for the FS. For the construction of
101 each 3D image, a total of 3142 projections were collected with an exposure of 500 ms per projection.
102 During an X-ray scanning, the objects with various material compositions and densities within the
103 sample attenuate different levels of X-ray beam energy, represented by distinct intensity values of the
104 voxels. The contrast of differing intensity levels allows for differentiation of the features within the

105 image. The sample container was made of Perspex with a diameter of 14 mm and a thickness of 2 mm,
106 and the transverse deflection of the container was limited to 0.003 mm under the ultimate loading.
107 Friction between the container and the x-ray window was avoided by allowing a 1 mm gap. The
108 vertical load was exerted by a micrometre and monitored by a load cell with a capacity of 500 N. The
109 sizes, in voxel, of the scanned images after cropping were $1536 \times 1536 \times 1600$ and $1536 \times 1536 \times$
110 1536 for CS and FS, respectively. Top view slices through the 3D images of both samples are shown
111 in Fig. 2a and 2b.

112 **3. Image analysis at the grain scale**

113 *3.1. Image segmentation and grain morphology*

114 The segmentation technique employed to identify the individual grains in the scanned images is
115 briefly explained here. Each image was binarised using the double intensity threshold method (Henry
116 et al., 2013) first, and then segmented using an adaptive segmentation technique proposed by Kong
117 and Fonseca (2018). Top view slices through the segmented images of CS and FS are presented in Fig.
118 2c and 2d. Prior to compression, approximately 700 grains were identified in CS and over 150,000 in
119 FS.

120 The quantification of grain morphology in terms of size and shape was done following the procedure
121 discussed in Kong and Fonseca (2018). The size of a grain is described by the length of the three
122 orthogonal axes termed the major (a), intermediate (b) and minor (c) axes, obtained from principal
123 component analysis (Fonseca 2011). The shape indices include elongation (I_E), flatness (I_F), convexity
124 (I_C) and sphericity (I_S), formulae provided in Appendix. They all take dimensional values between
125 zero and one, with the latter corresponding to the most extreme cases. The median values for these
126 parameters are presented in Table 2.

127 Fig. 3 shows the evolution of grain sizes (given by a , which better reproduce the sieve results)
128 throughout the loading. It can be inferred from Fig. 5a that the number of grains with sizes between 0-
129 1000 μm increases slightly, while that between 1800-4500 μm decreases slightly, under loading. This
130 suggests a small reduction in grain size as a result of chipping of asperities and sharp corners; since

131 grain splitting was not observed for the stress level investigated here (the fluctuations are likely to be
132 related to the small number of grains in the sample. Interestingly, the fine soil shows marginal grain
133 damage (Fig. 5b), which can be because due to the wider range of grain sizes as discussed in the
134 work by Altuhafi & Coop (2011). The statistical analysis of the shape parameters through the loading
135 stages did not show any conclusive observation.

136 3.2. Contact detection and coordination number

137 Following the application of the watershed algorithm, the ‘watershed ridges’ between the grains in
138 contact were removed from the solid phase. For the detection of grain contacts, it is necessary to
139 temporarily expand the grain in analysis so that the contact between it and the neighbouring grains
140 can be established. For clarity, this is illustrated by a 2D example image shown in Fig. 4a, where the
141 grain of interest, labelled n_0 , is potentially in contact with the surrounding grains labelled $n_1, n_2 \dots, n_6$.
142 The surrounding grains are isolated first (Fig. 4b), and the grain of interest is expanded (Matlab
143 function: *imdilate*) and given a temporary label N (Fig. 4c), which is greatly larger than the total
144 number of grains in the image to avoid possible mistakes. The isolated grains are then superimposed
145 and there will be overlapping areas where label values are larger than N can be identified (Fig. 4d),
146 based on which the labels of grains in contact with grain n_0 are identified and its coordination number
147 can be calculated accordingly. To avoid two ‘not-in-contact’ grains being mistakenly identified as a
148 contact pair, only the grains strictly attached to the same watershed ridges are searched using the
149 algorithm described here, which also greatly improves the searching efficiency. This contact detecting
150 algorithm proves to be computationally efficient and the corresponding calculation for the FS
151 containing more than 150,000 grains can be completed within in 10 minutes. This constitutes a
152 significant improvement in computational efficiency when compared with the algorithm used in
153 Fonseca (2011) and Fonseca et al. (2013b).

154 The coordination number (CN) is investigated here as a measure of the packing density, based on the
155 average number of contacts per particle (Fonseca et al., 2013b) The median values of CN measured in
156 the image at each stage throughout loading are presented in Table 2, for CS and FS. The calculated
157 distributions of CN throughout loading are shown in Fig. 5. For CS (Fig. 5a), the number of the grains

158 with smaller CN values appears to increase despite the fact that the sample becomes more compacted.
 159 This observation can possibly be related to chipping of sharp corners that result in the loss of contacts.
 160 The fluctuations caused by the limited number of grains in the CS, however, prevent a very
 161 conclusive remark. For FS (Fig. 5b), the number of grains with high CN values between 8 and 16
 162 increases, while that between 1 and 6 decreases significantly, in agreement with the formation of a
 163 more compacted packing. For silica sands, an increase in the average CN value under loading was
 164 also observed (Fonseca et al. 2013b).

165 **4. Grain kinematics**

166 *4.1. Parameters definition*

167 The translation of a grain was calculated as the change in the position of its centroid, expressed as:

$$\Delta = [\text{mean}(x_t), \text{mean}(y_t), \text{mean}(z_t)] - [\text{mean}(x_r), \text{mean}(y_r), \text{mean}(z_r)] \quad (1)$$

168 For the quantification of rotation, a new scalar rotation factor is proposed here, defined as follows:

$$\delta = \|\beta_{1,t} - \beta_{1,r}\| + \|\beta_{2,t} - \beta_{2,r}\| + \|\beta_{3,t} - \beta_{3,r}\| \quad (2)$$

170 where β_1 , β_2 and β_3 are the three orthogonal principal components (directions) of the major,
 171 intermediate and minor principal axes of the grain obtained using the principal component analysis
 172 (Matlab function: *pca*). For a grain having two (or all) principal axis with similar lengths, it is possible
 173 that the order of the three axes is not the same at the target and reference positions, and in some cases,
 174 the direction of some axes could even be ‘reversed’. Therefore, for an arbitrary principal component
 175 $\beta_{i,r}$, its counterpart ($\beta_{i,t}$) is chosen when $|\beta_{i,r} \cdot \beta_j|$ has the largest value for $j = 1, 2$ and 3 (with the
 176 smallest intersection angle). Then, $\beta_{i,t}$ is determined as:

$$\beta_{i,t} = \text{sign}(\beta_{i,r} \cdot \beta_j) \cdot \beta_j \quad (3)$$

178 where the first term is used to consider the possibility of a ‘reversed’ direction.

179 4.2. DVC-based reconstruction of grains

180 For a reference grain (G_r) in the reference image (IM_r), the corresponding displacements extracted
181 from the displacement field throughout the image, calculated from DVC, are used to reconstruct the
182 target grain (G_t) in the target image (IM_t). An open source DVC code provided by Bar-Kochba *et al.*
183 (2015) was used and further details can be found in the original paper. The code utilises a fast Fourier
184 transform based cross-correlation formulation in conjunction with the iterative image deformation
185 method (Huang *et al.*, 1993; Jambunathan *et al.*, 1995) and proves to be efficient in analysing general
186 non-linear 3D deformations. The size of each grid element in the DVC mesh was defined as $8 \times 8 \times 8$
187 (in voxel), and the DVC outputs are three displacement matrices (in x , y and z directions). These
188 matrices were then expanded through linear interpolation to generate matrices with the same size as
189 the segmented images.

190 The coordinates of an arbitrary grain, formed by a total number N of voxels, in the segmented image
191 are represented as $[x, y, z]$, where x , y and z are $N \times 1$ vectors. Then the displacements, denoted as $[u_x,$
192 $u_y, u_z]$, of this grain can be extracted from the expanded displacement matrices (MATLAB function:
193 *find, ind2sub*), and the coordinates of the grain are updated as:

$$[x_t, y_t, z_t] = [x_r, y_r, z_r] + [u_x, u_y, u_z] \quad (4)$$

194 where the subscripts r and t correspond to the quantities assessed at the reference and target positions,
195 respectively. Figs. 6a and 6b shows an example of a binarised grain in its initial (undeformed position)
196 and in its deformed position, respectively; together with the associated displacement field (Fig. 6c).

197 4.3. ID tracking method

198 The size and shape properties of the grains in the sample provide the basis for the ID-tracking method.
199 For an arbitrary reference grain G_r , a searching process is performed by matching its properties with
200 those of the grains segmented in IM_t , to find its counterpart. The properties used for the matching in
201 the present study are: volume, principal axes length, elongation, flatness, convexity and sphericity. If
202 the differences calculated for these properties are within a specified tolerance, taken as 20% in this
203 study, the corresponding grain is recognised as a potential 'target grain'. In the case of more than one

204 such grains being found, the best match is chosen as G_r . Similar technique was used by Smit (2010)
205 and Andò et al. (2012), where the properties considered for the tracking were the volume and surface
206 area of the grains. The limitation of this method lies in the fact while G_r is readily derived from IM_r ,
207 its counterpart (G_l) cannot be necessarily found in IM_l , due to ill-segmentation caused by possible
208 surface damage. For all 700 grains in CS sample only 239 could be tracked between loading stages 0-
209 1 and 199 between loading stages 1-2, and as deformation progresses fewer grains can be tracked.

210 4.4. Measurements and analysis

211 Geometrical characteristics such as grain volume and grain shape are affected by chipping of sharp
212 corners of shelly carbonate grains even under relative low loading as it is the case of the tests here
213 presented. Grain damage can thus make tracking not practical. Those grains that can be, however,
214 effectively tracked, are used here to validate the DVC-reconstruction method. The key advantage of
215 the DVC-reconstruction method is that it is less vulnerable to grain damage since only the
216 segmentation the grains prior to loading is required, unlike the ID-tracking method that highly relies
217 on the accurate segmentation of the grains throughout the loading.

218 For a more detailed inspection, the magnitude of the translation vectors for the grains that can be
219 tracked, *i.e.* 239 between loading stages 1-2 and 199 for loading stages 2-3, are compared in Figs. 7a
220 and 7b. Good agreement can be observed since approximately 92% of points are located near the
221 agreement line with discrepancies within $\pm 10\%$ at both loading intervals. For the rotation values the
222 agreement was of approximately 80% with the ID-tracking method yielding slightly higher results.
223 This is likely to be associated with ill-segmentation that alters the shape of the grain and the
224 orientation of the principal axes, thus leading to larger rotation values. Overall, and for the large
225 majority of the grains the agreement is good, which shows the capability of the proposed method to
226 assess grain kinematics.

227 Possible sources of error associated with the DVC-reconstruction method are likely to be related to
228 partial volume effects. While this can be alleviated by high resolution, which indeed is the case of the
229 present study, it cannot be perfectly avoided when dealing with angular and highly irregular surfaces

230 found in shelly grains. Important to highlight here is the advantage of the DVC-reconstruction method
231 in providing the displaced positions for almost all grains, provided that grain detachment following
232 grain cracking does not take place.

233 **5. Discussion**

234 *5.1. Evolution of grain kinematics under loading*

235 The translation mechanisms are investigated here using the distribution of the magnitude of
236 translation vectors. For CS (Fig. 8a), relatively high frequencies can be seen for translation values
237 above 200 μm during interval 0-1, while the higher frequencies are located between 50 and 200 μm
238 for the two subsequent intervals. This observation suggests that intense grain movement took place
239 initially as the grains rearrange to accommodate the imposed load for the sample with large initial
240 voids. This initial rearrangement is not so pronounced in FS (Fig. 8b) and for both intervals the most
241 frequent translation peak locates between 50 μm and 100 μm . Regarding the distribution of the
242 rotation factors, also a markedly difference between the first loading interval and the two subsequent
243 ones can be found for CS (Fig. 8c) but not for the FS case (Fig. 8d).

244 In order to better understand the spatial distribution of the kinematics within the sample, the grains in
245 the CS sample have been coloured according to their rotation value, as shown in Fig. 9. It can be seen
246 that, for the first loading interval, the grains with larger rotations are randomly distributed, which
247 reflects the initial adjustments in the sample. For the subsequent intervals the higher rotations are
248 located at the top half of the sample and this can be due to the use of a fixed ring oedometer and also
249 the related to sample preparation.

250 The correlation between the rotation values and the magnitude of the translation vectors for each grain
251 was investigated but no clear trend was observed. Regarding the effect of CN on grain rotation, it was
252 observed that the largest rotation factor a grain can achieve is hindered by large coordination number
253 values. This is expected as a grain with high coordination number (*i.e.* more contacts with
254 neighbouring grains) is more likely to have less degrees of freedom and rotation is less likely to take
255 place. This observation is in agreement with previous results that link the occurrence of chipping of

256 asperities to high CN (Karatzas et al., 2019) and, thus, demonstrates the need for grain damage as an
257 unlocking mechanism to enable grain rearrangement. On the other hand, grain translation is less
258 affected by the coordination number of the grain, as a cluster of grains, regardless of their
259 coordination numbers, could translate as an ensemble in the direction of the loading.

260 5.2. Effect of grain morphology on grain kinematics

261 The effect of grain size and shape on the rotation and translation is examined in this section. The plot
262 of grain rotation against grain size (given by a), shown in Fig. 10a, suggests that higher rotation
263 values are attained by smaller grains and that larger grains are generally limited to the lowest
264 measured rotation factors. This trend can be observed for both CS and FS (although only CS is
265 shown).

266 Since the axis length do not provide any information on whether the grain is large and bulky or just
267 has one large principal axis length, the correlation of rotation with elongation and flatness was
268 analysed. As shown in Figs. 10b and 10c, despite the scatter, it can be seen that more elongated grains
269 (higher I_E) and plate-like grains (higher I_F) are associated with smaller rotation values, suggesting that
270 the grains with more elongated and plate-like shapes tend to form interlocked structures that hinder
271 rotation. The link between grain interlocking and grain shape is also demonstrated by considering
272 grain convexity. As shown in Fig. 10d, for grains with low I_C , i.e. with concave features, the rotation
273 values are seen to be lower when compared with more convex grains. This is expected as the small re-
274 entrances in the grain surface will promote interlocking. The angular features of the grain surface,
275 captured by the high angularity values, have a similar effect, though not presented here. No expressive
276 trend was found for the effect of I_S on grain rotation.

277 6. Conclusions

278 This paper uses a DVC-reconstruction method to quantify grain kinematics in shelly carbonate sands
279 for sands. This technique has the advantage of overcoming limitation related to the complex
280 morphologies and/or proneness to grain damage, for which, for which ID-tracking methods can be of
281 limited application. Since the grain in the deformed image is identified based on the associated

282 displacement field, this method is less affected by ill- segmentation or subtly changes in the outline of
283 the grain. This enabled to measure rotation and translation for shelly carbonate sands under oedometer
284 compression for the first time in the literature.

285 For the stress/strain level considered in this study, there is very limited grain splitting taking place for
286 both the coarse and fine samples. However, chipping of asperities was found for the coarse sand, as
287 indicated by the reduction in grain size and coordination number as loading progresses. This
288 phenomenon is less pronounced for the fine sand, probably owing to the well-graded nature of the soil
289 sample. The translation of grains is less affected by coordination number than rotation. The results
290 show the effect of grain shape on rotation, as more elongated or plate-like shapes as well as concaved
291 grains tend to exhibit less rotation. This supports the linkage between shape-induced interlocking and
292 rotation of the grains. The rich image-based experimental data from this study will be instrumental for
293 the development and validation of advanced discrete numerical approaches to model the behaviour of
294 shelly carbonate sands.

295 **7. Appendix**

296 The four shape parameters used in this study, I_E , I_F , I_C and I_S were calculated as follows:

$$297 \quad I_E = \frac{a-b}{a} \quad (5)$$

$$298 \quad I_F = \frac{b-c}{b} \quad (6)$$

$$299 \quad I_C = \frac{V_{fill}}{V_{con}} \quad (7)$$

$$301 \quad I_S = \frac{V_{fill}}{V_s} \quad (8)$$

302 where V_{fill} is the volume of the grain after being filled, calculated based on the triangular surface mesh
303 described above, V_{con} is the volume of the minimum convex hull that encloses the grain and V_s is the
304 volume of the circumscribed sphere of the grain, with radius R_o (Welzl, 1991). More details can be
305 found in Kong and Fonseca (2018).

306 **Acknowledgement**

307 The authors gratefully acknowledge the financial support provided by the UK Engineering and
308 Physical Sciences Research Council (EPSRC) under the grant MuMShell: Multiscale modelling of
309 shelly carbonate sands for foundation design of offshore structures (EP/N018168/1).

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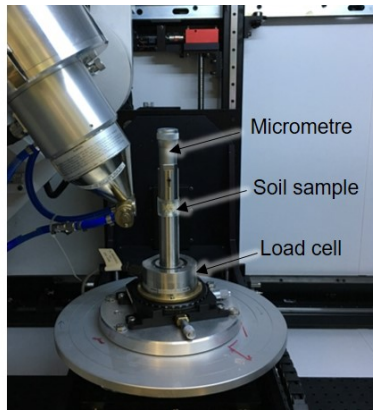
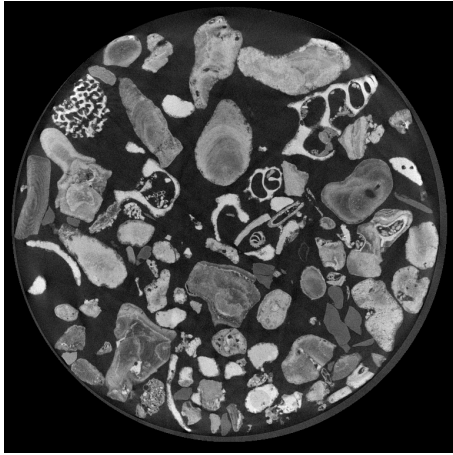
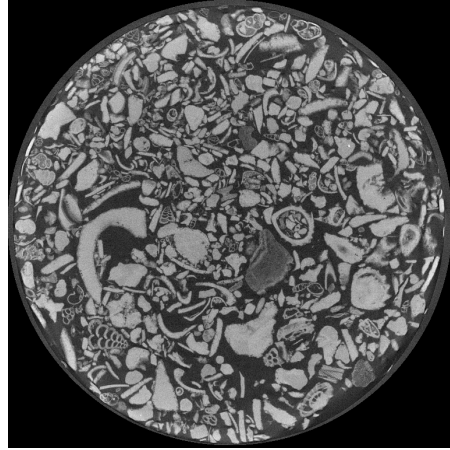


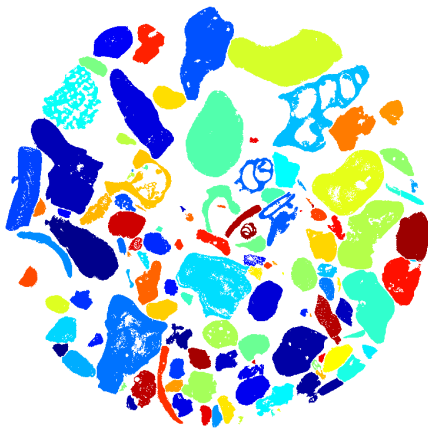
Figure 1: Set-up of the one-dimensional compression tests inside a μ CT scanner



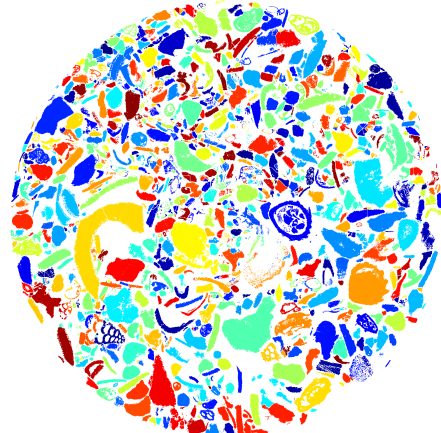
(a)



(b)



(c)



(d)

Figure 2: Top view slices through 3D images of the samples prior to loading: (a) CS raw data; (b) FS raw data; (c) CS segmented; (d) FS segmented

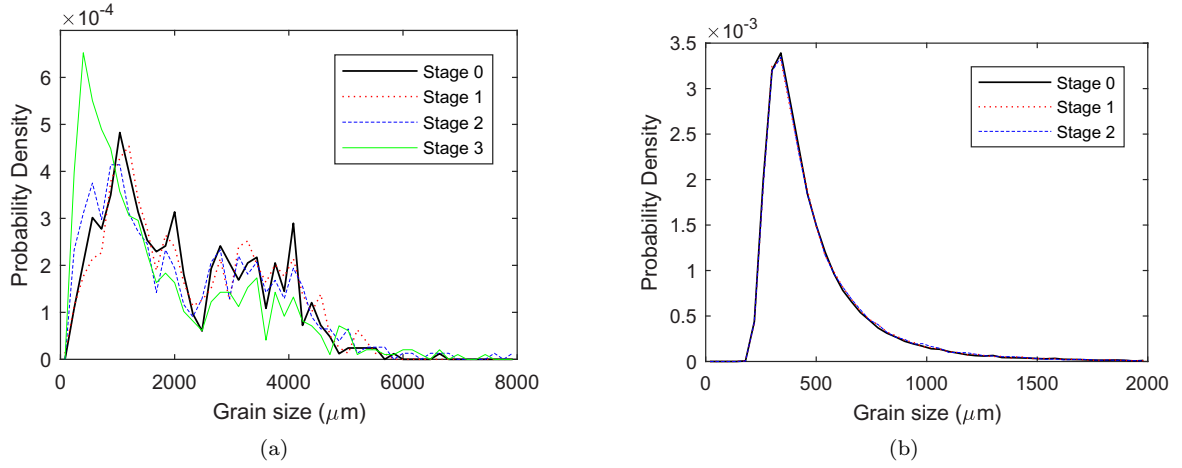


Figure 3: Evolution of grain size with loading (given by major axis length a): (a) CS; (b) FS

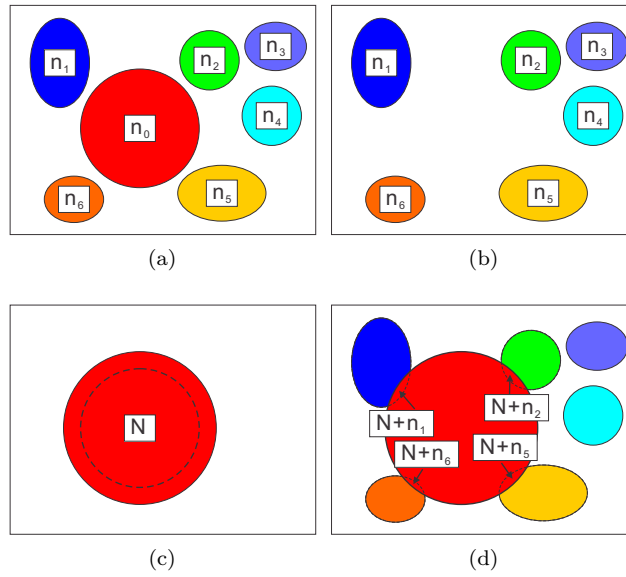


Figure 4: Illustration of the contact detection algorithm: (a) grain $n - 0$ with neighbouring grains; (b) isolated neighbouring grains; (c) dilated and temporarily re-labeled grain $n - 0$; (d) identification of in-contact neighbouring grains

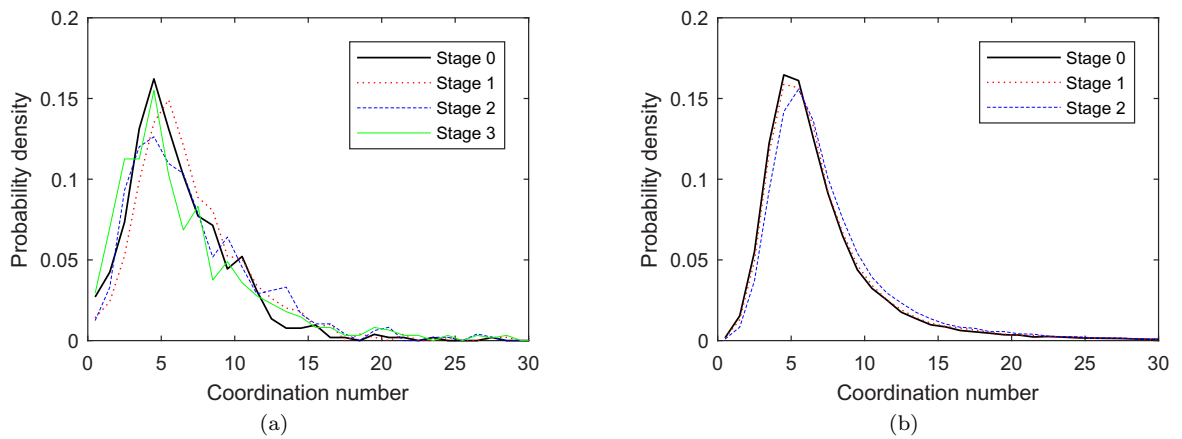


Figure 5: Evolution of coordination number with loading: (a) CS; (b) FS

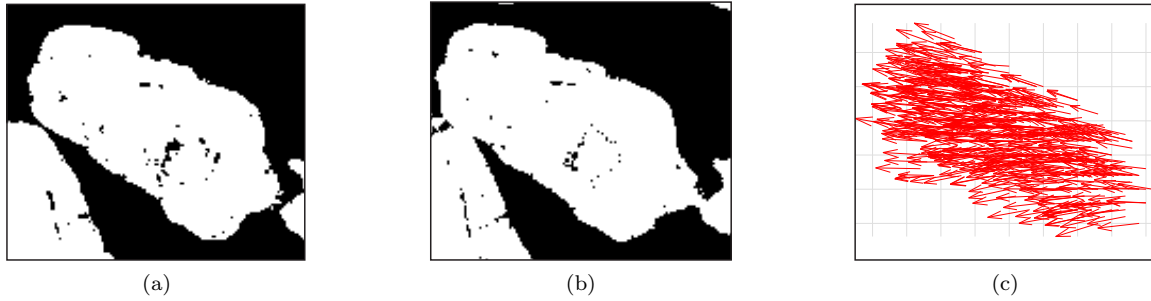


Figure 6: Illustration of the DVC-reconstruction method: (a) binary grain at reference position; (b) binary grain at target position; (c) associated displacement vectors

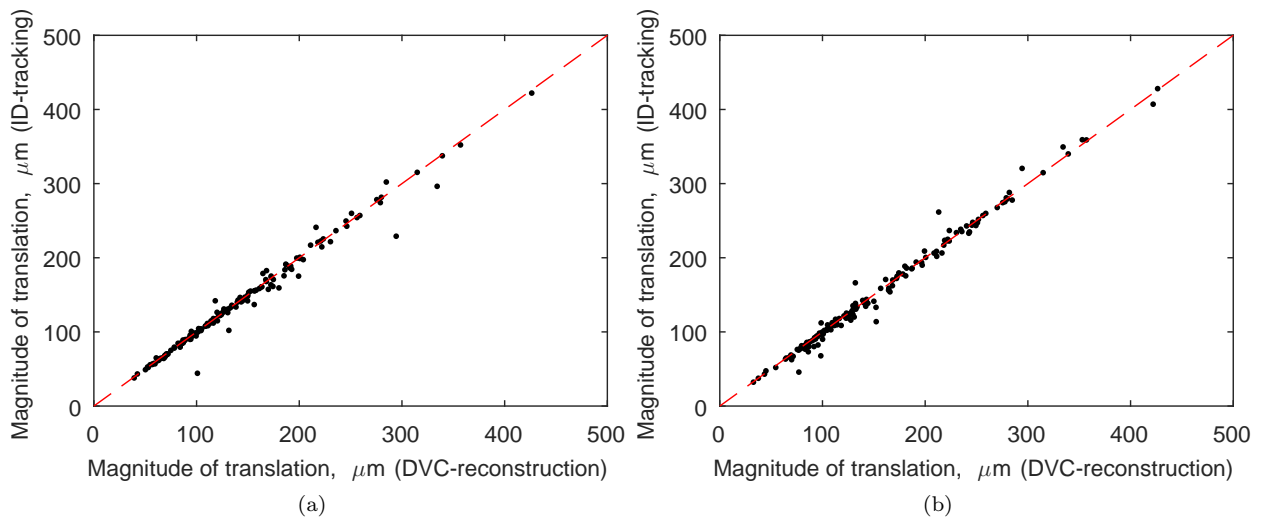


Figure 7: Comparison of grain translation measured using ID-tracking and DVC-reconstruction methods (showing CS): (a) interval 1-2 (b) interval 2-3

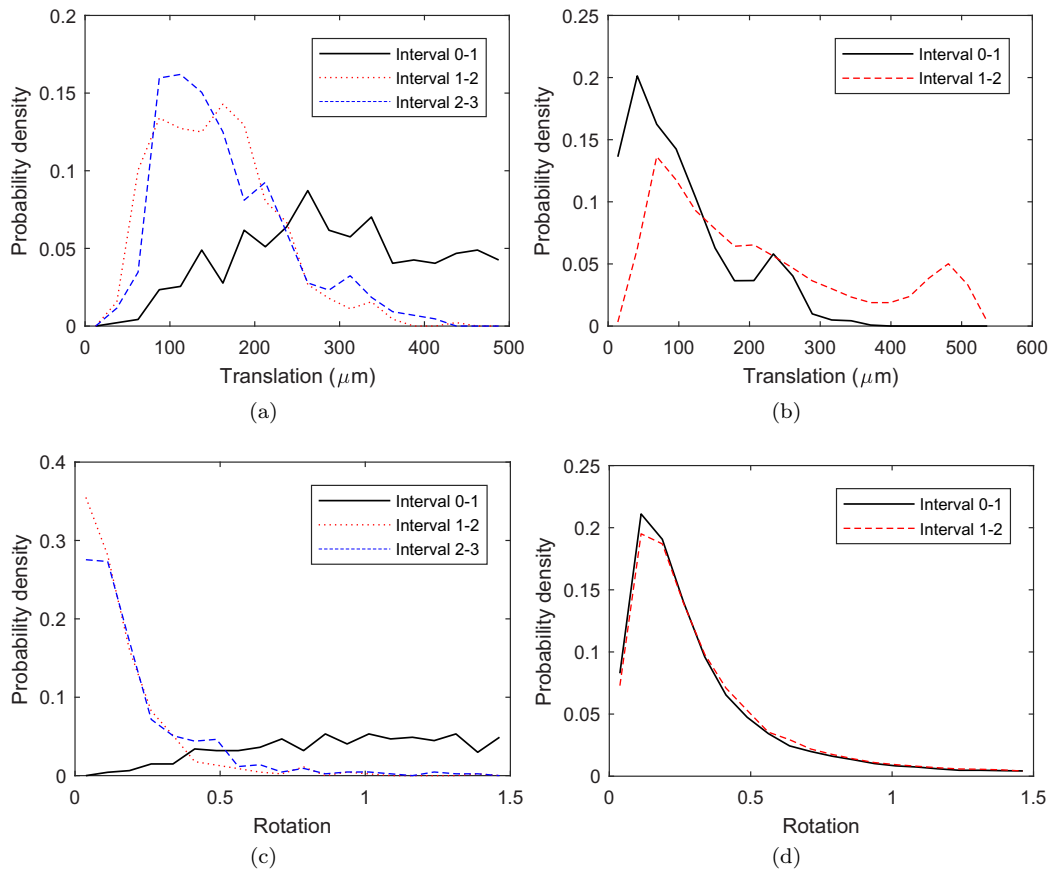


Figure 8: Frequency distribution of grain translation and rotation for different loading intervals: (a) CS translation; (b) FS translation; (c) CS rotation; (d) FS rotation

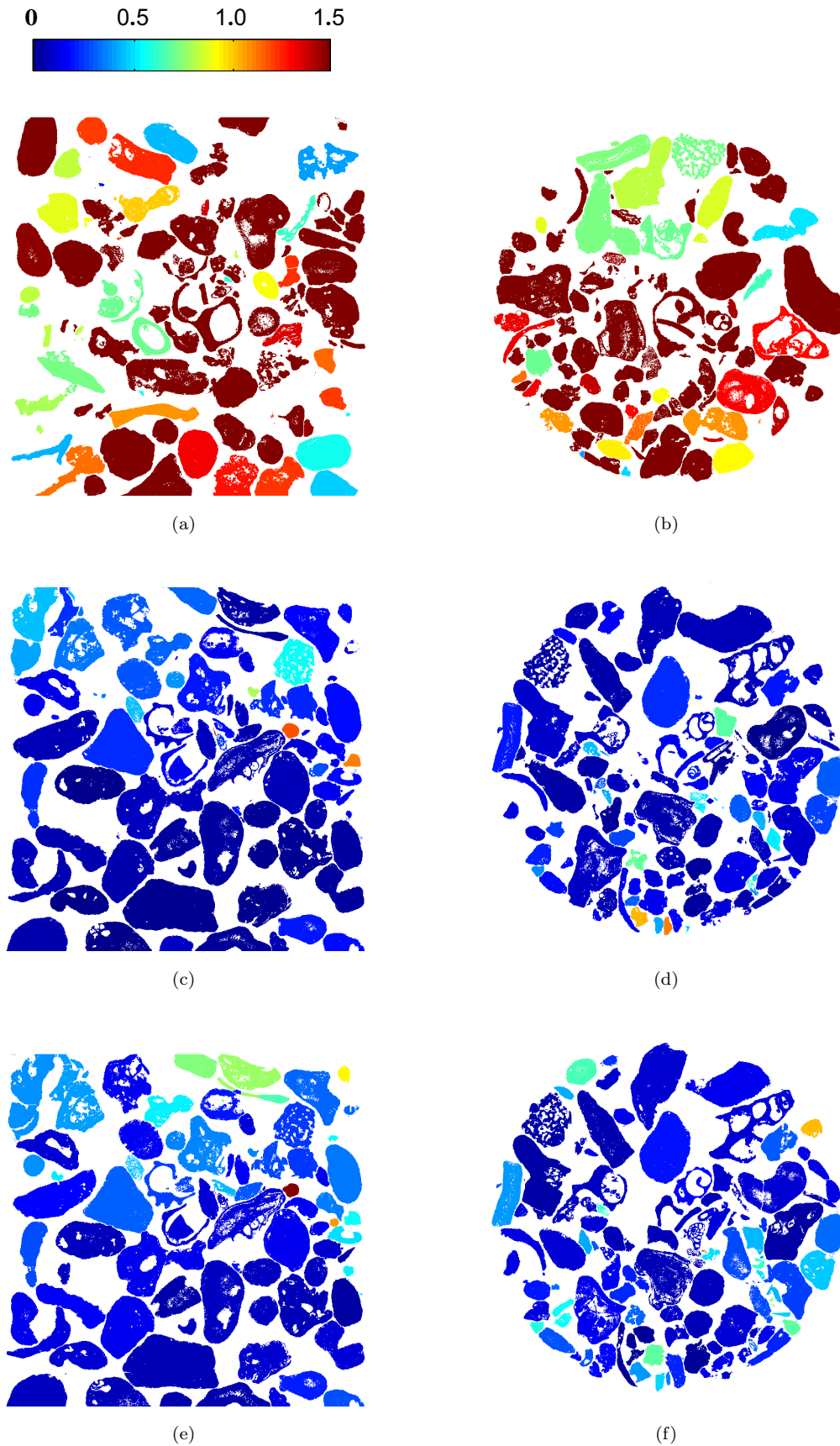


Figure 9: CS sample with each grain coloured by associated rotation factor (showing CS): (a) side view interval 0-1 (b) top view interval 0-1; (c) side view interval 1-2; (d) top view interval 1-2; (e) side view interval 2-3; (d) top view interval 2-3

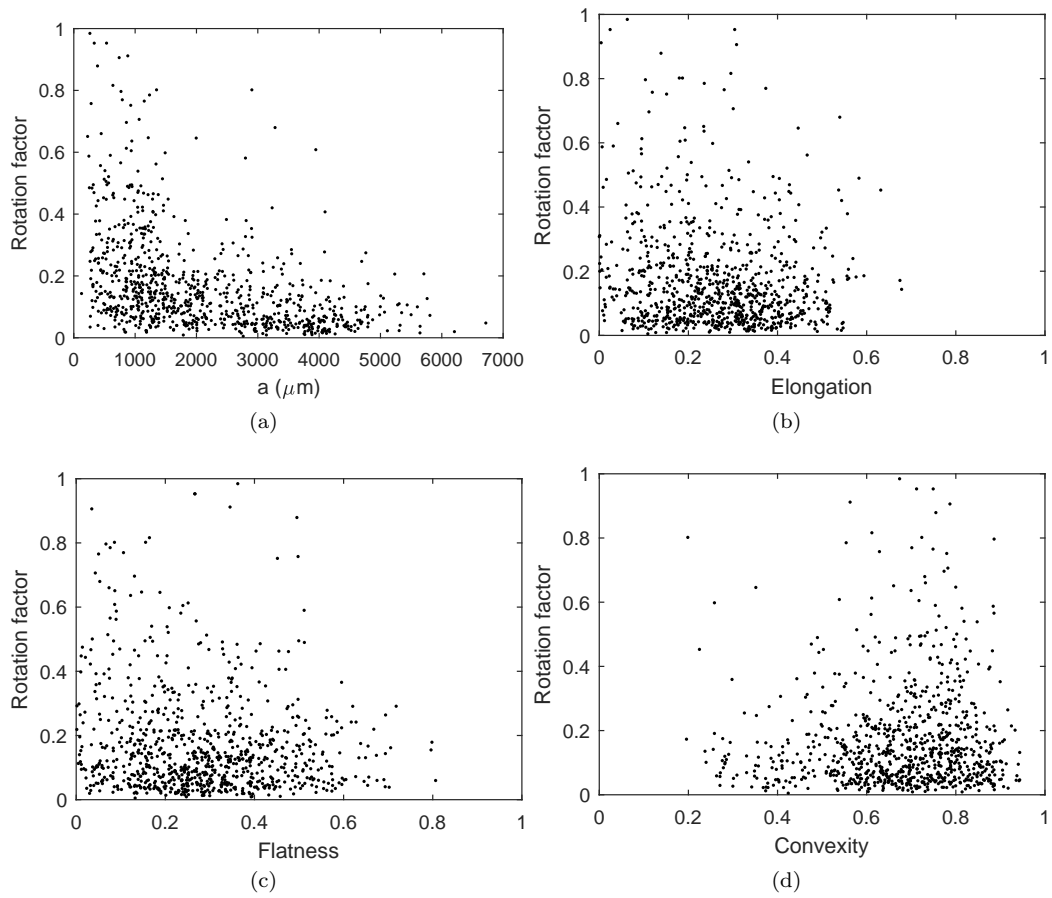


Figure 10: Plot of rotation factor against grain size and shape indices (showing CS): (a) size given by a ; (b) elongation; (c) flatness; (d) convexity