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1 **Analysis of the Fabric of Undisturbed and Pluviated Silty Sand under**

2 **Load over Time**

3
4 Microstructure of two undisturbed silty sands with 4% fines and 35% fines is
5 described and quantified. The materials were sampled by the gel push sampling
6 method. Upon reloading to their in situ stresses, the material fabric was fixed by
7 resin impregnation. A qualitative and quantitative comparison of the
8 microstructure was made with laboratory prepared dry deposited specimens (15%
9 fines) which were loaded over different periods of time. The microstructure is
10 quantified statistically by measuring particle orientation and the distribution of
11 spatial distance between particles. Both undisturbed and reconstituted specimens
12 show a preferred horizontal particle orientation, with little detectable change over
13 time in the reconstituted samples. Spatial microstructural change was assessed
14 using new parameter called index of dispersion. A greater index of dispersion
15 suggests a more interlocked structure (hence, more structurally stable sample).
16 Analysis of the reconstituted samples show that index of dispersion tends to
17 increase with ageing, with the denser sample displaying greater change over time
18 than the looser sample. Values of index of dispersion of reconstituted samples
19 (15% fines) tend to lie between those of the undisturbed sample with 35% silt
20 fines and with 5% fines, showing that this measure is not independent of the
21 particle size distribution.

22 Keywords: Microstructure, apparent particle orientation, spatial distance, silty
23 sand, undisturbed, dry deposition

24 **Introduction**

25 Granular disturbed soils exhibit time dependent behaviour regardless of their near-
26 instantaneous pore water dissipation and chemically hard inert properties. The majority
27 of this evidence comes from the increase in penetration resistance in hydraulically
28 placed fills and freshly disturbed deposits after ground improvement, such as via
29 explosive blasting and dynamic deep compaction Ashford, Rollins, & Lane,; Saftner,
30 2009). This phenomenon usually is referred as *sand ageing*. Another phenomenon

31 related to *sand ageing* is the increase in pile capacity of driven piles in sands (Bullock,
32 Schmertmann, McVay, & Townsend, 2005; Ng, Selamat, & Choong, 2010). Ageing is
33 particularly important to the behaviour of shallow soils after artificial deposition or
34 disturbance and the time-dependent development of shear resistance after seismic
35 liquefaction.

36 It is well known that the microstructure of granular soil has a profound influence
37 on its mechanical behaviour. Particle orientation and arrangement of the contacts
38 between grains are the most important microstructural characteristics to affect stress-
39 strain behaviour (Kang, Yun, Lau, & Wang, 2012; Oda & Iwashita, 1999). Different
40 methods of preparation of reconstituted granular soils have been found to result in a
41 different microstructure and consequently different mechanical response (Hoeg, Dyvik,
42 & Sandbaekken, 2000; Yamamuro, Wood, & Lade, 2008). However, the majority of
43 the microstructure studies were conducted on clean sand, whilst most granular materials
44 occurring in nature are composed of a broad range of particle sizes (Astedt, Weiner, &
45 Holm, 1992; Mitchell & Soga, 2005). Furthermore, very limited microstructure studies
46 are related to ageing of sand with fines.

47 This research describes an experimental approach to obtain detailed observations
48 of soil microstructure from resin injected granular soils. The experimental techniques
49 can be applied to soils of a relatively wide grain size distribution, and here we focus on
50 their application to silty sands. We provide observations and quantitative measurements
51 of fabric of two undisturbed soils, one fine sand with relatively low silt content and one
52 with high silt content, obtained using a gel push sampler (Taylor, Cubrinovski, &
53 Haycock, 2012). Extending from a preliminary study (Yusa, Bowman, & Cubrinovski,
54 2017) the particular focus here is on understanding how we can examine and
55 quantitatively compare the fabric of soils of different particle size. These fabric features

56 are then compared with fabric developed in laboratory tests on reconstituted silty sand
57 samples over time under constant stress loading. Here we examine whether we can
58 detect ageing effects in silty sand.

59 **Material and Experimental Procedure**

60 *Material*

61 Natural undisturbed soil samples were recovered using the gel-push sampling
62 technology (Huang, Tai, Lee, & Ishihara, 2008; Kazuo & Kaneko, 2006). Following
63 the Canterbury earthquake sequence 2010-2011, the method was brought to New
64 Zealand as part of a research project on liquefaction assessment within the Christchurch
65 area (Stringer, Cubrinovski, & Haycock, 2016). The samples were obtained in August
66 2011 from two sites within the Christchurch Business District (CBD), i.e. Kilmore
67 Street (Gel Push-A) and Madras Street (Gel Push-B), that were liquefied by the Mw 6.3
68 earthquake that occurred in February 2011 (Cubrinovski, 2013; Cubrinovski et al.,
69 2011). Samples Gel Push-A and Gel Push-B were taken approximately from 6m depth
70 and 4m depth, respectively. Careful handling of the sample during the gel-push
71 operations and transportation to the laboratory is essential for minimizing disturbance.
72 After extrusion of the sample from the tube, the samples are cut and stored, and then
73 trimmed to about 40mm in height and 50cm in diameter. The particle size distributions
74 (PSD) obtained by laser sizer are shown in Figure 1(a). Gel Push-A was a relatively
75 clean sand with 4% fine particles (smaller than 75 μm), while Gel Push-B was a silty
76 sand with 35% fines. The mean diameter D_{50} of Gel Push-A and Gel Push-B was 235
77 μm and 95 μm , respectively. The coefficient of uniformity C_U of Gel Push-A and Gel
78 Push-B was 1.7 and 3.7, respectively.

79 Lab C was ejected soil following the Canterbury earthquake, collected from

80 Rydal Reserve, Christchurch, New Zealand. Lab C is a non-plastic silty sand with 15%
81 fines, mean diameter of 150 μm and coefficient of uniformity of 4.1. For Lab C only,
82 fines particles smaller than 32 μm were removed by wet sieve to avoid difficulty in
83 precise fabric quantification in related work. The maximum and minimum void ratio
84 e_{max} and e_{min} for Lab C were determined as 0.973 and 0.565, respectively, according to
85 the Japanese Geotechnical Standard (2009). Lab C specimens were reconstituted by dry
86 funnel deposition (Yamamuro & Wood, 2004). Although size segregation can occur
87 during dry deposition, segregation also generally occurs in the field. Thus for this study,
88 we considered the method is reasonable to make qualitative and quantitative comparison
89 between the microstructure of the natural undisturbed soil and reconstituted soil, and to
90 examine if short term changes in microstructure of the soil under K_0 loading could be
91 detected by image analysis.

92 [Figure 1 here]

93 To illustrate the influence of fines content on the maximum and minimum void
94 ratio achievable for Lab C silty sand, Figure 1(b) presents data for a range of sand-fines
95 mixtures. At 15% fines content, the soil is sand dominated – that is, the fines do not
96 participate in the sand matrix and are generally able to move freely between them. As
97 the fines content increases, the fines increasingly fill the voids and, through the
98 transition zone, act to separate the sand particles, resulting in a decrease of e_{min} ,
99 followed by an increase as fines begin to dominate the soil's matrix. Although the
100 transition zone is not distinct in the figure, it is taken to be within the range of 20-40%
101 as found by other researchers (Cubrinovski & Ishihara, 2002; Lade, Liggió, &
102 Yamamuro, 1998). Assuming similar soil characteristics, Gel Push-A is expected to be
103 highly sand dominated, while Gel Push-B is in the transition zone although close to
104 being fines dominated.

105 *Experimental Procedure*

106 *Sample preparation*

107 Microstructure studies can be undertaken by direct methods e.g. injection of a low
108 viscosity epoxy resin to fix the soil particles in place, then sectioning (Palmer & Barton,
109 1986) or non-direct methods, such as use of x-ray tomography (Vlahinic, Ando, Viggiani,
110 & Andrade, 2014). Reporting on x-ray tomography, Vlahinic et al. (2014) found that,
111 despite the advantage of inducing no disturbance to samples, tomography has limitations
112 with respect to imaging soils that have either wide grain size distribution, irregular shape
113 or fine particles. Hence, it was decided to adopt a direct method of visualisation here.

114 The setup used for sample preservation by epoxy resin is shown in Figure 2. The
115 epoxy resin used in this study was EPO-THIN from Buehler Inc, which has specific
116 gravity of 1.1299, viscosity of 200-250 centipoise (cPs) at 20°C and shrinkage strain of
117 0.01%. The viscosity of the resin can be reduced to be close to water (1 cPs) when
118 heated to 50°C for 10 minutes, and has been used in previous research by Masad (1998)
119 and Bowman and Soga (2003). The mixing ratio for the resin and hardener was as
120 recommended by the manufacturer i.e. 5:1.95. The Gel Push-A and Gel Push-B
121 specimens were carefully placed inside the chamber (half split steel cylinder) and dried
122 in the oven under 50°C for at least two days to achieve full dryness. The maximum
123 axial strain after drying was 0.2%, indicating low disturbance. They were then loaded to
124 80 kPa and 50 kPa vertical stresses, respectively (Table 1). The vertical stresses were
125 based on the estimated in situ stresses corresponding to the sampling depth and
126 groundwater level at the borehole (assuming an average unit weight of 18 kN/m³).
127 Resin was placed in the upper part of the water epoxy chamber (D) separated from the
128 lower water filled section by a rubber membrane. Pressure was applied using an air-
129 water interface (B) to inject the resin into the base of the impregnation chamber (E) via

130 the rubber membrane. The air-water interface (B) was connected to an automatic system
131 for volume change (C). In-house software was made to allow monitoring of the resin
132 volume infiltrated. Precaution was taken to ensure air-bubbles were expelled from both
133 sides of the interface chamber. This enabled an accurate assessment of the quantity of
134 resin being used as the infiltration was carried out.

135 [Figure 1 here]

136 [Table 1 here]

137 For Lab C, two pairs of samples were reconstituted by dry deposition (Lab C-
138 DD) to a relative density of 40% (loose) and 70% (dense), respectively, making four
139 samples in all. The samples were then loaded one dimensionally under K_0 condition and
140 left for one hour or one week, respectively. This was thought to be sufficient to result in
141 detectable changes in relative microstructure with time (e.g. Bowman & Soga, 2003;
142 Muszynski, 2000). The field stresses under which many soils age may be approximated
143 by the K_0 -condition where lateral (horizontal ground) strain is zero. The applied vertical
144 load was in accordance with the K_0 value to achieve 60kPa horizontal effective stress as
145 determined by triaxial testing under K_0 condition (Yusa & Bowman, 2013). This
146 resulted in applying vertical effective stresses of 113 kPa for the loose and 125kPa for
147 the dense specimens.

148 The resin was warmed for 10 minutes at 50⁰C to reduce the viscosity. After
149 mixing with the hardener, the epoxy mix then was poured inside the interface chamber
150 and pressurized using an air-water interface to a low pressure to minimize disturbance
151 to the microstructure during injection. The maximum, minimum and average axial strain
152 after the process of injection and curing were 0.3%, 0.0% and 0.15% respectively,

153 indicating insignificant disturbance (Yamamuro, 2008). Impregnated samples were then
154 left for 24 hours before being removed from the chamber.

155 The samples were assumed to be cross anisotropic both with respect to their
156 fabric and stress, with the major principle stress in the vertical direction and minor in
157 the horizontal. Vertical sections were therefore used to capture the fabric in the major
158 and minor principle stress directions. Cured samples were cut vertically down the
159 middle of the specimen using a thin 5” diameter of wavering diamond blade for
160 minimal surface damage. The end result was a thick section of 0.5cm. Each section was
161 then ground using successive abrasive discs i.e. grit grades 180, 240, 320, 600 and
162 1200. The section was visually inspected by optical microscope and rotated 90°
163 between steps to remove scratches. From this, no bias in damage to or removal of
164 particular particle sizes could be detected. Finally the sample was polished using 0.3
165 micron alpha alumina powder to remove scratches from the finest sandpaper without
166 imparting additional disturbance to the sample.

167 *Capturing image*

168 Scanning electron microscopy (SEM) was used to capture the images, using both
169 secondary electron and back scattered electron detection modes. Back scattered
170 detection produces images based on the atomic weight (Llyod, 1987), giving a clear
171 contrast between the higher atomic weight grains (appearing lighter) and the epoxy
172 filled voids with lower atomic weight. Figure 3 shows image examples of the same area
173 i.e. 211 pixels by 211 pixels equivalent to 437 μm by 437 μm produced by (a)
174 secondary electron and (b) back scattered detector modes, captured at 45x
175 magnification. It can be seen that secondary electron mode produces images that contain
176 less detail and are prone to creating confusion between grains and voids, while clearer
177 and more accurate grain edge definition is achieved with greater contrast by use of back

178 scatter mode. Thus back scatter mode was chosen at a scale resolution of 0.48 pixels /
179 micron. It should be noted that each image or coupon taken represents only a small area
180 of the whole i.e. covering an area of just over a square cm. To represent the statistics of
181 each test to a suitable degree, nine images were taken from the left, centre, and right,
182 and in three rows, from the top, centre and bottom of each section.

183 [Figure 3 here]

184 *Processing image*

185 Captured images were processed and analyzed using image analysis software *ImagePro*
186 *Plus v.7.0*. Steps involved in this included contrast enhancement, correction for noise
187 and thresholding. Watershed was then performed to separate the grains automatically.
188 Finally some manual corrections were made, where necessary, by visual inspection due
189 to imperfections in the watershed process. As the final check, the mean void ratio from
190 the combined images compared with that determined from bulk measurements show a
191 good consistency e.g. for dense samples (Lab C_70601H_DD and Lab C_70601W_DD)
192 0.684 and 0.687, respectively, from images compared to 0.686 bulk; for loose samples
193 (LabC_40601H_DD and LabC_40601W_DD) 0.873 and 0.852, respectively, compared
194 to 0.810.

195 **Analysis Method**

196 *Particle measurement orientation*

197 The orientation of a non-spherical particle can be represented by the orientation of the
198 long axis of the particle relative to a reference axis. The true three dimensional long axis
199 of the particle is difficult to determine, however a measure of this can be taken from two
200 dimensional projections. Thus in this study, particle orientation is defined by the angle

201 of the apparent long axis of the projected particle in two dimensions (a vertical plane in
 202 this study). The orientation of each particle was determined as the angle between the
 203 long axis and the vertical direction and represented on a rose diagram. Statistical
 204 parameters were then determined to summarize the distribution of particle orientation
 205 using Fisher distribution analysis (Fisher, 1993). The Fisher distribution function $P_{dA}(\alpha)$
 206 gives the normalized probability of finding a unit vector direction within an angular area
 207 dA , at angle of α from true mean direction (at which $\alpha=0$):

$$P_{dA}(\alpha) = \frac{\kappa}{2\pi \sinh(\kappa)} \exp[\kappa \cos(\alpha)] \sin(\alpha) \quad \text{Eq. 1}$$

208 Where α is the angle between the unit vector and the true direction and κ is a measure of
 209 the concentration of the distribution about the true mean direction. The value of κ ranges
 210 from zero to infinite. Zero value of κ means that the particle distribution direction is
 211 random. When κ approaches infinity the particles are oriented in the same direction.
 212 The properties of particle orientation distribution can be obtained by the resultant vector
 213 length (Ψ), mean resultant length (r), and mean angle (α_m) determined using Equation 2
 214 to Equation 4:

$$\Psi^2 = \sqrt{\left\{ \sum_{i=1}^N [l_i \sin(2\alpha_i)] \right\}^2 + \left\{ \sum_{i=1}^N [l_i \cos(2\alpha_i)] \right\}^2} \quad \text{Eq. 2}$$

$$r = \frac{\Psi}{\sum_{i=1}^N l_i} \quad \text{Eq. 3}$$

$$\alpha_m = \frac{1}{2} \tan^{-1} \left(\frac{\sum_{i=1}^N [l_i \sin(2\alpha_i)]}{\sum_{i=1}^N [l_i \cos(2\alpha_i)]} \right) \quad \text{Eq. 4}$$

215

216 where l_i is the length of long axes of the particle, N is the number of measurements, α is
217 the angle between the unit vector and the true direction. The value of r ranges from zero
218 to one. Higher r value indicates more orientated data. For number of data > 15 , κ can be
219 estimated from r as follows(Fisher, 1993):

$$\kappa = \begin{cases} 2r + r^3 + \frac{5}{6}r^5 ; r < 0.53 \\ -0.4 + 1.9r + \frac{0.43}{1-r} ; 0.53 \leq r < 0.85 \\ \frac{0.43}{1-3r^2+r^3} ; r \geq 0.85 \end{cases} \quad \text{Eq. 5}$$

220 The influence of different scales of particle structure on the behaviour of soil is
221 unknown. A silty sand with a relatively large number of fines particles, i.e. silt
222 dominated, may have different scales of interest from one that is dominated by larger
223 particles. The statistical results of rose diagrams in which all fines are included, for
224 example, will be controlled by the fine particles although the large particles may
225 predominantly form the major force columns and govern the soil's mechanical
226 behaviour. Hence, to avoid bias related to particle size, we use a weighted value by
227 grain areas for the orientation of each particle. The weighted rose diagram gives a
228 higher significance to the orientation of larger particles (sand in this study), as described
229 in Yang (2002).

230 ***Particle aspect ratio distribution***

231 Particle aspect ratio (AR) is a measure of elongation and is defined as the ratio of the
232 particle's long axis length, dL , to its short axis, dS , as formulated in Equation 6.

$$AR = \frac{dL}{ds} \quad \text{Eq. 6}$$

233 Normalized frequency (frequency in each bin is divided by total number of
234 particles) distribution histograms of aspect ratio are shown in Figure 4. It can be seen
235 that most particles (approximately 70%) for both Gel Push-A and B have aspect ratio
236 between 1.5 and 2, showing that they are elongated. A similar aspect ratio distribution is
237 seen for Lab C.

238 [Figure 4 here]

239 *Spatial Distance Statistic*

240 In addition to particle orientation, the spacing or size of local voids between the
241 particles has important influence on soil behaviour. For example, Masad (1998) used
242 the mean free path (distance between grains in a given direction, also known as the
243 mean intercept length) to examine the seepage anisotropy through granular soils, while
244 Kang et al. (2012) shed light on the mechanism of creep by drawing the evolution of
245 void orientation with time. Bowman (2002) thought that interlocking of particles may
246 cause soils to age. The interlocking of particles is related to particle edge proximity, so
247 that a mean free path method was used in that study to measure the distribution of
248 spatial distance between particles. Following the same reasoning, we use the approach
249 here. For the mean free path method, a series of scanning lines is drawn which pass
250 through both solid particles and voids and the lengths of the spacing between solid
251 particles are measured (Kuo, 1998; Masad & Muhunthan, 2000). The directions of the
252 scanning lines used here were vertical and horizontal, commensurate with principal
253 vertical and radial stresses in axisymmetry. In this study, the shift distance of scan line
254 was set to be small enough (i.e. 10 pixels) so it could pass through the fine particles,

255 hence in one image (1280 pixels x 1024 pixels) the number of lines are 128 in the
256 vertical direction and 102 in the horizontal direction.

257 The distance between particles as measured along a scan line generally produces
258 a highly skewed distribution with many small gaps and few larger ones. In order to
259 apply meaningful statistics, this type of distribution should be transformed to approach
260 normality (Chatfield, 1983), as previously proposed by Bowman and Soga (2003).
261 Parameters used in this analysis are therefore mean log of void distance, kurtosis of the
262 log of void distance, and the ratio of variance of the log of void distance to the mean log
263 void distance, also known as the index of dispersion. The mean void distance of a
264 sample image is, as expected, somewhat related to the whole sample void ratio. Void
265 ratio of the sample, e , is defined as the volume (or image area) of voids (white area) to
266 that of the solids (black area), as illustrated in Figure 5. Kurtosis is defined as the fourth
267 moment of a probability distribution and is a measure of the shape of a curve. High
268 values of kurtosis can occur where there are large numbers of values concentrated in the
269 extreme tails of the distribution, with a value of 3 indicating a normal distribution.
270 The excess population kurtosis, β , used here, is defined as kurtosis minus 3, so a value
271 of zero indicates a normal distribution. It is formulated for a sub-set of samples within a
272 population as:

$$\beta = \left[\frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum \left(\frac{x-\mu}{s} \right)^4 - \frac{3(n-1)^2}{(n-2)(n-3)} \right] \quad \text{Eq. 7}$$

273 Where x is the log void distance along a scan line, μ is the mean value, n is the number of
274 samples and σ is the standard deviation, defined as:

$$\sigma^2 = \frac{\sum (x - \mu)^2}{n} \quad \text{Eq. 8}$$

275 where σ^2 is also known as the variance. Low (more negative) values of excess population
276 kurtosis β (henceforth simply referred to as “kurtosis”) generally implies “shoulder-
277 heavy” distributions, while high values indicates greater “tailness” (Johnson, Tietjen, &
278 Beckman, 1980).

279 [Figure 5 here]

280 Figure 6 shows this concept generally, using probability density functions of
281 three normal distributions in which $\beta = 0$ (Line P, B and G) and one raised cosine
282 distribution (Line R) in which $\beta < 0$ at -0.6 (noting that this is just one illustrative non-
283 normal distribution). Increasingly low values of kurtosis of void distribution were
284 considered by Bowman and Soga (2003) to relate to particle interlock with time – that
285 is, the particles would become clustered together, increasing the shoulders of the
286 distribution. In the extreme long term however, it may be that kurtosis values will then
287 increase as a result of void distance distributions entering the extreme tails. For
288 example, in Figure 6, lines P and R and have the same mean and variance, but different
289 kurtosis, with R having a higher (more positive) value. The shoulders of the distribution
290 of R are broader, but the extremes are less – indicating the ambiguity of kurtosis as a
291 true measure of cluster. As a result, a new measure is also introduced here.

292 [Figure 6 here]

293 The variance to mean ratio (index of dispersion) is a normalized measure of
294 whether a set of data is clustered or dispersed. Comparing lines P and R (as above), the
295 index of dispersion is the same, which seems reasonable as it accounts both for the
296 shoulders and tail of the distribution. It is also useful when comparing populations with
297 different means. In Figure 6, lines G and B have the same variance but for G the mean
298 is higher than for B, so that the index of dispersion is lower. For distributions that have

299 either larger shoulders or tails, relative to the mean, the index of dispersion should be
300 greater (e.g. B versus all others in Figure 6). Therefore, a higher index of void
301 dispersion is expected to indicate a more interlocked fabric, that is, the soil fabric would
302 contain greater numbers of large and small gaps between the particles for a given mean
303 void ratio, than for a non interlocked structure. Note that here, we report results on both
304 kurtosis and index of dispersion, in order to examine which may be the most appropriate
305 measure of particle interlock.

306 **Results**

307 *Qualitative Results*

308 Examples of captured and processed 2650 μm x 2120 μm images from Gel Push-A, Gel
309 Push-B and Lab C are presented in Figure 5a to 5c, respectively. Notable bands of fine
310 particles are visible in this figure for Gel Push-B and for Lab C. Lab C shows a band of
311 silt running from the bottom to the right edge. For Gel Push-B, a band runs from the left
312 edge to the top, showing that particle size segregation occurs naturally in the field as
313 well as in reconstituted dry deposition samples. The typical number of particles in one
314 image is approximately 200, 2000 and 1000 for Gel Push-A, Gel Push-B and Lab C,
315 respectively. With nine images taken per section, statistical analysis involved
316 approximately 1800, 18000 and 9000 particles for Gel Push-A, Gel Push-B and Lab C,
317 respectively.

318 *Particle orientation and diagrams*

319 Jang (1997), based on extraction of soil by ground freezing, found qualitatively that
320 sands under natural deposition have a preferred orientation towards the horizontal. Here
321 we present results of quantification of grain orientation for natural deposits of silty sand.

322 Histograms of particle orientations for each test are grouped into ten degree intervals.
323 Separate analyses for ‘sand’ sized particles and ‘fines’-sized particles were also
324 performed in order to see whether there was difference in the orientation anisotropy
325 between large and small grains. It is not possible to determine which particles truly are
326 fines (taken as $< 75 \mu\text{m}$ in diameter) due to the fact that a 2D slice through each particle
327 may not occur diametrically. Regardless, it can be determined that particles having a
328 feret minimum (smallest distance between two parallel tangents) equal to or larger than
329 $75 \mu\text{m}$ are sand. In this study, the rest of the particles are assumed to be fines. This
330 results in higher fines percentages being reported than those from the true particle size
331 distribution, as shown in Table 2.

332 [Table 2 near here]

333 It can be seen from Table 3 that the fabric of natural undisturbed sand (Gel
334 Push-A and B) has a preferred apparent orientation to the horizontal with mean angles
335 of 87.8° and 89.1° to the vertical axis, respectively. A similar trend was found for Lab C
336 with dry pluviation. Table 3 also reveals that sand size particles and fines tend both to
337 be horizontally oriented, but that fines are less orientated than sand particles, as
338 indicated by smaller κ values. The latter result is likely to be influenced also by the fact
339 that some particles marked as “fines” are actually small portions of larger particles.
340 Examination of the reconstituted specimens suggests that the orientation of particles
341 may increase slightly, from an already aligned near-horizontal direction over one week
342 for both dense and loose Lab C samples, while the degree of concentration for all
343 particles tends not to change much.

344 [Table 3 near here]

345 Rose diagrams for Gel Push-A and B are shown in Figure 7a and 7b,
346 respectively and for reconstituted samples are presented in Figure 8 (loose) and Figure 9
347 (dense). The rose diagrams visually confirm the similarity between natural soils and dry
348 deposition samples in terms of particle orientation.

349 [Figure 7 here]

350 [Figure 8 here]

351 [Figure 9 here]

352 *Spatial distance distribution*

353 In order to carry out a particle spatial distribution analysis, a minimum representative
354 elementary area (REA) is needed for each image. The REA was determined by drawing
355 a circular area which was progressively enlarged until a constant void ratio was
356 obtained (Yusa, 2015). For example, for Lab C_70601H_DD this occurred at an area of
357 about 900000 pixels which is equivalent to an REA diameter of 1070 μm .

358 The determined distribution of particle spacing gave a highly positive-skewed
359 void distribution as seen previously (Bowman & Soga, 2003). Hence the log of the void
360 spacing was used to produce a near-normal distribution upon which statistical analysis
361 could be performed. Table 4 presents spatial void distance results for gel push and
362 reconstituted samples for all particles while Table 5 presents the same data with the
363 ‘fines’ removed (i.e. particles $< 75\mu\text{m}$). Averaged data across all images taken for each
364 test are given for all results including mean log spacing, index of dispersion and
365 kurtosis. Effective void ratio is also reported in these tables – Table 5 highlights how
366 fines removal results in a large increase in the void ratio determined by image
367 processing. In order to examine the results considering local density effects, data from

368 the individual images (nine for each test) are separately presented in the following
369 analysis against the mean void ratio of each image.

370 [Table 4 near here]

371 [Table 5 near here]

372 *Mean log spacing against void ratio*

373 As shown in Table 4, both gel push and dry deposition samples generally have smaller
374 void distances in the vertical direction than in the horizontal due to the horizontally
375 orientated fabric (Masad, 1998). Plots of mean void distance against void ratio for the
376 gel push and reconstituted samples are shown in Figure 10 and Figure 11, respectively.
377 Here we see that Gel Push-A, a relatively clean sand, has a narrow range of void ratios
378 across the images, while Gel Push-B, with a much greater degree of fines, has a much
379 wider range. The populations are also quite distinct, with Gel Push-B plotting at much
380 lower values than Gel Push-A due to the larger quantity of fines reducing the void
381 distance at the same void ratio. In Figure 11, the two populations of images taken for
382 the loose and dense samples plot adjacent to each other in terms of void ratio (indicated
383 by the ovals), irrespective of ageing. However, they overlap considerably in terms of
384 mean log mean spacing (Table 4) and there is much greater variation within the
385 populations than for the gel push samples. The likelihood is that the particle populations
386 in which spacing is large (e.g. in 70601W_DD) are dominated by greater numbers of
387 large particles than usual, i.e. images taken do not contain so many fines. When this
388 occurs the void ratio can be the same, but the mean distance is increased. This
389 segregation of particles is evident in Figure 7b and 7c.

390 [Figure 10 here]

391 [Figure 11 here]

392

393 With respect to the influence of duration of loading on particle spacing, based on
394 all particles, Table 4 and Figure 11 show no clear trends between one hour and one week
395 samples. However, as the fines content for these samples is 15%, below the transition
396 fines content of this material (see Figure 1b), the overall behaviour is expected to be sand
397 dominated. Thus, further image analysis was carried out using sand-sized particles only.

398 Figure 12 present the mean log void distance relationships for sand-sized
399 particles only for dense and loose samples, respectively. For dense samples, statistical
400 examination shows that there are strong correlations, horizontally and vertically,
401 between void ratio and mean log spacing, for one hour and one week. For loose
402 samples, while the trend is similar, the correlation is reduced as a result of its fabric
403 being more variable (Jang & Frost, 1998). The close relationship between void ratio and
404 spacing upon removal of the fines also highlights the dominant role that the sand sized
405 particles play at this fines content.

406 [Figure 12 here]

407 *Kurtosis against void ratio*

408 Figure 13 plots kurtosis of the log mean spacing versus void ratio for dense and loose
409 reconstituted samples. The relationships seen are relatively weak although some trends
410 can be observed. For loose samples, kurtosis tends to decrease (become more negative)
411 with time under load vertically i.e. from -0.745 to -0.787 while in the horizontal
412 direction, kurtosis increases i.e. from -0.770 to -0.699. For dense samples, the kurtosis
413 reduces with time, i.e. from -0.681 to -0.759, vertically, and from -0.623 to -0.684,
414 horizontally. Considering the sand-sized particles only, both dense and loose samples

415 also show that kurtosis becomes lower with time, as can be seen in Figure 144, and
416 Table 5.

417 [Figure 13 here]

418 [Figure 14 here]

419 While there is no systematic difference between Gel Push-A and B samples
420 with respect to kurtosis (Table 4 and Figure 15), comparing these with the Lab C
421 samples (Figures 13 and 14) we see both Gel Push-A and B generally have higher (less
422 negative) kurtosis values – however, when fines are removed via image analysis (which
423 increases the kurtosis values in all cases) the values do not change as much as for Lab
424 C. It is particularly notable that, despite the large quantity of fines present, the kurtosis
425 for Gel Push-B does not shift as much in the positive direction as the others. This may
426 be because this sample had a large portion of its fines below 32 μm (which were
427 removed for the Lab C tests) – in which case kurtosis is shown to be very sensitive to
428 both the fines size and its proportion. This means that while kurtosis can show changes
429 due to age within soils of a particular PSD, it may not be appropriated to compare
430 between soils of differing PSD.

431 [Figure 15 here]

432 *Index of dispersion against void ratio*

433 Figure 16 and Table 4 show index of dispersion versus void ratio. For the dense
434 reconstituted samples, the index of dispersion from one hour to one week increases both
435 in the vertical (from 0.167 to 0.177) and horizontal directions (from 0.164 to 0.181). A
436 similar tendency for dispersion to increase also applies to sand-sized only particles
437 (Figure 17 and Table 5). For loose samples, Table 4 shows that the index of dispersion

438 tends to increase with time but to a lesser degree, i.e. 0.179 to 0.186 (vertical) and 0.173
439 to 0.174 (horizontal) from one hour to one week. Sand-sized only particles also show
440 the same tendency, with Figure 17 giving a clearer indication than examining Table 5
441 alone. We see that changes in spatial dispersion for dense samples with time tend to be
442 larger than that for loose samples, which is keeping with the findings of previous
443 researchers (e.g. Baxter & Mitchell, 2004; Bowman, 2002) who noted that the ageing
444 effect is more profound in dense than in loose materials.

445 [Figure 16 here]

446 [Figure 17 here]

447

448 Regarding the undisturbed samples (Figure 18), the index of dispersion of Gel
449 Push-A is larger than Gel Push-B, which may be related to the different dominant
450 particle sizes (noting that A has considerably fewer fines than B). The index of
451 dispersion of reconstituted samples also tends to lie between Gel Push-B and A, which
452 supports the idea that fines content (which is intermediate), plays a role, although the
453 dispersion measure is meant to enable populations with different means to be directly
454 compared. Further analysis of this measure is needed to enable population comparisons
455 of different particle sizes to be more directly made.

456 [Figure 18 here]

457 The lack of a distinct difference between the gel push and reconstituted samples
458 suggests that the undisturbed samples in this study are little structured. This is not
459 altogether surprising considering that large strains will have been applied to the soil
460 during the main earthquake shocks on 4th September 2010 (Darfield Earthquake, Mw
461 7.1) and 22nd February 2011 (Canterbury Earthquake, Mw 6.3, which caused

462 liquefaction at the site) – as shown schematically in Figure 19. The soil also continued
463 to be disturbed during the many aftershocks that occurred until sampling, with a notable
464 aftershock series (Mw 6.3) occurring on 13th June 2011. In addition, although care was
465 taken to minimize the disturbance during the sampling (on 5th August 2011),
466 transportation, laboratory handling and final testing (on 13th August 2011), some degree
467 of disturbance may have occurred. Taylor et al (2012) evaluated the quality of gel push
468 samples by comparing the shear wave velocity from the laboratory (bender element test)
469 and from field tests (downhole seismic test). The comparison showed close agreement
470 between them, indicating high sample quality. However, when the laboratory data was
471 normalized by the field data, they reported that undesirable strain may still be induced
472 in samples taken. From this, it seems that time “zero” at which aging would commence
473 can be taken, at the earliest, from the date of the Canterbury Earthquake when the site
474 was liquefied but could be as late as the date of sampling.

475 [Figure 19 here]

476 **Conclusions**

477 Methods and challenges in quantifying the microstructure of sand containing fines and
478 time dependent microstructural changes have been described. Based on circular statistical
479 analysis, it is seen that the microstructure of undisturbed natural silty sands and dry
480 deposition silty sand samples have a very similar preferred horizontal orientation, as
481 expected. Parameters previously used for clean sands to statistically measure particle
482 spatial relationships, namely mean log spacing, variance, and kurtosis were rigorously
483 examined for their application to silty sands. In doing so, a new parameter, index of
484 dispersion (variance to mean ratio) applied to the spacing distribution was found to be
485 better than kurtosis to unambiguously indicate a more interlocked structure, thus a more
486 aged sample according to the theory of mechanical interlock. As determined by the index

487 of dispersion increasing with age, the loading of reconstituted samples under K_0 condition
488 resulted in particles clustering together over time up to a week, with this trend being
489 greater in dense than in loose soil. This may be due to void collapse in loose soil
490 dominating creep behaviour, in contrast to particle clustering via void growth dominating
491 in dense soil. This behaviour reflects similar findings from the field that indicates granular
492 soil ageing to be greater in dense than in loose soil.

493 It was seen that it may be difficult to directly apply the index of dispersion
494 measure to compare the ages of samples of different particle size distribution. That is,
495 the values found for the reconstituted samples, which had an intermediate level of fines
496 (15%), tended to lie between that of Gel Push-B (35%) and Gel Push-A (4%) field
497 samples of the same age. This means that dispersion is influenced by the PSD, albeit in
498 a systematic manner. Hence, further work is needed to identify how this parameter or a
499 combination of parameters can be developed to enable such comparisons to be directly
500 made

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508 Sciences).

Table 1. Fabric tests conducted

No	Test ID	Method	Dr	σ'_v (kPa)	K_0	Period of constant load
1	Gel Push-A	UD	na	80	na	1 hour
2	Gel Push-B	UD	na	50	na	1 hour
3	Lab C_70601H_DD	DD	70	113	0.53	1 hour
4	Lab C_70601W_DD	DD	70	113	0.53	1 week
5	Lab C_40601H_DD	DD	40	125	0.48	1 hour
6	Lab C_40601W_DD	DD	40	125	0.48	1 week

DD=Dry deposition; UD=Undisturbed from gel push sampling Dr= Relative density; na=not available

Table 2. Fines content (<75 μm) from PSD and Image Analysis

Test	Description	Measured fines content (%)	
		PSD	Image Analysis
Gel Push-A	Undisturbed sample	4	5.4
Gel Push B	Undisturbed sample	35	52.8
Lab C 40601H_DD	Loose – 1 hour aged	15	20.4
Lab C 40601W_DD	Loose – 1 week aged	15	17.4
Lab C 70601H_DD	Dense – 1 hour aged	15	28.3
Lab C 70601W_DD	Dense – 1 week aged	15	25.5

Table 3. Fischer statistical result

Sample		$\alpha_m(^{\circ})^*$	κ
Gel Push-A	All	87.8 \pm 1.2	0.53
	Sand size	88.9 \pm 0.9	0.60
	Fines size	81.9 \pm 3.0	0.33
Gel Push-B	All	89.1 \pm 0.7	0.52
	Sand size	87.3 \pm 0.9	0.80
	Fines size	89.1 \pm 0.6	0.51
Lab C 40601H_DD	All	86.5 \pm 1.1	0.42
	Sand size	86.5 \pm 0.8	0.65
	Fines size	87.1 \pm 1.3	0.29
Lab C 40601W_DD	All	89.6 \pm 0.8	0.40
	Sand size	90.5 \pm 0.8	0.68
	Fines size	88.2 \pm 1.7	0.25
Lab C 70601H_DD	All	84 \pm 0.9	0.36
	Sand size	81.2 \pm 0.9	0.63
	Fines size	87.9 \pm 1.6	0.24
Lab C 70601W_DD	All	89.1 \pm 0.8	0.42
	Sand size	87.5 \pm 0.9	0.63
	Fines size	91.5 \pm 1.4	0.30

Note: *Angle measured from vertical clockwise

Table 4. Spatial void distance results for gel push and reconstituted samples

Sample	Image 'Fines' content (%)	Void ratio	Mean log spacing		Kurtosis		Index of dispersion	
			V	H	V	H	V	H
Gel Push-A	5.4	0.73 3	1.281	1.325	0.620	0.585	0.185	0.188
Gel Push-B	52.8	0.72 6	0.944	1.028	0.660	0.695	0.151	0.157
Lab C 40601H_DD	20.4	0.87 3	1.064	1.079	0.745	0.770	0.179	0.173
Lab C 40601W_DD	17.4	0.85 2	1.051	1.088	0.787	0.699	0.186	0.174
Lab C 70601H_DD	28.3	0.68 4	1.056	1.097	0.681	0.623	0.167	0.165
Lab C 70601W_DD	25.5	0.68 7	1.087	1.125	0.759	0.684	0.182	0.182

Note: V=vertical; H=Horizontal;

Table 5. Spatial void distance results for Gel push and reconstituted samples – small particles less than 75µm ('Fines') removed from images

Sample	Image 'Fines' removed (%)	Void ratio	Mean		Kurtosis		Dispersion	
			V	H	V	H	V	H
Gel Push-A	5.4	0.827	1.38 0	1.42 9	0.53 4	0.46 0	0.183	0.183
Gel Push-B	52.8	2.191	1.70 1	1.74 2	0.43 7	0.43 7	0.208	0.224
Lab C 40601H_DD	20.4	1.248	1.49 2	1.49 9	0.32 1	0.20 2	0.175	0.176
Lab C 40601W_DD	17.4	1.188	1.47 7	1.52 3	0.33 1	0.27 6	0.181	0.184
Lab C 70601H_DD	28.3	1.174	1.52 3	1.56 9	0.26 7	0.16 8	0.167	0.164
Lab C 70601W_DD	25.5	1.132	1.47 3	1.51 2	0.32 5	0.37 8	0.177	0.181

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