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Assessment of tamping-based specimen preparation methods on static liquefaction of loose silty sand

Zhehao Zhu^{a,b}, Feng Zhang^{a*}, Jean-Claude Dupla^a, Jean Canou^a, Evelyne Foerster^b, Qingyun Peng^a

^aEcole des Ponts ParisTech, Laboratoire Navier/CERMES, 6-8 av. Blaise Pascal, 77455 Marne La Vallée cedex 2, France

^bCommissariat à l'énergie Atomique, DEN, DANS, DM2S, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

*Corresponding Author:

Feng Zhang

Ecole des Ponts ParisTech

Laboratoire Navier/CERMES, 6-8 av. Blaise Pascal, 77455 Marne La Vallée cedex 2, France

Email: feng.zhang@enpc.fr

27 Abstract

28 Dry and moist tamping methods are widely used for the investigation of sandy soil liquefaction.
29 However, the effect of these two tamping-based reconstitution methods on composite soil liquefaction
30 behavior have been rarely assessed. In this study, the dry and moist tamping methods were assessed
31 using loose silica sand matrix (HN31) containing various amounts of non-plastic silt particles (C500),
32 and by performing a series of undrained triaxial compression tests. Microstructural observations using
33 a high-resolution optical microscope were also performed on loose silty sand specimens that had the
34 similar initial states to those for the undrained triaxial tests. Triaxial results show that for silty sand
35 specimens prepared by dry tamping method, a global dilatant behavior was observed and the
36 undrained shear strength decreased as the fraction of silt particles increased. By contrast, a total
37 reversed phenomenon was observed for those prepared by moist tamping method: all specimens
38 showed more or less limited liquefaction behavior and silt particles mitigated the contractive tendency,
39 which provided beneficial contribution to the undrained shear strength. Microstructural observations
40 show that in the dry tamping method, overall structure formed by the host sand and silt particles was
41 regularly deposited, promoting a more stable strain-hardening response. Moreover, some silt particles
42 were found to be located near sand-sand contact points, significantly loosening the sand matrix. On the
43 contrary, by using moist tamping method, the sand was uniformly covered by bulked silt particles, and
44 the aggregated sand formed the metastable structure, facilitating the occurrence of static liquefaction.
45 Moreover, with the increase of fines fraction, this metastable structure was weakened, characterized by
46 the filling of large inter-sand voids, leading to the increase of undrained shear strength. Thus, a critical
47 value of total fines fraction F_c^{Tot} equalling to 21% was determined, which theoretically verified the
48 insignificant effect of specimen preparation methods on the undrained shear strength. In that case, the
49 metastable structure in specimen prepared by moist tamping method was expected to disappear and the
50 overall response of specimen changed from the dominance of host sand to that of fines.

51 Keyword: Dry and moist tamping methods, silty sand, undrained triaxial compression test,
52 microstructural observation

53 1. Introduction

54 Research activities in clean sand liquefaction have been initiated since the occurrence of two
55 destructive earthquakes in Alaska (United States) and Niigata (Japan) in 1964 that caused tremendous
56 disasters. Substantial understandings of liquefaction characteristics reported in the literature, whether
57 subjected to monotonic or cyclic loadings, are mainly based on reconstituted specimens in triaxial
58 apparatus in laboratory research. As for clean sand, it was found that relative density and confining
59 pressure were two determinant indicators incorporated in the framework of state parameter to delineate
60 between liquefiable and non-liquefiable deposits [1–5]. More importantly, while fixing the test
61 conditions (e.g., relative density and confining pressure) using the same materials, the preparation
62 methods (e.g., dry and moist tamping methods) have also significant effect on liquefaction
63 characteristics: the moist tamping facilitates the occurrence of liquefaction due to the formation of
64 metastable structure, whilst no risk of flow liquefaction by dry tamping due to the absence of
65 metastable structure [6–11].

66 Nevertheless, a large number of in-situ investigations showed that liquefied sand layer usually
67 contained some fine particles [12,13], especially non-plastic silt content. This explains why, in
68 laboratory research, the impact of fine particles based on distinct specimen preparation methods (e.g.,
69 dry and moist tamping methods) did draw numerous attentions. It was found that with the addition of
70 fines at low fraction, the liquefaction resistance could either increase [14–18] or decrease [19–21].
71 Attempts were made to explain the above controversial phenomena from the plasticity index, grain
72 shape and gradation characteristic of the added fines, as well as the relative mean size of fine particles
73 to that of host sand [22–25]. In the case of sand-fines specimens prepared by moist tamping method,
74 Pitman [15] reported that the liquefaction resistance of Ottawa reference sand was enhanced by adding
75 both plastic Kaolinite and non-plastic crushed quartz particles, which is also consistent with the
76 conclusions drawn by other researchers that the undrained shear strength of specimens formed in
77 submerged condition increased with the increase of fines fraction [14,16–18]. On the contrary, in dry
78 condition, Zhu [25] examined the liquefaction of loose HN31 sand mixed with plastic Kaolinite/Illite
79 particles and non-plastic Silt particles, and observed that the presence of fines reduced the undrained

80 shear resistance in all cases and a good correlation existed between mean diameter ratio (D_{50}/d_{50} , D_{50}
81 and d_{50} represent the mean diameters of the HN31 sand and added materials, respectively) and
82 undrained shear strength ($S_u=q_{max}/2$). Similar conclusions about this adverse impact of fine particles in
83 dry condition have been repeatedly obtained by others [19–21]. Moreover, Wood [26] performed
84 undrained compression tests on Nevada Sand containing non-plastic silt by altering specimen
85 preparation methods (e.g., tapped funnel deposition, water sedimentation, slurry deposition, mixed dry
86 deposition and air pluviation). With respect to uniformity, visual segregation between the host sand
87 and silt was observed for specimens formed by water sedimentation and air pluviation. Furthermore,
88 the effect of depositional method was reported to be a function of density index: (i) more significant
89 for specimens especially at lower densities; (ii) less important for specimens at higher densities. In its
90 accompanying paper, Yamamuro [27] discussed the effect of two depositional methods (between dry
91 funnel and water sedimentation) on the corresponding microstructure and experimentally found that (i)
92 specimens formed by dry funnel deposition were more prone to liquefaction; (ii) whilst, specimens
93 formed by water sedimentation were much more stable upon shearing. As fines fraction increased, a
94 reasonable explanation was proposed in conjunction with a special procedure allowing the
95 microstructure to be quantitatively analyzed: in dry funnel method, specimens contained a higher
96 percentage of unstable grains contacts as compared with those formed by water sedimentation method
97 [27]. To the authors' knowledge, the role of added fines to undrained shear strength is quite different
98 in distinct preparation methods, as well as whether the metastable structure can be formed under the
99 effect of fines in moist condition (as for clean sand), have not been well understood yet, and further
100 investigation is thus needed. From practical and academic points of view, clarifying the role of fine
101 particles in two commonly used tamping-based specimen preparation methods (e.g., dry and moist
102 tamping methods) would be also helpful to well understand the mechanism behind in different
103 methods.

104 In this study, a series of undrained triaxial tests was performed on loose silty sand specimens
105 prepared by dry and moist tamping methods at different fines fractions. Microstructural observations
106 using a high-resolution optical microscope were also performed on loose silty sand specimens that had
107 the similar initial states to one of the specimens prepared for the undrained triaxial tests, allowing the

108 mechanism behind, as well as the different roles of fines to be identified in dry and moist tamping
109 methods.

110 2. Materials and methods

111 2.1. Materials

112 All tests in this experimental programme were performed on a commercially available reference sand
113 named Huston 31 (HN31) with a mean grain size $D_{50} = 0.35$ mm and a specific gravity of $G_s = 2.65$.
114 The added material is a non-plastic silt flour: C500 with a mean grain size $d_{50} = 0.006$ mm and a
115 specific gravity of $G_s = 2.65$. Note that the HN31 host sand and C500 silt have very similar colours:
116 grey-white for HN31 and white for C500 since they are both primarily composed of quartz
117 ($\text{SiO}_2 > 99\%$). The grain size distribution curves measured by laser diffraction is shown in Fig. 1. The
118 principle of the method is that while passing through a laser beam, a particle could scatter the light at a
119 certain angle and intensity that related to its grain size [23]. Detailed index properties of the used
120 materials are tabulated in Table 1.

121 The maximum void ratios (e_{\max}) of HN31-C500 mixture at each fines fraction were determined,
122 in air-dried state, by using a funnel to introduce well-mixed soil into a constant volume container.
123 Note that, during this procedure, the falling rate needed to be as slow as possible in order to achieve a
124 low-energy deposition in which a loosest configuration could be attained. As for minimum void ratios
125 (e_{\min}) that represent the possible densest compacting configuration, the well-mixed soil was introduced
126 into a hand-held container in air-dried state and then subjected to alternative mechanical vibrations (at
127 the bottom of the container above a vibratory table). When no further settlement occurred, the
128 corresponding value could be calculated by postulating that the theoretical densest state has been
129 practically achieved. Fig. 2 presents e_{\max} , e_{\min} versus the total fines fraction
130 ($F_c^{\text{Tot}} = (m_{\text{C500}} / (m_{\text{C500}} + m_{\text{HN31}})) \cdot 100\%$) determined on air-dried HN31-C500 mixtures [18], where m_{C500} ,
131 m_{HN31} stand for the dry mass of added C500 silt and host HN31 sand, respectively. As for e_{\min} in
132 connection with the densest state of composite soil, two phenomena can be identified in Fig. 2: (i) with
133 the initial addition of fine particles, e_{\min} decreased; (ii) with the further addition of fine particles,

134 especially after a threshold value, e_{\min} tended to gradually increase [28]. This is because at low fines
135 fraction, sand skeleton was formed and coarse sand grains remained in contact with each other. In that
136 case, fine particles primarily filled the skeleton voids (see Fig. 3a), resulting in the decrease in e_{\min} . By
137 contrast, at higher fines fraction, sand grains started to disperse in fines matrix (see Fig. 3b), resulting
138 in the increase in e_{\min} [28]. The characteristic value F_c^{Tot} (about 19% for HN31-C500) in Fig. 2 was
139 defined as the “transitional fines fraction” (TFC), at which the main soil matrix changed from sand-
140 dominance to fines-dominance [16,29]. On the contrary, as for e_{\max} representing the possible loosest
141 state in connection with the liquefaction collapsibility analysis, the curve steadily increased without
142 any drop [30,31]. This suggests that at this extremely loose state, a majority of added fines loosened
143 the sand matrix by separating coarse sand grains (**loosening effect**) instead of preferentially filling the
144 large skeleton empty voids (**densifying effect**) as observed in the evolution of e_{\min} in the case of F_c^{Tot}
145 smaller than 19%. It should be mentioned that some investigators (including [28,32–34])
146 experimentally observed an initial declining tendency of e_{\max} , very similar to the e_{\min} . This is probably
147 related with (i) gradation parameters of test material [28,32]; and (ii) different experimental
148 methodologies for extreme void ratio (e_{\min} and e_{\max}) determination [33].

149

150 2.2. Depositional method

151 Several well-documented earthquakes suggested that, at liquefied site, the silt particles commonly
152 existed with limited percentage [12,35]. It can be logically deduced that the silty sand is still
153 dominated by coarse sand but polluted by a small quantity of fines. In that case, the impact of low
154 percentage non-plastic silt particles is then of major interest while assessing the liquefaction
155 collapsibility of loose silty sand. For this purpose, the void ratio of sand matrix (see Fig. 4a) instead of
156 global void ratio (see Fig. 4b) was considered as controlled parameter in the preparation stage by
157 adopting the density index of sand matrix [18,36]: $I_{D\text{mat}}=(e_{\max}-e_{\text{mat}})/(e_{\max}-e_{\min})$, where e_{mat} is the void
158 ratio of sand matrix and e_{\max} , e_{\min} represent the maximum and minimum void ratios of clean HN31
159 sand [37], respectively. A clear benefit of this concept is the ability to keep the quantity of sand
160 forming the global soil matrix exactly constant, irrespective of the fines fraction (see Fig. 4a). It

161 should be mentioned that density index of sand matrix has been also termed “sand skeleton void ratio”
162 by Polito [38] and Dash [39]. A loosest state of $I_{Dmat}=0.00$ (or $e_{mat}=1.00$) favouring liquefaction
163 collapsibility analysis was selected in the present work. The fines fraction ($F_c=(m_{C500}/m_{HN31})\cdot 100\%$)
164 was defined as the dry mass of added fines divided by that of the host sand matrix.

165 2.2.1 Tamping-based specimens preparation methods

166 Dry tamping

167 Air pluviation is a common technique to prepare uniform loose specimens for liquefaction
168 collapsibility analysis [37]. However, air pluviation of well-graded soil is not as successful as that of
169 poorly graded soil. This is because the well-graded soil such as binary silty sand (e.g., $D_{50}\gg d_{50}$) may
170 become significantly segregated when deposited by pluviation through air, as coarse grains fall faster
171 than fine particles [40]. In order to overcome this non-uniform problem, dry tamping was thus adopted
172 as an alternative. The silty sand specimens (100 mm in diameter and 200 mm in height) were prepared
173 by 10 layers. In each layer, two materials were mixed by shaking in an enclosed container. Afterwards,
174 they were carefully introduced into a membrane-lined spilt mould by spooning. During this operation,
175 particular attention should be paid to minimize the particles drop height in order to: (i) reduce the
176 potential energy as much as possible to create very loose specimens; (ii) avoid any possible
177 segregation between coarse and fine grains during freefall. It is worth noting that, although extreme
178 attempts were made in this method, it was still difficult to create silty sand specimens with extremely
179 low fines fraction (e.g., $F_c<3.5\%$) in very loose state. This is because the composite soil layer after
180 spooning did not fairly satisfy the thickness requirement (2 cm in height for each layer) for further
181 compaction. Thus, 3 relatively high fines fractions were selected: 5%, 10% and 15%. The good
182 repeatability of this dry tamping method has been reported by Zhu [25] who performed the two
183 parallel undrained triaxial tests with the addition of either plastic (Speswhite) or non-plastic (C500)
184 fines, as well as by Jradi [17], who performed both monotonic and cyclic triaxial tests on NE34 sand-
185 Speswhite mixtures.

186

187 Moist tamping

188 Moist tamping has been widely employed in many experimental investigations of liquefaction
189 [2,6,9,15–17]. This method provides a clear benefit: it is readily able to create very loose specimens
190 with capillary force, which is viewed as beneficial particularly in liquefaction analysis, where
191 extremely contractive responses are desirable. As for composite soil in this research, the technique
192 consisted of mixing the sand and silt particles in a large blender in partially submerged condition
193 created by adding 5% water (by weight) to the total dry mass. The total mixtures were afterwards
194 divided into 10 layers to fabricate a triaxial specimen of 100 mm in diameter and 200 mm in height.
195 Each layer was consecutively poured in a membrane-lined split mould and compacted to a required
196 thickness (2 cm) using a hand-held tamper before the next layer was placed. Note that, while keeping
197 sand matrix unchanged with the gradual addition of fine particles, the latex membrane did not allow
198 very strong compaction effect. Thus, 5 relatively low fines fractions were respectively selected: 0%,
199 1%, 2.5%, 5% and 10%.

200

201 2.2.2. Summary of other sandy specimen preparation methods

202 Dry funnel deposition

203 Owing to the practical convenience, dry funnel deposition is another common technique to prepare
204 silty sand specimens in laboratory research [3,32,41]. The composite soil (after mixing either in
205 blender or by spoon) is placed into a large funnel, which is afterwards slowly raised in the split mould
206 along the specimen axis of symmetry. The movement of the funnel needs to be minimized (similar to
207 dry tamping method) in order to cancel the freefall of composite soil, which eventually leads to the
208 segregation phenomenon. Specimen of higher density could be achieved by means of (i) tapping the
209 split mould in a symmetrical pattern; (ii) raising the funnel more quickly (still without a drop height
210 [26]).

211

212 Slurry deposition

213 For the purpose of mimicking a natural fluvial or hydraulic fill deposit and of overcoming inherent
214 problem related to segregation phenomenon, an innovant technique called the slurry deposition
215 method has been develop by Kuerbis [40] and Carraro [42] since the method is capable to reconstitute
216 exceptionally homogeneous specimens in terms of void ratio and particles size gradation, regardless of
217 fines fraction. Slurry deposited specimens are firstly boiled (e.g., in a flask the night before testing) in
218 order to achieve a fully saturated condition. Afterwards, a special mixing tube is needed prior to the
219 placement of soil [26] rather than directly depositing soil into the split mould. After this mixing tube is
220 filled with de-aired water, the flask containing the boiled soil is inverted and lowered through a top
221 central hole of the mixing tube to introduce the soil by removing the cap of the flask. A series of small
222 rotations (about one hour) is indispensable to the mixing tube during this process to create a uniform
223 distribution. In the final step, the triaxial cell base and split mould are respectively installed onto the
224 mixing tube, and the mixing tube could then be carefully removed leaving the sandy specimen in the
225 split mould with the aid of an extension component (on the mixing tube) [26]. It is worth noting that
226 sandy specimens are initially prepared in a very loose state, and uniformly densified specimens could
227 be obtained by inducing mechanical vibration.

228

229 Water sedimentation

230 In water sedimentation method, sandy specimen is initially put in a large flask half filled with water,
231 which is then boiled (similar to slurry deposition method) in order to remove undesirable air bubbles
232 and latter filled up with de-aired water. Prior to placing sandy specimen into split mould: (i) the mould
233 and all drainage lines connecting to specimens need to be seriously saturated by de-aired water; (ii) the
234 capped flask needs to be thoroughly rotated in order to achieve a satisfactory homogeneity. The flask
235 is then inverted and lowered as much as possible to the bottom of the split mould. While the specimen
236 is still located in the split mould, mechanical vibration is a common way to achieve higher density
237 [3,43].

238

239 3. Triaxial tests programme

240 In this study, the specimens were prepared by two tamping-based methods (the dry and moist tamping
241 methods); once the specimens had been formed, the top base was placed and carefully sealed with two
242 O-rings. A slight vacuum between 15-20 kPa was then applied to prevent specimen collapse while
243 removing the split mould, as well as to check the leakage of fragile latex membrane. The saturation of
244 the specimens was carried out as a three-steps process. Firstly, the carbon dioxide (CO₂) was
245 percolated through the specimen for about 15 min in order to replace the air since CO₂ dissolved much
246 more easily in water. Secondly, de-aired water was flushed to saturate the specimens. It should be
247 noted that the flux of CO₂ gas and de-aired water were controlled as low as possible in order not to
248 disturb the soil structure during the saturation phase. Finally, the confining pressure and back pressure
249 were increased in equal incremental step of 20 kPa, until they were respectively equal to 300 kPa and
250 200 kPa. In all tests, the Skempton's B value ($B=\Delta u/\Delta\sigma_{\text{conf}}$) was equal to or greater than 0.98. This
251 value was believed to be high enough to achieve full saturation of sandy soil. Afterwards, drainage
252 valves were closed and the specimen was sheared at a constant rate of 0.5%/min in axial strain (ϵ_a).
253 The equilibrium of pore water pressure during shearing was verified by the measurements at both top
254 and base parts of specimen. All tests were generally terminated after the axial strain reached about 20%
255 and performed at a controlled ambient temperature of 20 ± 1 °C. The q_{max} was defined as the
256 maximum shear strength during the axial strain range of 0-20%. Note that, the axial load was
257 measured using an internal load cell to eliminate the need to consider any ram friction that may
258 remarkably affect the measurement of deviator stress especially in terms of liquefaction study of
259 loosely prepared sandy soil. Details of the triaxial tests are summarized in Table 2. Note that identical
260 tests are also included in two companion papers [18,25], respectively.

261

262 4. Microstructural tests programme

263 As mentioned previously, the colours of two test materials (grey-white and white) are highly similar
264 due to the similar mineral composition ($\text{SiO}_2 > 99\%$). In that case, it seems difficult to distinguish the
265 coarse and fine particles, especially in relatively small scale. Hence, for the purpose of distinction, the

266 HN31 sand was, in particular, dyed blue using a commercially available colorant (Basacid Blue 762
267 liquid supplied by BASF), as shown in Fig. 5. Afterwards, fresh dyed sand was carefully placed in a
268 huge oven for more than an hour at a constant temperature of 105 °C to further maintain its colour.
269 Finally, the grain size distribution curve of coloured HN31 sand was roughly re-measured by classic
270 dry-sieving, and results showed that neither particles size change nor sand grain aggregation occurred
271 during the dyeing procedures described above.

272 In order to represent as much as possible the initial fabric of silty sand specimens
273 corresponding to the one of specimens installed into the triaxial apparatus before the saturation phase,
274 the composite soil was deposited in a cylindrical cup of 70 mm in diameter and 14 mm in height (see
275 Fig. 6a) by dry and moist tamping methods, respectively. Microstructural observations were
276 performed using a high-resolution optical microscope (see Fig. 6b). Due to the intrinsic constraints in
277 two reconstitution methods as mentioned previously, microstructural observations were only
278 performed on two fines fractions: 5% and 10%.

279

280 5. Triaxial test results

281 Fig. 7 schematizes the triaxial tests of silty sand specimens reclaimed by dry tamping method at three
282 fines fractions. The evolution of q described in Fig. 7a shows that (i) all the three curves
283 monotonically rise without any downward tendency, showing an extremely strong dilatant behavior;
284 (ii) after the initial increase in pseudo-elastic stage ($\varepsilon_a < 0.5\%$ [18]), q almost linearly increased till the
285 end of test (q_{\max} at $\varepsilon_a = 20\%$). In addition, the deviator stress decreased with the increase of fines
286 fraction, which could serve as evidence that the addition of fine particles changed the overall soil
287 mechanical response. As for evolution of Δu identified in Fig. 7b, after a very short contractive phase
288 ($\dot{\Delta u} > 0$), all specimens were characterized by a remarkable dilatant phase ($\dot{\Delta u} < 0$) where the
289 dissipation of Δu became increasingly important as the fines fraction decreased. The above two
290 phenomena suggest that: (i) the collapsibility of silty sand specimens reconstituted in dry state was
291 very low; (ii) the increase in fines fraction could, to some extent, increased the collapsibility potential.

292 Fig.8a shows the evolution of deviator stress (q) against axial strain (ϵ_a) of silty sand specimens
293 reclaimed by moist tamping method. In the case of clean sand specimen ($F_c=0\%$), the q firstly
294 increased and then significantly decreased after a peak value, exhibiting a very strong liquefaction
295 collapsibility potential. By contrast, in the cases of silty sand at $F_c=1\%$, 2.5% , 5% and 10% , the
296 specimens could re-gain the undrained shear resistance after a short-lived temporary reduction and this
297 beneficial phenomenon became much more conspicuous at higher fines fractions, indicating that the
298 addition of fine particles mitigated the strain-softening collapsibility. Regarding the evolution of
299 excess pore water pressure against axial strain identified in Fig. 8b, it can be observed that, for clean
300 sand specimen ($F_c=0\%$), Δu increased continually and reached the highest value Δu_{max} of about 98 kPa
301 at the end of test, exhibiting a pure contractive response. By contrast, for silty sand specimens at
302 $F_c=1\%$, 2.5% , 5% and 10% , all Δu tended to decrease after a peak value Δu_{max} , showing a dilatant
303 response. Thus, the role of added silt fines could be distinguished in two stages: (i) before Δu_{max} , the
304 increase in fines fraction inhibited the fast generation of Δu ; (ii) after Δu_{max} , the increase in fines
305 fraction facilitated the dissipation of Δu . The above two phenomena proved that, the response of clean
306 sand reclaimed by moist tamping method was liquefiable with a comparatively high collapsibility
307 potential, but with the addition of fines, silty sand became much less collapsible. Also, the above
308 results (moist tamping method) are opposite to the phenomena observed in Fig. 7a for specimens that
309 were reclaimed by dry tamping method, suggesting that the specimen preparation method has a
310 significant effect on the static liquefaction behaviour of loose silty sand. Moreover, at the same fines
311 fraction, the undrained shear strength in moist tamping method was found to be lower than that in dry
312 tamping method, indicating the high collapsibility in specimen created by moist tamping method.

313

314 6. Microstructural observations

315 Fig. 9a and Fig. 9b display the microstructural observations of silty sand stacked up in dry state at two
316 fines fractions of 5% and 10% , in which the black/white/blue regions graphically represent the inter-
317 sand voids (black), the stacked up C500 silt (white) and the coloured HN31 sand (blue), respectively.

318 It can be observed from two images that the added fine particles not only filled the inter-sand voids,
319 but also located nearby the sand-sand contact points by separating them [44]. In that case, the host
320 sand was placed in a regular manner, forming a relatively stable internal voids system. The results in
321 Fig. 9a and Fig. 9b could further explain why the maximum void ratio e_{\max} determined on air-dried
322 composite soil nonlinearly increased with fines fraction (see Fig. 2): (i) there was always an increasing
323 number of fine particles stuck between host sand, leading to the sustaining loosening of the overall soil
324 structure; consequently, the e_{\max} rapidly increased with the addition of fine particles; (ii) with the
325 addition of fine particles before TFC (about 19%), still a little fine particles filled the inter-sand voids,
326 leading to the slow increase of e_{\max} . On the contrary, in the case of fines fraction higher than TFC, the
327 inter-sand voids were expected to be fully filled up with fines, leading to the fast increase of e_{\max} .
328 Similarly, Fig. 10a and Fig. 10b show the microstructural observations for silty sand prepared by moist
329 tamping method at fines fractions of 5% and 10%, respectively. It appears from the two figures that: (i)
330 fines were bulked together, and this phenomenon became more pronounced as fines fraction increased;
331 (ii) the coarse sand was covered by the bulked fines [15] with very few fines falling in the inter-sand
332 voids, which might be attributed to the capillary force while employing moist tamping method; (iii)
333 the coarse sand with the fines were generally in contact with each other, and the initial fabric of this
334 composite soil was irregular and primarily governed by aggregated coarse sand forming large
335 metastable macropores in such a loose state. This observed metastable structure for silty sand mixtures
336 is similar to that in clean sand specimen that was previously defined as “bulked sand” or “honeycomb-
337 structure” by Casagrande [11].

338

339 7. Discussion

340 As regards the impact of fine particles observed in this study, the undrained shear resistance decreased
341 as the fines fraction increased by employing dry tamping method, while a total reversed phenomenon
342 was observed in the case of moist tamping method. Moreover, at the same fines fraction, the undrained
343 shear resistance in dry tamping method was found to be higher than that in moist tamping method.
344 Obviously, the different phenomena in the former might be attributed to the different roles of fines,

345 while in the latter might be due to the different soil arrangements created by two preparation methods
346 since all other controlled factors in the experimental procedure (e.g., I_{Dmat} , σ'_c and I_p of fines employed)
347 were kept exactly identical.

348 For a clear exposition, representation of different structures of silty sand created by dry and
349 moist tamping methods are shown in Fig. 11 and Fig. 12, where large hollow and small solid circles
350 represent the host sand and the silt grains, respectively. In the case of silty sand reclaimed by dry
351 tamping in Fig. 11, the silt particles not only (i) fill the inter-sand voids, but also (ii) locate nearby the
352 sand-sand contact points by separating them since the mean diameter of C500 silt is about 6 μm , being
353 far smaller than that of host HN31 sand (350 μm). In the former case, the fine particles make no actual
354 mechanical contribution to the soil response and could be viewed as inactive since they are totally free
355 to shift. This is consistent with the conclusion drawn by Finn [45] that liquefaction brittleness is
356 irrespective of fine particles completely accommodated within inter-sand voids. In the latter case,
357 these silt particles initially loosen the host sand grains by separating them and facilitate the contractive
358 sliding of host sand [25] as well as inhibit the dilatant response when subjected to an imposed shearing
359 effort, especially in such a loose state ($I_{Dmat}=0.00$). And this weakening effect could be expected to be
360 much conspicuous at higher fractions. As a result, the deviator stress decreased with the increase of
361 fines fraction, as shown in Fig. 7a. As for overall host sand structure, the regularly placed soil fabric
362 (as compared with “metastable” macropores that presents in the moist tamping method in Fig. 10)
363 normally promotes an overall stable behavior and the limited quantity of silt grains in this study
364 ($F_c < 15\%$) could not sufficiently suppress the inherent dilatant tendency of this stable structure. Soon
365 after shearing, the silt grains in the latter case (weakening) commence to fall into inter-sand voids.
366 Concurrently, the host sand grains come into firmer contact with each other [32] and the weakening
367 effect of silt grains becomes much less important as loading continues. It should be also noted that (i)
368 the relatively low confining pressure (100 kPa) used in the present work normally supports a more
369 dilatant tendency [17,37]; (ii) the adoption of density index of sand matrix (or skeleton void ratio)
370 ensures that the degradation of host sand matrix due to the addition of fine particles (as compared with

371 the global void ratio) cannot occur as explained in the foregoing section. By combining the above
372 reasonings, a global strain-hardening response identified in Fig. 7a could then be expected.

373 In the case of silty sand reclaimed by moist tamping depicted in Fig. 12, the presence of
374 macropores (or large inter-sand voids) makes the composite soil exhibiting an extremely high
375 collapsibility potential and these macropores tend to decrease in volume upon loading, leading to more
376 generation of excess pore water pressure under undrained condition, as compared with that
377 reconstituted by dry tamping method. Subsequently, the overall soil becomes prone to liquefaction [6].
378 This could be the reason why composite silty sand reconstituted in submerged state exhibits a more or
379 less strain-softening response, as clearly identified by Fig. 8a. It is worth noting that, the silt particles
380 attached to the sand surface created during the preparation of specimen may fall into the inter-sand
381 voids due to the disappearance of capillary force after saturating. Due to the inherent limitation of
382 high-resolution optical microscope, it seems impossible to obtain the photo for fully saturated silty
383 sand (with back pressure) prior to shearing. However, it does not alter the fact that the metastable
384 structure could be weakened with the increase in silt particles due to the following two factors: (i) in
385 the initial state, the mechanical property of sand matrix is kept almost constant (sand grains still in
386 contact) even with the presence of fine particles since they are mostly attached to host sand; (ii) during
387 the saturation phase, the filling of large inter-sand voids (macropores) becomes increasingly more
388 important, mitigating the collapsibility of macropore. From a macro perspective, this weakening effect
389 owing to the addition of silt particles on metastable structure (or the clog of inter-sand voids) could
390 also be justified in triaxial conditions by: (i) the moderated decline tendency of deviator stress (see Fig.
391 8a) with axial strain after a peak value of deviator stress; (ii) the inhibited generation of excess pore
392 water pressure (see Fig. 8b) at small axial strain range, at which the soil structure could be represented
393 by the initial one. Moreover, during shearing, host coarse sand tends to contract each other; they could
394 possibly slide over the residual small-size silt particles surrounding them [18]. This fines-induced
395 separating effect favours, in particular, the dilatant movement between two successive sand grains,
396 leading to more rapid dissipation of Δu at higher fines fraction (see Fig. 8b).

397 According to the above analysis, it could be logically deduced that if the large inter-sand voids
398 (forming the metastable structure) created in the moist tamping method are totally filled up with silt
399 particles, the static liquefaction would not occur. In that case, the deviator stress obtained in the moist
400 tamping would be very close to that in the dry tamping method. To verify this point, the q_{\max} against
401 the total fines fraction (F_c^{Tot} in Table 2) of silty sand specimens reclaimed by two methods is
402 schematized in Fig. 13. It is worth noting that to compare with the evolution of e_{\min} with F_c^{Tot} in Fig. 2,
403 the total fine fraction F_c^{Tot} is used in Fig. 13 as comparison basis. It can be observed that q_{\max} linearly
404 increased in moist tamping method and decreased in dry tamping method. By fitting with two straight
405 lines, a critical value F_c^{Tot} of about 21% was obtained at the intersection point, which is in good
406 agreement with the TFC (approximately 19%) determined on air-dried sand-fines mixture, as shown in
407 Fig. 2. This confirms that the large inter-sand voids forming the metastable structure was the main
408 reason why liquefaction collapsibility was observed in the specimen prepared by moist tamping, and
409 this metastable structure could be further gradually weakened by the addition of silt particles,
410 characterized by the filling of large inter-sand voids.

411 It is worth noting that the above mechanism may not be appropriate for the following cases: (i)
412 with higher fines fraction ($F_c^{\text{Tot}} > \text{TFC}$) while the global void ratio is used as comparison basis; (ii)
413 dense silty sand specimen; (iii) with the addition of highly expansive clayey fines. In the first case, a
414 decrease in undrained shear resistance with the addition of fines (e.g., fines fractions exceeded 30%)
415 was reported by Erten [46] while using moist tamping method. This could be explained by the
416 degradation of sand matrix. During the reconstitution stage, in order to keep global void ratio
417 unchanged, the addition of fines significantly reduced the quantity of sand matrix (see Fig. 3a and 4a)
418 providing the main shear resistance, and this adverse phenomenon became increasingly conspicuous at
419 higher fines fraction, which certainly weakened the global granular structure. In the second case,
420 Wood [26] performed undrained compression tests on Nevada Sand containing non-plastic silt and
421 revealed that the effect of specimen preparation on the shear strength was negligible for specimens at
422 higher densities. This may be attributed to the disappearance of metastable structure formed in the
423 submerged state. In the last case, by examining sandy specimens with the addition of natural fines and

424 bentonite (e.g., $I_p=98$) reclaimed by moist tamping method, Abedi [47] reported that increasing a small
425 amount of fines fraction made the specimens to sustain more instability in the small range of fines
426 fraction. This phenomenon could be explained by the following two independent factors: (i) even with
427 a small amount of water in moist tamping method, the clayey fine particles such as bentonite were
428 highly sensitive to stick together and created aggregated structure, which rendered composite
429 specimen non-uniform; (ii) swelling pressure generated from bentonite during the saturation phase
430 introduced a non-negligible change of σ'_c . To the authors' knowledge, this variation linking to the
431 addition of highly expansive fines remains an open question, and more studies are still needed.

432

433 Conclusion

434 In this study, the effect of two tamping-based specimen preparation methods was assessed using loose
435 silica sand matrix containing various amounts of non-plastic silt, and by performing a series of
436 undrained triaxial compression tests. For further analysis, microstructural observations were also
437 conducted on loose silty sand specimens. The results obtained allow the following conclusions to be
438 drawn:

- 439 1. When employing dry tamping method, the overall granular structure is very regular exhibiting
440 a strong dilatant behaviour. In the case of mean diameter of silt being much smaller than that
441 of host sand, there are always some parts of silt particles stuck between the adjacent sand
442 grains, facilitating the relative contractive sliding of loose host sand. As a result, the deviator
443 stress decreased as the silt fraction increased, exhibiting much less strain-hardening response.
- 444 2. When employing moist tamping method, due to the presence of large inter-sand voids forming
445 the metastable structure, liquefaction collapsibility was observed. With the addition of silt
446 particles, this metastable structure was weakened, characterized by the filling of large inter-
447 sand voids, leading to the increase of liquefaction resistance.

448

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452 optical microscope is also gratefully acknowledged.

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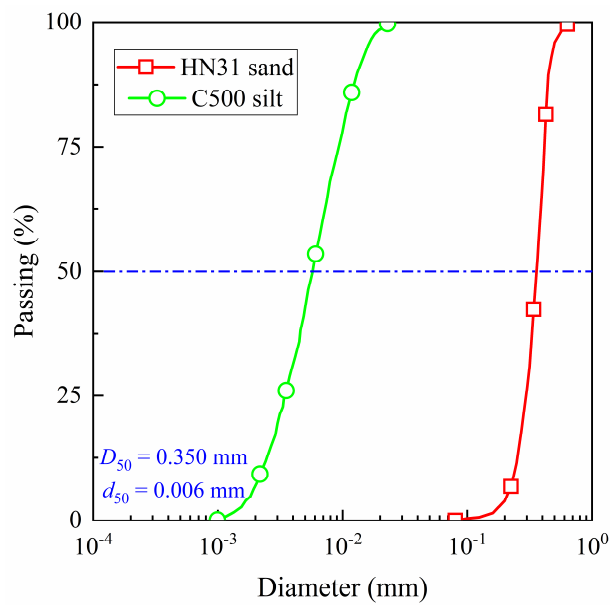
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563 Figures and Tables

564 Figure 1 Grain size distribution curves for HN31 sand and non-plastic C500 silt



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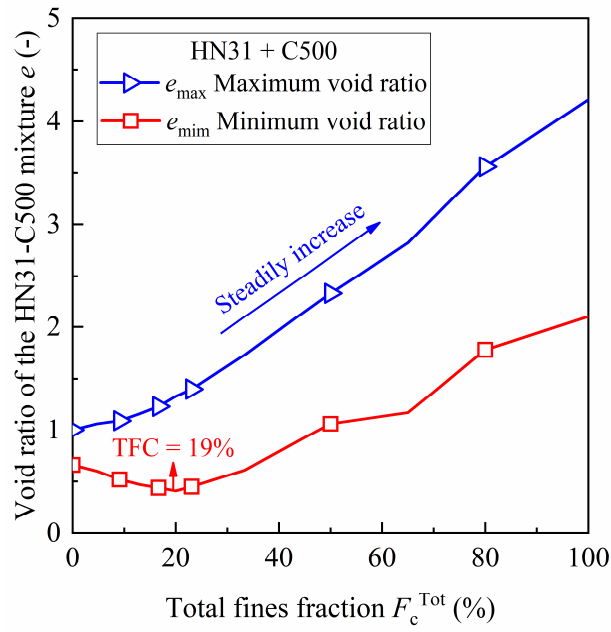
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572 Figure 2 Evolution of maximum and minimum void ratios of HN31-C500 mixtures with the addition
573 of C500 silt (after [18])



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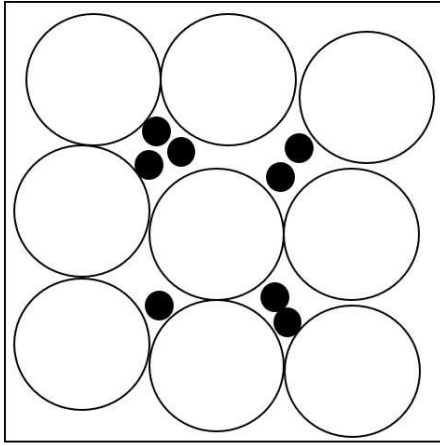
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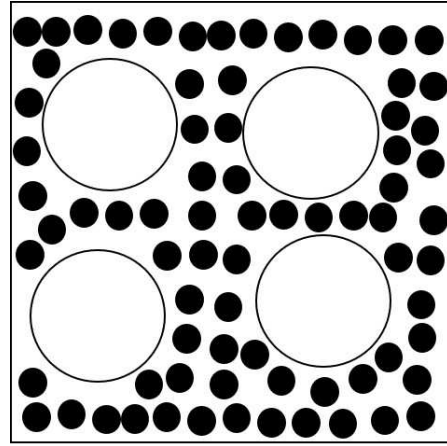
587 Figure 3 Configurations of sand containing fines: (a) sand-dominance ($F_c^{Tot} < TFC$); (b) fines-
588 dominance ($F_c^{Tot} > TFC$) (after [18])

(a) sand-dominance



$$F_c^{Tot} < TFC$$

(b) fines-dominance



$$F_c^{Tot} > TFC$$

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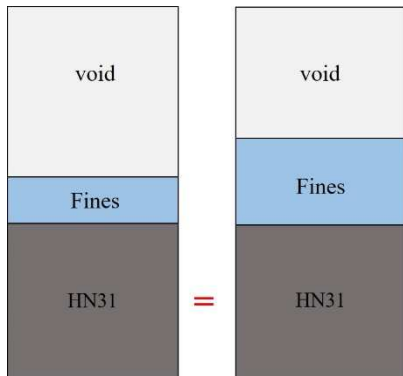
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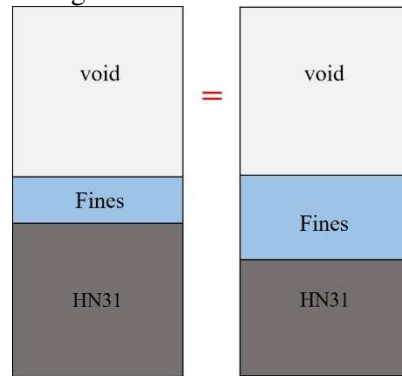
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602 Figure 4 Concept of (a) constant sand matrix; (b) constant global void ratio (from [25])

(a) constant sand matrix



(b) constant global void ratio



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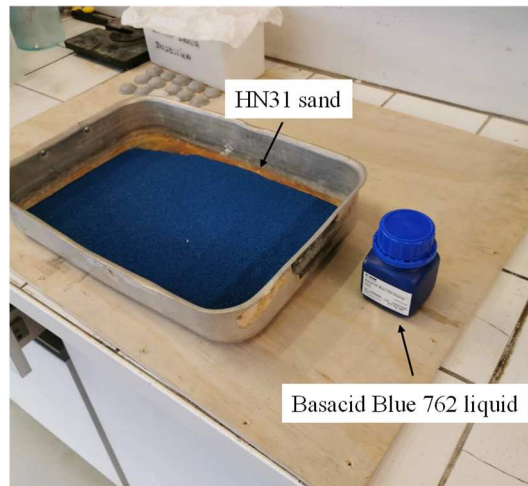
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618 Figure 5 HN31 sand coloured by Basacid Blue 762 liquid



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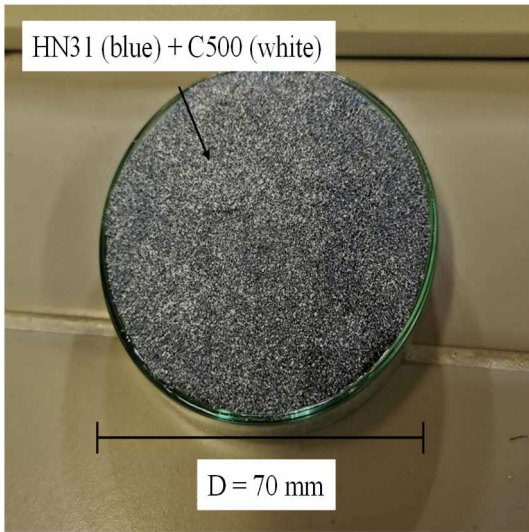
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634 Figure 6 (a) Silty sand specimen with coloured HN31 sand; (b) high-resolution optical microscope

(a)



(b)



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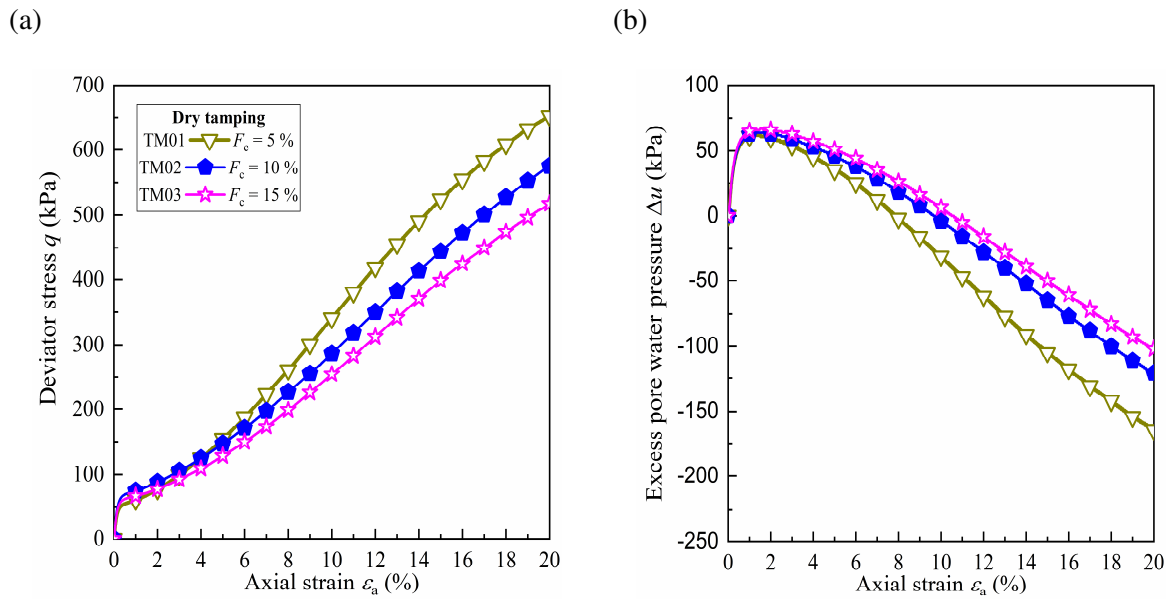
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648 Figure 7 Triaxial test results of silty sand specimens in very loose state at various fines fractions of
649 confining pressure equalling to 100 kPa reclaimed by dry tamping: (a) deviator stress against axial
650 strain; (b) excess pore water pressure against axial strain (from [25])



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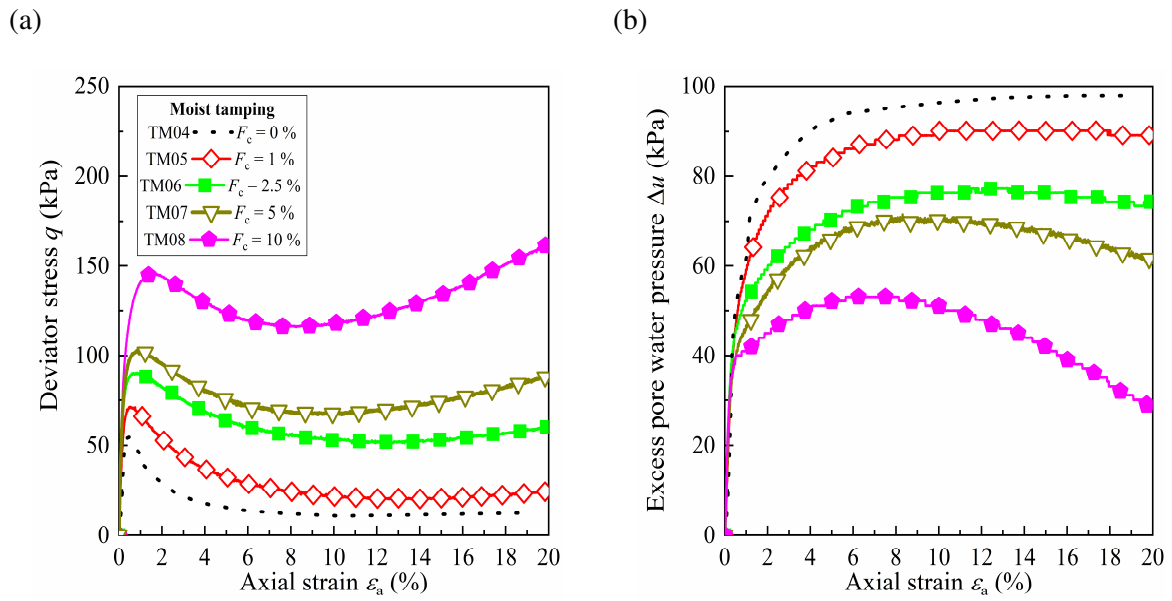
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663 Figure 8 Triaxial test results of silty sand specimens in very loose state at various fines fractions of
 664 confining pressure equalling to 100 kPa reclaimed by moist tamping: (a) deviator stress against axial
 665 strain; (b) excess pore water pressure against axial strain (from [18])



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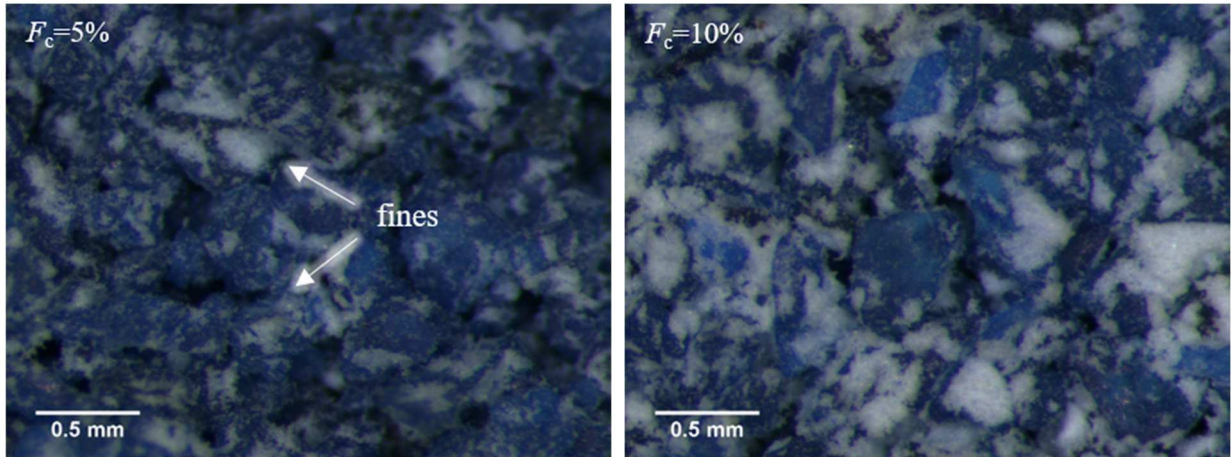
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679 Figure 9 Microstructural observations of silty sand specimens in very loose state reclaimed by dry
680 tamping at (a) $F_c=5\%$; (b) $F_c=10\%$

(a)

(b)



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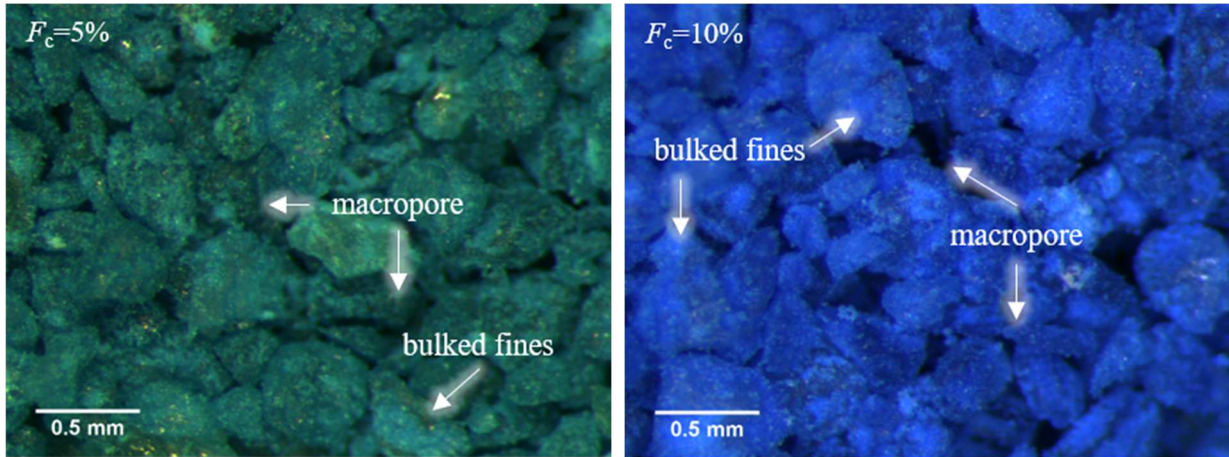
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695 Figure 10 Microstructural observations of silty sand specimens in very loose state reclaimed by moist
696 tamping at (a) $F_c=5\%$; (b) $F_c=10\%$

(a)

(b)



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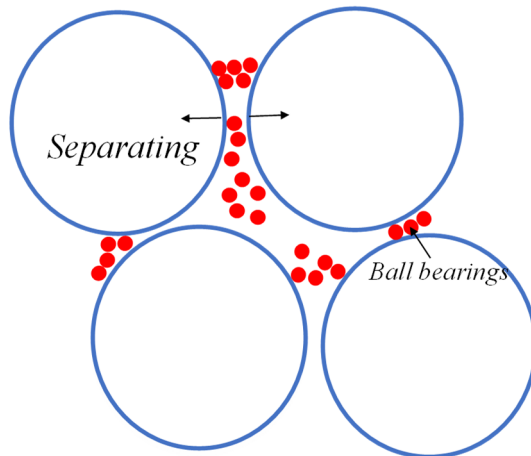
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Figure 11 Schematic diagram of hypothesized silty sand fabric reconstituted by dry tamping



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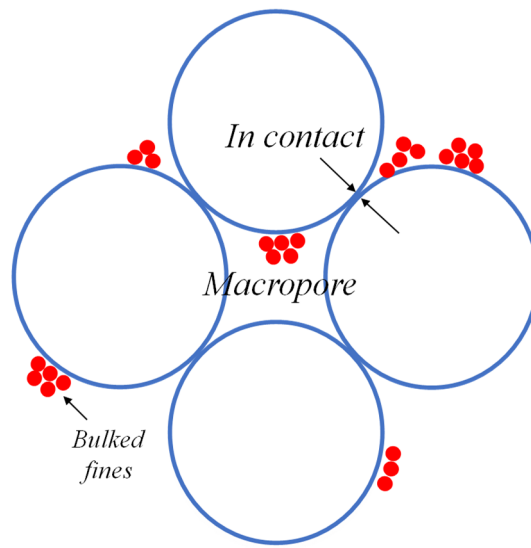
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Figure 12 Schematic diagram of hypothesized silty sand fabric reconstituted by moist tamping



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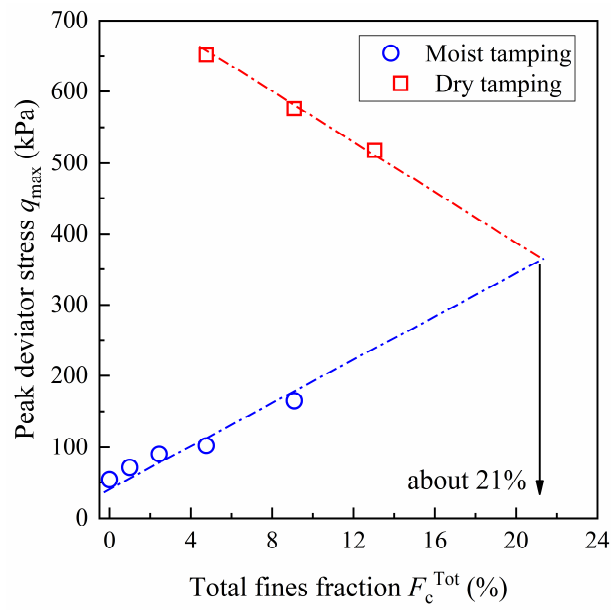
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Figure 13 Evolution of peak deviator stress against total fines fraction



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758 Table 1 Index properties of test materials

Material	D_{50} or d_{50} (μm)	D_{10} or d_{10} (μm)	C_u	e_{\min}	e_{\max}	G_s	I_p
HN31	350	250	1.57	0.656	1.00	2.65	NP (non-plastic)
C500	6	2	3.15	-	-		

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777 Table 2 Details of triaxial tests programme

Reference	F_c (%)	F_c^{Tot} (%)	Depositional method	I_{Dmat}	σ'_c (kPa)
TM01	5.0	4.8	D ⁽ⁱ⁾		
TM02	10.0	9.1	D		
TM03	15.0	13.0	D		
TM04	0.0	0.0	M ⁽ⁱⁱ⁾	0.00	100
TM05	1.0	1.0	M		
TM06	2.5	2.4	M		
TM07	5.0	4.8	M		
TM08	10.0	9.1	M		
Note	D ⁽ⁱ⁾ : Dry tamping				
	M ⁽ⁱⁱ⁾ : Moist tamping				

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