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1 Consequences of scalping and scalping/replacement
2 procedures on strength properties of coarse-grained
3 gap-graded soils

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Abstract

10 Evaluation of shear strength characteristics of coarse-grained soils by performing labora-
11 tory tests resorts often to a scalping or scalping/replacement procedure due to the presence of
12 oversized particles in comparison with the device size. This work aims to study consequences
13 of these two procedures on the resulting shear strength characteristics. Experimental tests
14 are performed on soils having gap-graded particle size distributions by using triaxial appa-
15 ratuses with small and medium diameters $\Phi = 50$ and 100 mm. Original soils are mixtures of
16 fine particles (sand and glass beads) and coarse particles (two types of gravel). The original
17 soils are scalped and/or scalped/replaced by two different procedures. Different factors that
18 influence the mechanical properties of the scalped and scalped/replaced soils in comparison
19 with those of the original soils are analyzed: (i) the compactness parameter controlled for
20 scalped and scalped/replaced soils, (ii) the fine content of the original soils and (iii) the
21 procedure used for the scalping/replacement.

22 *Keywords* : Coarse-grained soils, scalping, scalping/replacement, mechanical behavior,
23 triaxial device.

24 1 Introduction

25 Coarse-grained soils are characterized by widely graded particle size distributions. For this
26 particular class of soils, large grains (stone, gravel) coexist with fine particles (sand, silt, clay).
27 Rock fill, alluvial soils, till, sandy and/or silty gravels are examples of coarse-grained soils.
28 They are widely used as construction materials for embankment dams, dikes, subgrade of roads,
29 banks, etc. However, the measurement of the mechanical properties of these granular soils
30 requires triaxial apparatuses or shear boxes whose dimension must be sufficiently larger than
31 the maximum particle diameter. According to ASTM standard (ASTM D4767–88 1988), the
32 ratio of the specimen diameter Φ to the maximum particle diameter d_{\max} must be bigger than 6.
33 AFNOR - Association Française de Normalisation (1994) requires this ratio Φ/d_{\max} to be bigger
34 than 5 for widely graded soils and 10 for uniformly graded soils. For instance, Hu et al. (2011)
35 used a large triaxial device to perform triaxial tests on rock fill specimens whose diameter can
36 go up to 1 m. It is worth mentioning that only a few geotechnical laboratories in the world are
37 equipped with such large devices. It is very tedious to prepare large specimens and perform tests.
38 In addition, it is not easy to guarantee the homogeneity of large samples and the repeatability
39 of their strength properties. Geotechnical laboratories are often equipped with experimental
40 apparatuses such as triaxial cells and shear boxes whose diameter rarely exceeds 300 mm. When
41 using these apparatuses to test coarse-grained soils, the ratio Φ/d_{\max} is often reduced as much
42 as possible. Nevertheless, some studies pointed out that the shear strength depends on this ratio
43 Φ/d_{\max} although it fulfills the experimental standards. Reiffsteck et al. (2007) performed triaxial
44 tests on the same soil with $d_{\max} = 25$ mm but with two different triaxial devices of $\Phi = 150$
45 and 300 mm. At almost the same dry density, the authors found that under drained conditions,
46 the cohesion c' and the internal friction angle φ' obtained with the device $\Phi = 300$ mm, *i.e.*,
47 $\Phi/d_{\max} = 12$, are significantly lower ($c' = 9$ kPa and $\varphi' = 36^\circ$) than those obtained with the
48 device $\Phi = 150$ mm, *i.e.*, $\Phi/d_{\max} = 6$ ($c' = 44$ kPa and $\varphi' = 39^\circ$). Moreover, a shear band
49 was clearly observed for the smaller specimen, while it was not observed for the bigger one. In
50 fact, the specimen size has an important effect on formation of shear bands as found by Jefferies
51 et al. (1990). Omar & Sadrekarimi (2015) also observed a decrease in the friction angle of sand
52 as the specimen size increases. The last authors recommended to test specimens of diameters

53 no less than $117d_{\max}$ to obtain accurate mechanical properties of sands. However, this value
54 of Φ/d_{\max} is too high and unfeasible for testing coarse-grained soils whose maximum particle
55 diameter can be several centimeters, even several decimeters. In most experimental studies, the
56 specimen diameter is 10 times bigger than the maximum particle diameter. On the contrary,
57 numerical simulations based on the DEM (discrete element method) showed that the specimen
58 size beyond a certain value has a negligible effect on the shear strength (Huang et al. 2014). This
59 might be due to the fact that the periodic or rigid boundary conditions used in DEM simulations
60 prevent formation of shear bands.

61 In this context, with the aim to perform tests on coarse-grained soils with apparatuses avail-
62 able in the laboratory, the scalping and scalping/replacement procedures are often used. The
63 scalping consists in removing all the oversized grains from a given original soil and then re-
64 constituting specimens with the remaining fraction, while the scalping/replacement replaces the
65 oversized grains by an equal mass of smaller grains. While these procedures are usually used to
66 evaluate strength properties of coarse-grained soils, no clear experimental standard has been well
67 established so far. To the best of our knowledge, only some recommendations on preparation of
68 specimens for compaction tests on soils with particles larger than 50.8 mm [2 inches sieve size]
69 can be found in the manual established by U.S Army Corps of Engineers (1970) (Appendix VIA).
70 Consequences of these specimen reconstitution procedures on obtained strength properties have
71 not been well understood yet. In addition, a consensus has not been reached yet to choose a
72 compactness parameter to be controlled for the scalped or scalped/replaced specimen in com-
73 parison with that of the original soil, while this parameter is determinant of the obtained shear
74 strength. Different parameters have been actually considered: (i) the absolute dry unit weight
75 γ_d (Reiffsteck et al. 2007), (ii) the relative dry unit weight $\gamma_d/\gamma_{d,\max}$ (Leslie 1963, Donaghe &
76 Torrey III 1985), (iii) the relative density D_R (Al-Hussaini 1983, Dano 2001) or (iv) the dry unit
77 weight $\gamma_d^{\text{retained}}$ of the retained fraction in the original soil (El Dine 2007). The scalping procedure
78 has been extensively studied by several authors who showed divergent conclusions. It has been
79 shown that the scalping procedure can lead to an underestimation (Al-Hussaini 1983, Donaghe
80 & Torrey III 1985, Reiffsteck et al. 2007, El Dine 2007), an overestimation (Dano 2001, Dorador
81 & Villalobos 2020) or a good estimation (Leslie 1963) of the shear strength of coarse-grained
82 soils. A few studies on the scalping/replacement procedure have been carried out; and, like the

scalping one, the conclusions about this procedure are contradictory (Donaghe & Torrey III 1985, Reiffsteck et al. 2007, Hamidi et al. 2012). It should be noted that the reconstituted soils are different from the original soil so their mechanical properties cannot be expected to be the same as those of the original soil. Nevertheless, when the scalping or scalping/replacement procedure is necessary to evaluate the mechanical properties of a given coarse-grained soil, it is important to minimize this difference and manage consequences of the employed procedure on the obtained strength properties. Therefore, several questions remain still open. (i) Which procedure should be used for a given soil? (ii) Which compactness parameter needs to be controlled for the scalped or scalped/replaced specimen? (iii) If the scalping/replacement procedure is adopted, what is the material that can be used to replace oversized particles, particularly regarding to the particle size gradation and particle properties? The main objective of this research is to contribute to answering these complex questions for gap-graded cohesionless soils which have not been well studied in the literature. Sands and glass beads are used for the fine fraction and two types of gravel are used for the coarse fraction. Both scalping and scalping/replacement procedures are used with two different ways of controlling the compactness state of reconstituted soils. Triaxial apparatuses with small and medium diameters 50 and 100 mm are used to perform shear tests. We start by presenting the principle of the scalping and scalping/replacement procedures, compactness parameters that can be controlled for the scalped and scalped/replaced soils, and some knowledge issued from the literature about the effects of fine content and of the particle size gradation of the coarse fraction on the behavior of gap-graded soils. These elements are essential to understand the consequences of the scalping and scalping/replacement procedures. Next, the tested materials, the apparatuses used for this study as well as the experimental procedure are presented. Based on the experimental results, we analyze the influences of different factors on the behavior of the scalped and scalped/replaced soils such as the controlled compactness parameter, the fine content of the original soils and the scalping/replacement procedure used.

108 2 Framework of the scalping and scalping/replacement

109 2.1 Principle of the methods

110 Let α be the adopted admissible value of the ratio of the specimen size Φ to the maximum
111 particle diameter d_{\max} . The term “oversized particles” is used to refer to all the particles whose
112 diameters are greater than Φ/α . Three procedures are commonly used to overcome issues due to
113 these oversized particles. (1) The scalping procedure consists in removing all oversized particles
114 and preparing the specimen from the remaining material. (2) All oversized particles are replaced
115 by an equal mass of smaller particles by using the scalping/replacement procedure. (3) A model
116 soil is prepared with a grain size distribution (GSD) parallel to that of the original soil according
117 to the parallel gradation procedure. A parallel GSD is obtained by dividing particle diameters d_X
118 in the original GSD (X stands for cumulative percentages by mass) by a constant value greater
119 than 1. Figure 1 illustrates GSDs given by the three mentioned procedures in comparison with
120 the original GSD of a soil. It is worth mentioning that the parallel gradation procedure requires
121 also similarities in terms of compactness state and particle properties such as particle shape,
122 surface roughness and resistance to crushing. It is, in reality, very difficult, even impossible to
123 guarantee these similarities. Firstly, for the coarse-grained soils that contain a fraction of very
124 fine sand or silt, these finest materials cannot be replaced by another materials with the same
125 nature in the parallel GSD. As a consequence, the parallel GSD is sometimes cut off at the
126 minimum particle diameter d_{\min} as illustrated in Figure 1. Secondly, as particles in a natural
127 soil are heterogeneous, similarities in terms of particle shape and surface roughness between the
128 natural soil and the model soil are hardly guaranteed. Thirdly, the model soil suffers less grain
129 breakage during shearing than the original soil as the resistance of particles to crushing tends
130 to decrease with the particle size (Varadarajan et al. 2003). As a consequence, the behavior of
131 the model soil is different from that of the original soil. Several authors found that the shear
132 strength of the model soil is higher than that of the original soil (Marschi et al. 1972, Thiers
133 & Donovan 1981, Varadarajan et al. 2003). On the contrary, Hamidi et al. (2012) found that
134 the model soil with a parallel gradation has a shear strength significantly lower than that of an
135 original sandy gravel.

136 The scalping procedure is quite simple; however, it leads to a strong change in the GSD of the

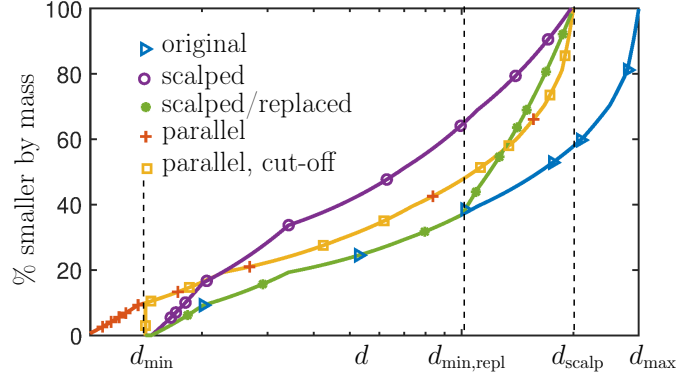


Figure 1: GSDs given by different reconstitution methods: parallel GSD, cut-off parallel GSD, scalping and scalping/replacement in comparison with the original one.

137 tested material (see Figure 1). U.S Army Corps of Engineers (1970) recommended the scalping
 138 procedure for testing coarse-grained soils when less than 10% by mass of the original soil is re-
 139 moved; above this value, a replacement is necessary. The key point in the scalping/replacement
 140 procedure is selection of the replacement material and its gradation. According to the scalp-
 141 ing/replacement procedure of U.S Army Corps of Engineers (1970) for testing soils with maxi-
 142 mum admissible particle diameter of 50.8 mm [2 inches sieve size], the replacement material must
 143 be taken in the fraction between 50.8 mm and 4.76 mm [No. 4 sieve size] in the original material
 144 and its gradation must be the same as that of this fraction. To extend this scalping/replacement
 145 procedure to a general coarse-grained soil, we need to introduce a parameter $d_{\min,\text{repl}}$ that is the
 146 minimum particle diameter for the replacement material (see Figure 1). This parameter can be
 147 considered as the limiting particle diameter to separate the coarse fraction from the fine one. For
 148 a gap-graded soil, the fine and coarse fractions are clearly separated; however, no clear rule has
 149 been established to select the value of $d_{\min,\text{repl}}$ for a continuous GSD. The main advantage of the
 150 scalping/replacement procedure in comparison to the scalping one is that it allows us to preserve
 151 the GSD of the original soil until the diameter $d_{\min,\text{repl}}$, and then the fine content of the original
 152 soil (see Figure 1). Deiminiat et al. (2020) presented a review about different reconstitution
 153 methods to determine the shear strength of coarse-grained soils. In the following, we focus our
 154 study on gap-graded cohesionless soils. As already mentioned, the boundary between the fine
 155 and coarse fractions can be easily defined for this particular kind of soils. Moreover, the fine

156 content is one of the most determinant parameters of their shear strength.

157 2.2 Control of specimen density

158 The specimen density has a key influence on the soil mechanical strength so it is important to
 159 choose a proper density parameter to be controlled for the scalped and scalped/replaced samples
 160 in comparison to that of the original soil. A gap-graded coarse-grained soil is composed of a fine
 161 fraction and a coarse fraction which can be, in turn, split into an oversized fraction ($d > d_{scalp}$)
 162 and an admissible fraction ($d \leq d_{scalp}$) as illustrated in Figure 2.a. The density of such a
 163 material can be described by several void ratios as proposed by Thevanayagam & Mohan (2000):
 164 the global void ratio e , intergranular void ratio e_c for the coarse fraction and interfine void ratio
 165 e_f for the fine fraction.

$$e = \frac{V^v}{V^s}, \quad e_c = \frac{V^v + V_f^s}{V_c^s} = \frac{e + f_f}{1 - f_f} \quad \text{and} \quad e_f = \frac{V^v}{V_f^s} = \frac{e}{f_f}, \quad (1)$$

166 where V^v and V^s are the respective void and solid volumes; V_f^s and V_c^s are the respective solid
 167 volumes of the fine and coarse fractions; and f_f is the fine content defined as $f_f = V_f^s/V^s$ (see
 168 Figure 2.b).

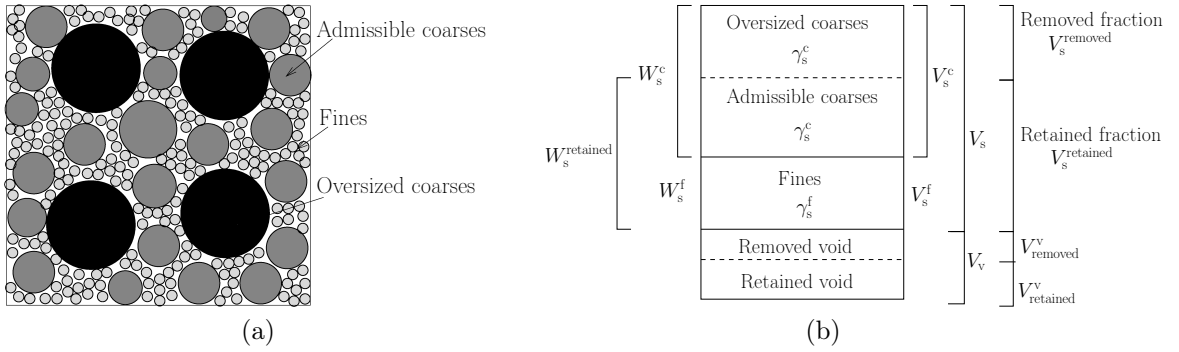


Figure 2: (a) Different fractions in a gap-graded coarse-grained soil, and (b) its phase diagram.

169 The retained fraction ($d \leq d_{scalp}$) in the original soil has a void ratio $e_{retained}$ defined as:

$$e_{retained} = \frac{V_{retained}^v}{V_{retained}^s}, \quad (2)$$

170 where $V_{\text{retained}}^{\text{s}}$ is the total solid volume of the retained fraction (fines and admissible coarses) and
 171 $V_{\text{retained}}^{\text{v}}$ is the void volume which is actually located between retained grains (see Figure 2.b).
 172 In fact, the total void volume comprises two parts: the void volume $V_{\text{retained}}^{\text{v}}$ between retained
 173 grains and the void volume $V_{\text{removed}}^{\text{v}}$ located at the interface between retained and oversized
 174 grains. When the oversized grains are removed, this associated void space should therefore be
 175 removed. However, it is very difficult to quantify the latter void volume; as a consequence, the
 176 void volume $V_{\text{retained}}^{\text{v}}$ is usually assumed to be equal to the total void volume V^{v} . It follows that

$$e_{\text{retained}} = \frac{V^{\text{v}}}{V_{\text{retained}}^{\text{s}}} = \frac{e}{f_{\text{retained}}}, \quad (3)$$

177 where f_{retained} is the retained solid fraction: $f_{\text{retained}} = V_{\text{retained}}^{\text{s}}/V^{\text{s}}$. Siddiqi et al. (1987) found
 178 that the above assumption leads to a significantly higher void ratio for the retained fraction than
 179 the value it should have in the original soil as the void volume $V_{\text{removed}}^{\text{v}}$ between retained and
 180 removed grains is considerable.

181 Studies in the literature used different ways to control the compactness state of the scalped
 182 and scalped/replaced samples. Their void ratio is determined such that:

- 183 (i) It is equal to the void ratio e of the original sample;
- 184 (ii) It is equal to the void ratio e_{retained} of the retained fraction;
- 185 (iii) It corresponds to the same relative density D_{R} as that of the original sample

$$D_{\text{R}} = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}}, \quad (4)$$

186 where e_{max} and e_{min} are the maximum and minimum void ratios of the material under
 187 consideration.

188 In the following, cases (i), (ii) and (iii) are referred to as controls of e , e_{retained} and D_{R} ,
 189 respectively. In some studies, the dry density γ_{d} of the original soil and the dry density $\gamma_{\text{d,retained}}$
 190 of the retained fraction were controlled (Reiffsteck et al. 2007, El Dine 2007). If the solid density
 191 γ_{s} is the same for the fine and coarse fractions, controls of e and e_{retained} are equivalent to controls
 192 of respective γ_{d} and $\gamma_{\text{d,retained}}$. In addition, e_{retained} is only controlled for the scalped sample.

193 In this case, it is prepared at a void ratio bigger than that of the original sample as shown
 194 in Equation (2). Dano (2001) and Hamidi et al. (2012) controlled the relative density D_R for
 195 scalped and scalped/replaced samples of well graded soils. It was pointed out that the scalping
 196 overestimates the shear strength of the original soil (Dano 2001), while the scalping/replacement
 197 gives a good estimation of the original shear strength (Hamidi et al. 2012). It should be noted
 198 that a control of the relative density D_R requires determination of the maximum and minimum
 199 void ratios e_{\max} and e_{\min} for each soil. The procedures to determine e_{\max} and e_{\min} of coarse-
 200 grained soils encounter the same technical problems as for the strength measurement due to
 201 the presence of very coarse elements and necessitate also scalping or scalping/replacement to
 202 reconstitute specimens. In addition, these procedures might not be applicable for gap-graded
 203 coarse-grained soils as vibrating them can lead to particle size segregation. Last but not least,
 204 the relative density D_R cannot be defined for cohesive soils that contain a fraction of plastic fines
 205 such as silt and clay. Therefore, the relative density D_R is not considered in our study.

206 When a gap-graded soil is scalped, its fine content increases to a value $f'_f = f_f / f_{\text{retained}}$ where
 207 symbol ($'$) is used to depict characteristics for the scalped sample. The interfine void ratio e'_f of
 208 the scalped sample when e_{retained} is controlled is given as follows:

$$e'_f = \frac{e'}{f'_f} = \frac{e_{\text{retained}}}{f'_f} = \frac{e}{f_{\text{retained}} \cdot f'_f} = \frac{e}{f_f} = e_f. \quad (5)$$

209 Equation (5) means that although fine content is increased by the scalping, a control of e_{retained}
 210 (*i.e.*, $e' = e_{\text{retained}}$) allows us to preserve the interfine void ratio e_f in the scalped sample;
 211 however, the intergranular void ratio e_c is increased. On the contrary, when the global void ratio
 212 e is controlled to be the same for both scalped and original samples, the interfine void ratio e_f
 213 is decreased, while the intergranular void ratio e_c is increased by the scalping. Regarding the
 214 scalping/replacement procedure, it allows us to preserve the fine content f_f , interfine void ratio
 215 e_f and intergranular void ratio e_c in the scalped/replaced sample when the global void ratio
 216 e is controlled. The two effects induced by this procedure are a reduction in the GSD of the
 217 coarse fraction and a potential difference between the particle properties of the replacement and
 218 replaced materials.

219 As mentioned previously, the scalping leads to an increase in the fine content, while the

220 scalping/replacement leads to a reduction in the GSD of the coarse fraction. In the following, we
221 present some studies in the literature on these effects on the behavior of gap-graded soils. This
222 knowledge is vital to understand potential consequences of the scalping and scalping/replacement
223 procedures. By considering the aforementioned advantages of the control of global void ratio e ,
224 we focus the following analyses on this case.

225 **2.3 Optimum fine content**

226 For gap-graded soils, there exists an optimum fine content f_f^* at which the fines best fill the
227 void space between the coarses without displacing greatly the latter ones. As a result, the void
228 ratio e reaches its minimum value at this optimum fine content. Lade et al. (1998) determined
229 the maximum and minimum void ratios e_{\max} and e_{\min} of mixtures of fine and coarse sands with
230 different fine contents. Different types of fine and coarse sands were tested, and the gap-ratio
231 G_r of the tested mixtures (defined as the ratio of the minimum diameter d_{\min}^c of coarse grains
232 to the maximum diameter d_{\max}^f of fine grains) is varied up to 11. The authors found that both
233 e_{\max} and e_{\min} decrease with an increase in fine content f_f and reach their respective minimum
234 values at an optimum fine content f_f^* around 30%. Above this value, e_{\max} and e_{\min} increase
235 with fine content. Thevanayagam et al. (2002) also found that e_{\min} of a silty sand reaches its
236 minimum value at a fine content of 25%. Given that fine content of 30% was not considered in
237 this study, the optimum fine content could be around 30%. An optimum fine content around
238 30% was confirmed in several studies on mixtures of silt and sand (Papadopoulou & Tika 2008,
239 Belkhatir et al. 2010). Shire et al. (2016), Minh & Cheng (2016), Taha et al. (2019) simulated
240 mixtures of fine and coarse spheres with different fine contents and different values of the gap
241 ratio G_r up to 10 by using the DEM. These numerical studies also showed an optimum fine
242 content around 30%. No data is available for mixtures of sand and gravels. Nevertheless, it is
243 judicious to assume that the optimum fine content of these mixtures with the same range of
244 gap-ratio G_r is about 30%.

245 2.4 Effect of fine content on the shear strength

246 We analyze here the effect of fine content on the mechanical behavior of gap-graded soils under
247 the condition that the global void ratio e is controlled to be the same for whatever fine content.
248 It should be noted that in order to keep e constant when fine content f_f is increased, the
249 interfine void ratio e_f decreases (*i.e.*, the fine fraction gets denser), while the intergranular void
250 ratio e_c increases (*i.e.*, the coarse fraction gets looser). Thevanayagam et al. (2002) studied
251 the undrained shear strength of silty sands and sandy silts with different fine contents f_f (silt
252 content). The samples were compacted to reach as much as possible nearly the same void ratio
253 $e = 0.6$. However, the samples with $f_f = 25, 40$ and 60% are too weak at this value of e ; as
254 a result, they were prepared at substantially lower values of e . For example, the samples with
255 $f_f = 40\%$ were prepared at $e = 0.425$. It was found that the undrained shear strength of silty
256 sands with $f_f < 25\%$ decreases with an increase in fine content f_f . The shear strength is lowest
257 at $f_f = 25\%$. Although the silty sand with $f_f = 25\%$ was prepared at much lower void ratio
258 ($e = 0.46$) than that of the clean sand ($e = 0.6$), the silty sand shows a contractive behavior and
259 has a low shear strength, while the clean sand shows a dilative behavior and has much higher
260 shear strength. On the other hand, the shear strength increases when fine content f_f is increased
261 above 25% up to 100% . At nearly the same void ratio, a sandy silt is weaker than a pure silt.
262 This study pointed out that the fine content of 25% , which is close to the optimum fine content
263 of about 30% as already mentioned, constitutes a turning point in the relationship between the
264 shear strength and fine content for silty sands and sandy silts. Ali Hassan et al. (2021) simulated
265 triaxial drained tests on mixtures of fine and coarse spheres with different fine contents f_f by
266 using the DEM. This numerical study also showed that, at almost the same void ratio, the shear
267 strength of mixtures decreases with an increase in fine content $< 30\%$ but increases with fine
268 content $> 30\%$.

269 2.5 Effect of the GSD of the coarse fraction on the shear strength

270 El Dine et al. (2010) studied the influence of the GSD of the coarse fraction on the behavior of
271 matrix coarse-grained soils which are mixtures of sands and gravels. The grading parameter for
272 the coarse fraction defined as the ratio d_{\max}^c/d_{\min}^c (d_{\max}^c and d_{\min}^c are the respective maximum

273 and minimum diameters of coarse particles) was varied while keeping the interfine void ratio e_f
274 and the fine content f_f constant. In this case, the global void ratio e is the same for different
275 mixtures. Different gravel fractions were used with $d_{\max}^c/d_{\min}^c = 10/8, 60/30, 60/10$ and $60/4$. It
276 was found that the shear strength of the tested mixtures decreases, on the whole, as the grading
277 parameter d_{\max}^c/d_{\min}^c increases. The influence of the coarse GSD is small for $d_{\max}^c/d_{\min}^c \leq 6$ but
278 becomes significant above this value. The mixture with $d_{\max}^c/d_{\min}^c = 10/8$ shows, indeed, a much
279 higher shear strength than that of the mixture with $d_{\max}^c/d_{\min}^c = 60/4$. In addition, the effect
280 of the coarse GSD was found to be more marked for higher coarse content (lower fine content).
281 It is worth mentioning that the matrix coarse-grained soils considered in this study have fine
282 contents $> 50\%$; therefore, the coarse fraction plays a secondary role after the primary role of
283 the fine fraction. For soils with fine contents $< 50\%$, the effect of the coarse GSD would be more
284 marked.

285 Ali Hassan et al. (2021) simulated triaxial tests on numerical mixtures of fine and coarse
286 spheres with different values of $d_{\max}^c/d_{\min}^c = 9/6, 12/6$ and $18/6$ but at the same global void
287 ratio e . The results of these simulations confirm the experimental finding of El Dine et al.
288 (2010). However, the influence of the coarse GSD is significant even at lower values of the grading
289 parameter d_{\max}^c/d_{\min}^c . This might be explained by the fact that these numerical mixtures are at
290 30% of fine content, which is much lower than the values considered by El Dine et al. (2010).
291 In addition, it is not easy to dissociate completely the grading parameter from other parameters
292 such as particle properties when performing experimental tests, while the numerical simulation
293 with the DEM enables this dissociation. The above experimental and numerical studies point
294 out that the shear strength of gap-graded soils at the same global void ratio e tends to increase
295 as the coarse GSD is reduced.

296 3 Materials, apparatuses and experimental procedure

297 3.1 Tested materials

298 Triaxial tests were performed on mixtures of fine and coarse particles. Fontainebleau sand,
299 which is a silica sand located in the region of Etampes in France, was used for the fine fraction

300 with particle diameter d between 0.01 mm and 0.6 mm. To study the effect of the shape and
 301 roughness of fine particles, Fontainebleau sand was replaced by glass beads with the same GSD.
 302 The coarse fraction is constituted of Palvadeau gravel coming from a quartz quarry in France
 303 for the fraction 2.4/5 and a natural gravel for the fraction 5/10. Palvadeau gravel is subangular,
 304 while natural gravel is angular. In the following, Fontainebleau sand, glass beads, Palvadeau and
 305 natural gravels are abbreviated as FS, GB, PG and NG, respectively.

306 Triaxial tests are first performed on each elementary material to determine their friction
 307 angle. Table 1 shows the global void ratio e , the coefficient of uniformity C_u and the drained
 308 friction angle φ' at the peak and residual states for Fontainebleau sand and the two gravels PG
 309 and NG. With the aim to see the effect of the particle properties (shape and surface roughness)
 310 on the shear resistance of each gravel, all their samples were prepared with parallel GSDs having
 311 almost the same value of C_u and at almost the same void ratio e as shown in Table 1. It is shown
 312 that the natural gravel (NG) with sharp corners is more resistant to shearing than Palvadeau
 313 gravel, *i.e.*, NG has a higher peak friction angle (47.8°) than that of PG (42°).

Table 1: Minimum and maximum diameters d_{\min} and d_{\max} , global void ratio e , coefficient of uniformity C_u and drained friction angle φ' for FS, PG and NG.

Material	d_{\min}/d_{\max} (mm/mm)	e	C_u	φ' ($^\circ$)	
				peak	residual
Fontainebleau sand (FS)	0.01/0.6	0.542	2.32	40.6	33.9
Palvadeau gravel (PG)	2.4/5	0.537	1.45	42.0	36.7
Natural gravel (NG)	5/10	0.554	1.45	47.8	36.8

314 Original soils with different fine contents (20, 30, 45 and 60%) are prepared by mixing the
 315 above elementary materials. Each original soil is named by its composition followed by its
 316 maximum particle diameter d_{\max} in mm. For example, the original soil FS30PG40NG30_10
 317 contains 30% by mass of Fontainebleau sand (FS), 40% by mass of Palvadeau gravel (PG),
 318 30% by mass of natural gravel (NG) and has a maximum particle diameter of 10 mm. Each
 319 original soil is scalped and/or scalped/replaced. For the scalping/replacement, the oversized
 320 particles can be replaced by either the whole remaining coarse fraction (scalping/replacement
 321 1) or by only the class of particles whose diameters are closest to the scalping diameter d_{scalp}
 322 (scalping/replacement 2). Figure 3 shows the GSDs of an original soil with a fine content of 30%
 323 and its corresponding scalped, scalped/replaced 1 and scalped/replaced 2 samples. It can be seen

324 that the scalping/replacement 2 leads to a GSD closer to the original one than the GSD given by
 325 the scalping/replacement 1. In addition, the scalping leads to an increase in fine content, while
 326 both scalping/replacement procedures preserve the fine content. In the following, each scalped
 327 or scalped/replaced sample is named by its corresponding original soil's name followed by letter
 328 S for scalping, SR1 for scalping/replacement 1 or SR2 for scalping/replacement 2, and followed
 329 by its maximum particle diameter (d_{scalp}). For all tested specimens, the ratio Φ/d_{max} is kept
 330 equal to 10; therefore, $\Phi = 100$ mm for the specimens of the original soils, and $\Phi = 50$ mm for
 331 the specimens of the scalped and scalped/replaced soils.

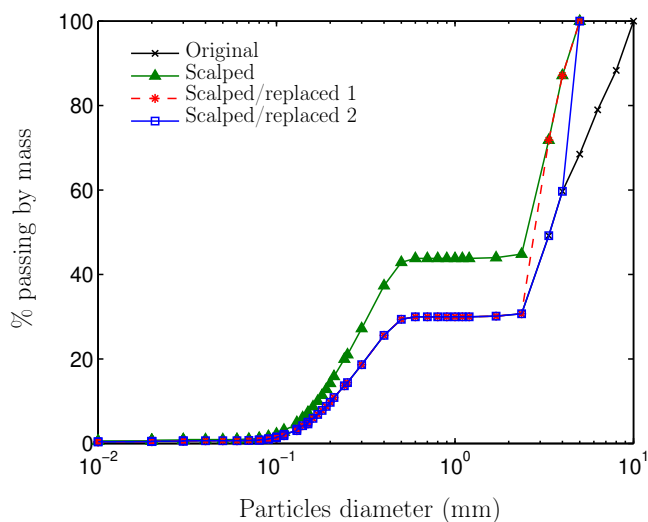


Figure 3: GSDs of an original soil with $f_f = 30\%$ and its corresponding scalped, scalped/replaced 1 and scalped/replaced 2 soils.

332 3.2 Apparatuses and experimental procedure

333 Small and medium triaxial cells with $\Phi = 50$ and 100 mm used in the current study are quite
 334 classical for soil testing. They are equipped with a mobile loading piston to apply a vertical force
 335 at the top of the specimen, which is measured by a force sensor with a maximum capacity of 3
 336 kN and a precision of about 0.5 %. A confining stress is applied by using an air-water pressure
 337 system. The vertical displacement of the piston is measured by a Linear Variable Differential

338 Transducer (LVDT) with a measuring range of 40 mm. The confining pressure, pore pressure
339 and back pressure are measured by a pressure sensor of maximum capacity of 1000 kPa. The
340 volume change is measured by a pressure volume controller (GDS) with a maximum capacity
341 of 200 cm³ and a precision of about 0.15 %, which is connected to the bottom drainage of the
342 sample and allows the back pressure to be applied to the specimen. The volume change of the
343 specimen is considered to be equal to the volume of water injected or expelled by the GDS if the
344 pore pressure is kept constant. All the measurement equipments are connected to a computer
345 equipped with a GDSLab software for the data acquisition.

346 The mixture is first moistened in order to avoid particle segregation and then placed in
347 successive layers having the same fine content. Each layer is manually compacted by using a
348 metal rammer in order to achieve the desired density. After that, the sample is saturated by an
349 injection of CO₂ from the bottom to the top of the sample, and then by a circulation of de-aired
350 water flow followed by a back pressure application. Next, the sample is consolidated isotropically
351 and finally, the deviatoric stress is applied.

352 In order to check the repeatability of results obtained with the triaxial cells Φ 50 and 100
353 mm, three drained triaxial tests were carried out on Fontainebleau sand using the cell Φ 50 mm
354 and four other tests using the cell Φ 100 mm. All the samples were prepared at nearly the same
355 void ratio. These tests show a good repeatability in terms of peak friction angle with a variation
356 less than 1°¹. Four triaxial tests were carried out on the original soil FS30PG40NG30_10 with
357 $d_{\max} = 10$ mm using the cell Φ 100 mm. Once again, we obtain a good repeatability in terms of
358 peak friction angle with a variation less than 1°². It should be noted that the residual friction
359 angle is less repeatable than the peak value: indeed, the variation of the residual friction angle
360 can be greater than 3°. Moreover, although a good repeatability in terms of friction angle at the
361 peak state was obtained, the volumetric behaviors of samples are not well repeated.

362 4 Test results and discussions

363 Table 2 presents the characteristics (composition, global void ratio e , interfine void ratio e_f
364 and intergranular void ratio e_c) and the drained friction angle φ' at the peak and residual

¹See Figure S1 and Table S1 in the supplementary materials

²See Figure S2 and Table S2 in the supplementary materials

365 states of all original, scalped and scalped/replaced samples tested in the current study. Some
366 of these tests are repeatability tests. For all the scalped and scalped/replaced samples except
367 FS60PG10NG30_S_5*, their global void ratio e is controlled to be close as much as possible to
368 the value of the corresponding original sample. For the scalped sample FS60PG10NG30_S_5*,
369 its global void ratio e is controlled to be equal to e_{retained} of the retained fraction in the original
370 one. The global void ratio e of each original soil is chosen by trial and error so that it can be
371 reached for not only the original soil but also for the scalped and scalped/replaced soils. For the
372 original soils with $f_f = 20$ and 30%, e around 0.33 was chosen; however, for those with $f_f =$
373 45 and 60%, higher values of e was chosen since the minimum void ratio e_{min} increases with an
374 increase in fine content. In addition, for the scalped soil for which the fine content is higher than
375 that of the original soil, higher compaction effort was given to reach the target void ratio of the
376 original soil. It should be noted that the relative density D_R would not be the same for all the
377 original, scalped and scalped/replaced samples since the minimum and maximum void ratios,
378 e_{min} and e_{max} , depend greatly on the fine content and on the grain size gradation of the coarse
379 fraction as discussed in Section 2.3. The two latter parameters could not be determined for the
380 coarse-grained soils studied here due to the technical difficulties already discussed in Section 2.2.
381 For the repeatability tests on the same soil, the void ratios of all the tested samples at the end
382 of the consolidation phase are more or less the same except for the tests N° 26 and 29. For these
383 two tests, although the samples were compacted to reach the same void ratio as that of the other
384 samples, their void ratio decreases significantly during the consolidation phase. As a result, their
385 void ratio at the end of the consolidation phase (around 0.37) is lower than the value of 0.41 for
386 the other tests.

387 In the following, we first discuss how the compactness parameter to be controlled for scalped
388 and scalped/replaced soils is chosen. Then, the behavior of the scalped and scalped/replaced
389 soils in comparison with that of the corresponding original soils with different fine contents is
390 analyzed. Our study focuses on the soil's shear strength at the peak state rather than the
391 value at the residual state. Firstly, in most geotechnical structures such as embankment dams
392 and dikes, their mechanical stability requires that the strains remain relatively small and the
393 stresses remain below the peak values. In a few problems such as landslides where the strains
394 are very large, the soil can reach the residual state. In this case, the residual shear strength

Table 2: Properties (composition, void ratios, and drained friction angle φ') of 35 tested specimens. S means scalping, SR1 & SR2 distinguish the two scalping/replacement methods.

Test N°	Soil name	Composition in %				Void ratios			φ' (°)	
		FS	GB	PG	NG	e	e_f	e_c	peak	residual
1	FS20PG50NG30_10	20	-	50	30	0.32	1.60	0.65	37.6	35.7
2	FS20PG50NG30_S_5	30	-	70	-	0.32	1.06	0.88	35.5	33.0
3	FS30PG40NG30_10	30	-	40	30	0.32	1.08	0.89	37.7	36.5
4		30	-	40	30	0.33	1.09	0.90	36.8	36.0
5		30	-	40	30	0.33	1.09	0.89	37.4	35.5
6	FS30PG40NG30_S_5	30	-	40	30	0.33	1.09	0.90	36.8	35.5
7		44	-	56	-	0.33	0.75	1.37	40.3	35.4
8		44	-	56	-	0.32	0.73	1.36	39.5	35.9
9		44	-	56	-	0.33	0.75	1.37	40.3	35.3
10		44	-	56	-	0.33	0.75	1.37	39.7	36.6
11	FS30PG40NG30_SR1_5	30	-	70	-	0.32	1.06	0.88	37.9	35.5
12		30	-	70	-	0.33	1.09	0.89	38.0	32.7
13		30	-	70	-	0.33	1.09	0.89	37.9	36.7
14	FS30PG40NG30_SR2_5	30	-	70	-	0.33	1.08	0.89	39.7	36.9
15		30	-	70	-	0.33	1.09	0.90	39.8	35.2
16		30	-	70	-	0.32	1.08	0.89	39.5	38.0
17	FS30PG26NG44_10	30	-	26	44	0.32	1.07	0.89	38.0	36.7
18	FS30PG26NG44_S_5	54	-	46	-	0.33	0.60	1.88	40.2	35.0
19	FS30PG26NG44_SR1_5	30	-	70	-	0.31	1.04	0.87	37.2	36.2
20	FS30PG26NG44_SR2_5	30	-	70	-	0.31	1.04	0.88	37.2	34.8
21		30	-	70	-	0.31	1.04	0.87	37.6	35.9
22		30	-	70	-	0.31	1.04	0.87	37.6	36.4
23	FS45PG25NG30_10	45	-	25	30	0.36	0.80	1.48	40.5	34.3
24	FS45PG25NG30_S_5	65	-	35	-	0.37	0.56	2.90	41.6	34.0
25	FS60PG10NG30_10	60	-	10	30	0.41	0.69	2.53	39.9	33.4
26		60	-	10	30	0.37	0.62	2.43	40.8	34.2
27		60	-	10	30	0.41	0.69	2.53	39.6	33.9
28	FS60PG10NG30_S_5	84	-	16	-	0.41	0.49	7.83	39.5	32.2
29		84	-	16	-	0.37	0.44	7.58	40.5	33.5
30		84	-	16	-	0.41	0.49	7.82	39.1	33.4
31	FS60PG10NG30_S_5*	84	-	16	-	0.58	0.69	8.88	36.7	33.0
32	FS60PG10NG30_SR1_5	60	-	40	-	0.41	0.68	2.51	39.8	36.2
33	FS60PG10NG30_SR2_5	60	-	40	-	0.41	0.68	2.51	39.9	34.4
34	GB30PG40NG30_10	-	30	40	30	0.33	1.10	0.90	-	27.5
35	GB30PG40NG30_S_5	-	44	56	-	0.33	0.76	1.38	-	30.0

S means scalping, SR1 & SR2 distinguish the two scalping/replacement methods

395 characteristics can be indeed used for a safe approach. Secondly, as shown in Section 3.2 and
396 in Table 2, the dispersion of values of the residual friction angle obtained from repeatability
397 tests is quite large, in comparison with that obtained for the peak friction angle. As a result,
398 consequences of scalping and scalping/replacement procedures on the residual friction angle are
399 much less clear and certain than those found in terms of peak friction angle.

400 4.1 Choice of the compactness parameter

401 As mentioned previously, the void ratio of a scalped soil can be controlled to be equal to either
402 e_{retained} of the retained fraction or the global void ratio e of the original soil. To study the effect
403 of the compactness parameter to be controlled, the original soil FS60PG10NG30_10 with 60%
404 of fine content is scalped by removing the natural gravel (NG) which occupies 30% by mass; and
405 e_{retained} and e are respectively controlled for the scalped samples FS60PG10NG30_S_5* and
406 FS60PG10NG30_S_5. Figure 4 shows the behavior of these scalped samples in comparison with
407 that of the original soil. It can be seen that the scalped sample FS60PG10NG30_S_5* with a
408 peak friction angle $\varphi' = 36.7^\circ$ is significantly less resistant and less dilative than the original one
409 with $\varphi' = 40.8^\circ$. It should be noted that for this original soil with a high fine content, the coarse
410 fraction plays only a secondary role. The peak friction angle of the scalped sample would be
411 much lower than the original value for soils with lower fine content. El Dine (2007) also found
412 that the scalping greatly underestimates the shear strength of coarse-grained soils if e_{retained} is
413 controlled.

414 The above result can be explained as follows. A gap-graded soil with a high fine content
415 can be considered as a composite soil which is composed of a matrix (fine particles and voids)
416 and inclusions (coarse particles). When a soil is scalped, its fine content f_f is increased but its
417 coarse content f_c is decreased. As mentioned in Section 2, the interfine void ratio e_f remains
418 unchanged if the void ratio e of the scalped sample is controlled to be equal to e_{retained} of the
419 original sample (see Equation (5)); however, the intergranular void ratio e_c of the scalped sample
420 is bigger than that of the original sample (see Table 2). This means that the matrix is preserved
421 but the inclusions are strongly discarded and contacts between them are destroyed by the matrix
422 in the scalped soil in comparison with the microstructure of the original soil. As a consequence,

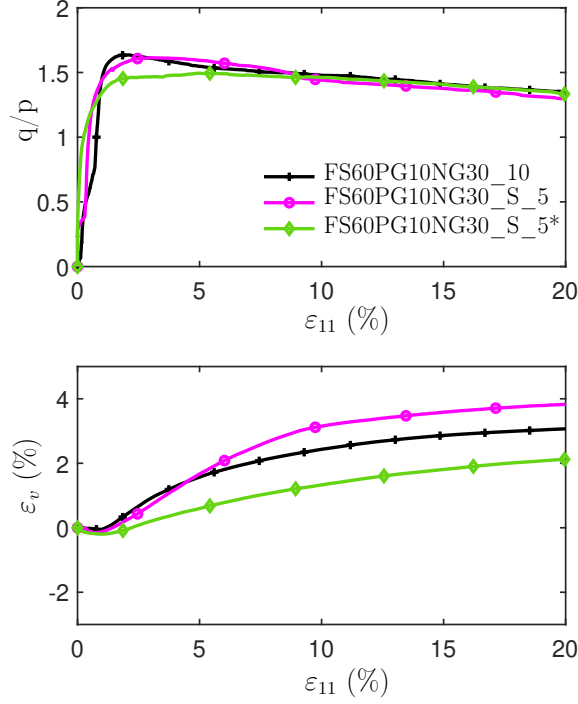


Figure 4: Behaviors of the original sample FS60PG10NG30_10 and the scalped samples FS60PG10NG30_S_5 and FS60PG10NG30_S_5*.

423 stresses carried by the inclusions decrease strongly in the scalped sample, leading to a decrease
 424 in its shear strength. This was confirmed by El Dine et al. (2010) who found actually a decrease
 425 in the shear strength of matrix coarse-grained soils with a decrease in coarse content f_c when
 426 the void ratio e_f of the matrix is kept constant. This result means that the higher the removed
 427 fraction is, the lower shear strength of the scalped soil is if e_{retained} is controlled. In addition, a
 428 control of e_{retained} is not always possible for gap-graded soils with lower fine contents. For such
 429 soils, the coarse fraction plays a primary role in carrying stresses; therefore, a removal of coarse
 430 particles makes the scalped soil too weak to be prepared at the void ratio equal to e_{retained} .

431 Figure 4 also shows that the scalped soil FS60PG10NG30_S_5 whose void ratio is controlled
 432 to be equal to the global void ratio e of the original soil gives a behavior close to the original
 433 behavior: the friction angles of both soils are close as shown in Table 2. The global void ratio
 434 e appears to be a more appropriate choice than e_{retained} for control of the compactness state of

435 the scalped soil, at least for gap-graded soils with high fine contents studied here. It is worth
436 mentioning that for the scalped/replaced soil, a control of the global void ratio e presents a
437 great advantage: it actually allows us to preserve the interfine and intergranular void ratios, e_f
438 and e_c , as shown in Table 2. In this context, we will study further the behavior of scalped and
439 scalped/replaced soils when the global void ratio e is controlled.

440 4.2 Effect of the fine content

441 In order to study the effect of the fine content on the behavior of the scalped and scalped/replaced
442 soils, four original mixtures FS20PG50NG30_10, FS30PG40NG30_10, FS45PG25NG30_10 and
443 FS60PG10NG30_10 were prepared at the respective fine contents $f_f = 20\%$, 30% , 45% and
444 60% (see Table 2). The void ratios e of these mixtures are controlled to be close as much as
445 possible to 0.33; however, this value cannot be achieved for all the considered fine contents as
446 the maximum and minimum void ratios e_{\max} and e_{\min} depend strongly on the fine content.
447 Indeed, the soil FS60PG10NG30_10 was prepared at a void ratio higher than the value for the
448 soil FS30PG40NG30_10.

449 Figure 5 shows the behavior of the four original soils with different fine contents. It can be
450 seen that an increase in fine content from 20% to 30% has a small effect on the behavior of the
451 gap-graded soils: the peak friction angles for both fine contents are almost the same (around
452 37.7°). However, an increase in fine content above 30% leads to a significant increase in the peak
453 friction angle. Although the soil with $f_f = 60\%$ has a void ratio $e = 0.37$ much higher than
454 $e = 0.32$ of the soil with $f_f = 30\%$, the former with a peak friction angle of about 40° is actually
455 more resistant and more dilative than the latter with a peak friction angle of about 37° . This
456 result confirms what has been found by Thevanayagam et al. (2002) and Ali Hassan et al. (2021)
457 as already discussed in Section 4.2. However, we do not observe an increase in the shear strength
458 with an increase in fine content above 45%. We can also remark that, while the fine content
459 has a positive effect on the peak shear strength, it shows a negative effect on the residual shear
460 strength starting from 30%. Indeed, the sample with $f_f = 60\%$ has a residual friction angle of
461 33.4° which is lower than the value of 36.5° of the sample with $f_f = 30\%$. Taha et al. (2019)
462 also found in their numerical simulations with the DEM that the residual friction angle tends to

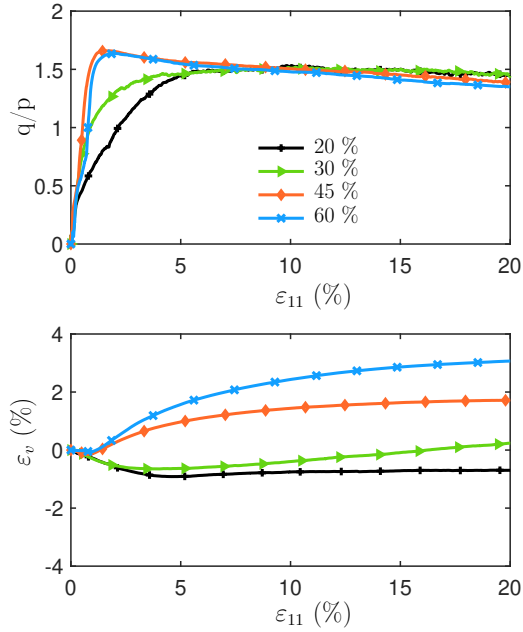


Figure 5: Behavior of the original soils with different fine contents f_f .

463 decrease with an increase in fine content.

464 In the following, we will show how the fine content f_f of the original soils aforementioned
 465 affects the behavior of the corresponding scalped and scalped/replaced soils. For this purpose,
 466 the original soils with $f_f = 30\%$ and 60% were scalped and scalped/replaced, while the soils
 467 with $f_f = 20\%$ and 45% are only scalped. For all the original soils, the natural gravel (NG)
 468 which occupies 30% by mass is removed for the scalped soils and replaced by the same mass
 469 of Palvadeau gravel (PG) for the scalped/replaced soils. The void ratio e of each scalped or
 470 scalped/replaced soil is controlled to be almost the same as that of the corresponding original
 471 soil.

472 Behavior of scalped soils

473 The behavior of the scalped soils in comparison with that of the corresponding original soils
 474 is shown in Figures 6 (for $f_f = 20$ and 30%) and 7 (for $f_f = 45$ and 60%). It can be seen
 475 that, for the original soil with $f_f = 20\%$, the scalped soil is less resistant than the original one

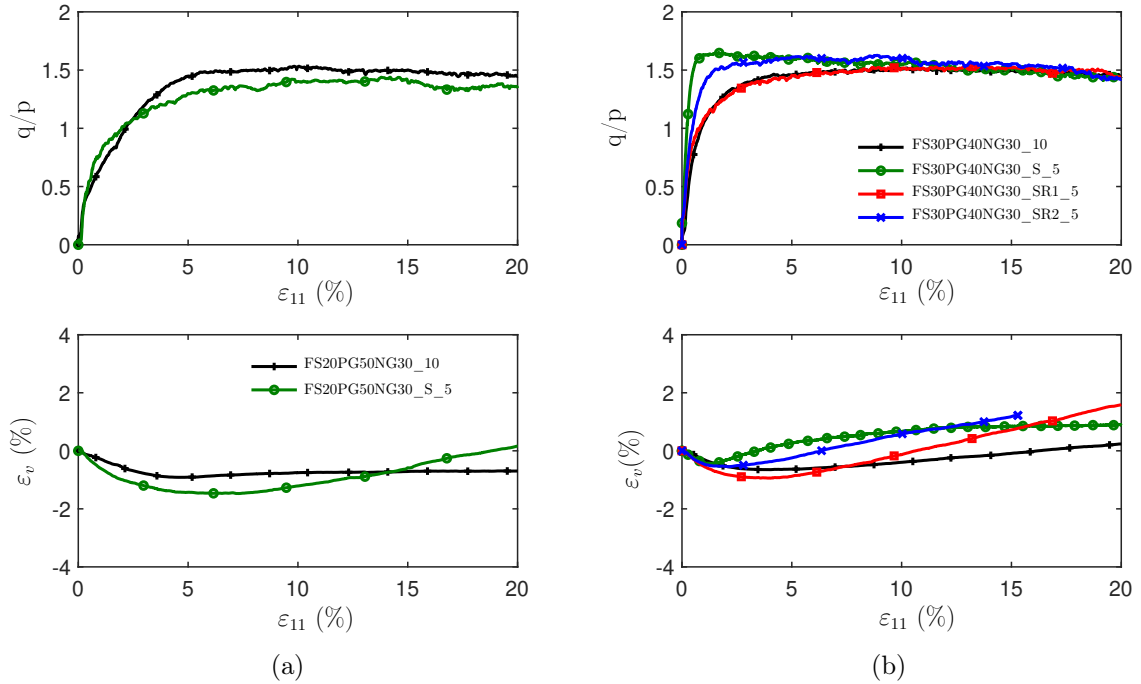


Figure 6: Stress ratio q/p and volumetric strain ε_v versus axial strain ε_{11} for the original soils with $f_f =$ (a) 20% and (b) 30% and for their scalped and scalped/replaced soils.

476 (Figure 6.a). The scalping of this original soil leads to an underestimation of about 2° of the
 477 peak friction angle. On the contrary, the soil scalped from the original soil with $f_f = 30\%$ is
 478 greatly stronger than the original one (Figure 6.b). For this original soil, the peak friction angle
 479 is actually overestimated by more than 2° by the scalping. The same result is observed for the
 480 original soil with $f_f = 45\%$ (Figure 7.a) but the overestimation of the peak friction angle is less
 481 marked (around 1°). For the original soil with $f_f = 60\%$, the scalped soil has almost the same
 482 behavior as that of the original soil. The fine content of 30% appears as a turning value under
 483 which the scalping induces an underestimation of the peak shear resistance but over which it
 484 leads to an overestimation of the peak shear resistance of coarse-grained soils. One can also
 485 remark that the effect of the scalping on the volumetric behavior for different fine contents is
 486 less clear than on the shear resistance. El Dine et al. (2010) also found that it is complicated to
 487 get a relevant information on the volumetric behavior during shearing for mixtures of fine and
 488 coarse grains that become no longer homogeneous due to localized shear bands.

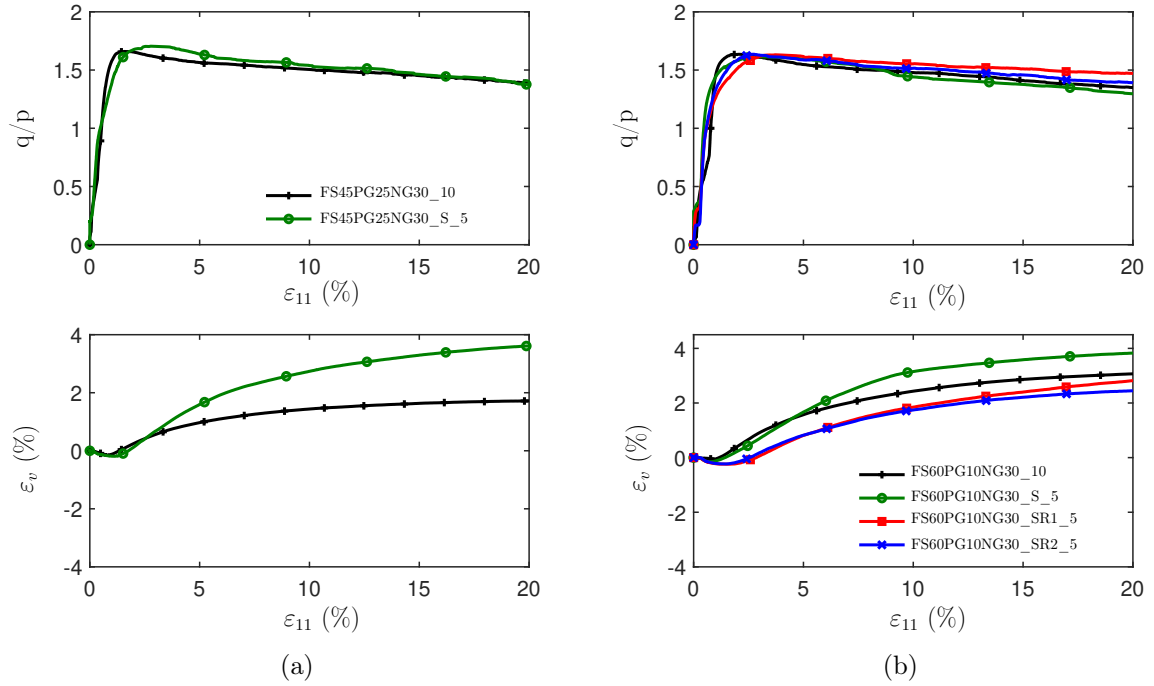


Figure 7: Stress ratio q/p and volumetric strain ε_v versus axial strain ε_{11} for the original soils with $f_f =$ (a) 45% and (b) 60% and for their scalped and scalped/replaced soils.

489 As already mentioned, when a gap-graded soil is scalped, its fine content increases; as a result,
 490 the fine fraction gets denser and its contribution to the shear strength increases as well when
 491 the global void ratio e is controlled. On the other hand, the coarse fraction decreases and gets
 492 looser; as a result, its contribution to the shear strength decreases. It should be noted that the
 493 fraction of natural gravel (NG) in the considered original soils has a better resistance to shearing
 494 in comparison with those of the Fontainebleau sand (FS) and Palvadeau gravel (PG) as shown
 495 in Section 3.1. The important role of this gravel fraction can be seen by comparing the samples
 496 FS20PG50NG30_S_5 and FS30PG40NG30_10. Both samples have the same fine content of
 497 30% and were prepared at the same void ratio (see Table 2). The last sample which contains
 498 30% of natural gravel has, indeed, a higher peak friction angle ($\varphi' = 37.7^\circ$) than $\varphi' = 35.5^\circ$
 499 for the first one without natural gravel. Scalping the soil FS20PG50NG30_10 leads to a great
 500 decrease in the peak shear strength due to the removal of this stronger gravel NG. In addition,
 501 this decrease is not sufficiently compensated by the increase in the peak shear strength due to

502 the increase in the fine content, which is not significant for a fine content $f_f < 30\%$ as shown
503 in Figure 5. As a consequence, the scalped soil FS20PG50NG30_S_5 has a lower peak shear
504 strength than the original one. Above $f_f = 30\%$, the increase in the peak shear strength resulting
505 from an increase in the fine content becomes so great that it exceeds the loss in the peak shear
506 strength due to the removal of natural gravel; therefore, the scalped soils have a better peak
507 shear resistance than that of the corresponding original soils with $f_f = 30\%$ and 45% . Above
508 $f_f = 60\%$, the behavior of mixtures is mainly governed by the fine fraction, and an increase in the
509 fine content does not lead to a significant increase in the peak shear strength as shown in Figure
510 5; as a result, the peak shear strength of the soil with $f_f = 60\%$ remains almost unchanged after
511 scalping.

512 A natural coarse-grained soil can contain a fine fraction of rounded particles which is much
513 less resistant to shearing than a coarse fraction of sub-angular or angular particles. One might
514 think that the scalping would underestimate the shear strength of this soil due to an increase
515 in the content of weak fine particles. However, this is not the result obtained with the original
516 soil GB30PG40NG30_10 with 30% of glass beads (GB) used for the fine fraction instead of
517 Fontainebleau sand. Figure 8 shows, indeed, that the scalped soil still has a higher shear strength
518 ($\varphi' = 30^\circ$) than the original one ($\varphi' = 27.5^\circ$). One can also remark that a replacement of
519 Fontainebleau sand by glass beads leads to a great reduction in the peak shear strength of the
520 soil GB30PG40NG30_10 in comparison with $\varphi' = 37.2^\circ$ of the soil FS30PG40NG30_10. The
521 above result means that even though the fine fraction is much less resistant than the coarse
522 fraction, an increase in fine content above 30% caused by the scalping procedure still leads to an
523 increase in the shear strength. This is likely due to the fact that, at higher fine content, the fine
524 fraction gets denser and bears higher stresses. As a result, they constitute a stronger bracing
525 system to reduce the buckling of the solid skeleton primarily constituted of coarse particles,
526 allowing the soil to support higher shear stresses.

527 Behavior of scalped/replaced soils

528 The behavior of the scalped/replaced soils in comparison with that of the corresponding original
529 soils with $f_f = 30$ and 60% is shown in Figures 6.b and 7.b, respectively. It can be seen that the
530 behavior of the scalped/replaced soils is, on the whole, quite close to that of their corresponding

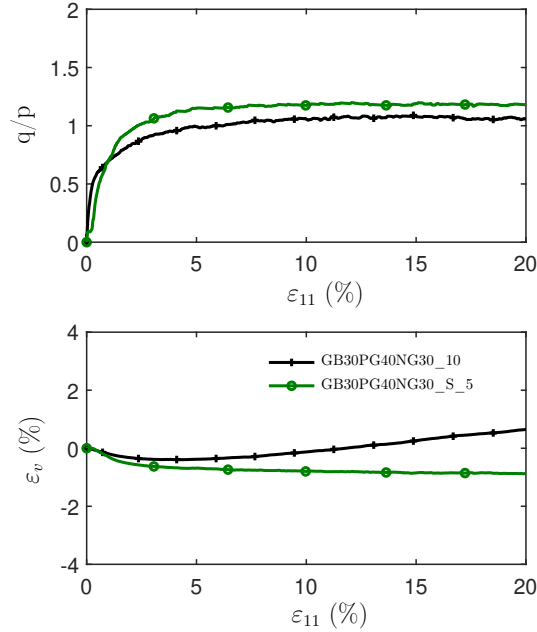


Figure 8: Stress ratio q/p and volumetric strain ε_v versus axial strain ε_{11} for the original soil GB30PG40NG30_10 and its scalped soil.

531 original soils for both original fine contents $f_f = 30\%$ and 60% . One can remark in Figure 6.b
532 that the two scalping/replacement methods presented in Section 3.1 (see Figure 3) give differ-
533 ent results for the original soil FS30PG40NG30_10 but close results for FS60PG10NG30_10.
534 While the scalping/replacement 1 gives a good estimation of the peak shear strength of the
535 first soil, the scalping/replacement 2 overestimates its peak shear strength. Another original
536 soil, FS30PG26NG44_10, with the same fine content as that of FS30PG40NG30_10 but with
537 44% of natural gravels was studied. The behavior of this original soil and its scalped and
538 scalped/replaced ones is shown in Figure 9. For this soil, the scalping still overestimates the
539 peak shear strength, while both scalping/replacement methods give a good estimation of the
540 peak shear strength. The reason why the two scalping/replacement methods give different re-
541 sults for the soil FS30PG40NG30_10 but not for FS30PG26NG44_10 is not well understood
542 yet. We can also remark that the consequence of the scalping/replacement 1 on the residual
543 friction angle is not clear: while this procedure gives a good estimation of the residual friction
544 angle for the soil FS30PG40NG30_10, it significantly overestimates this characteristic of the soil

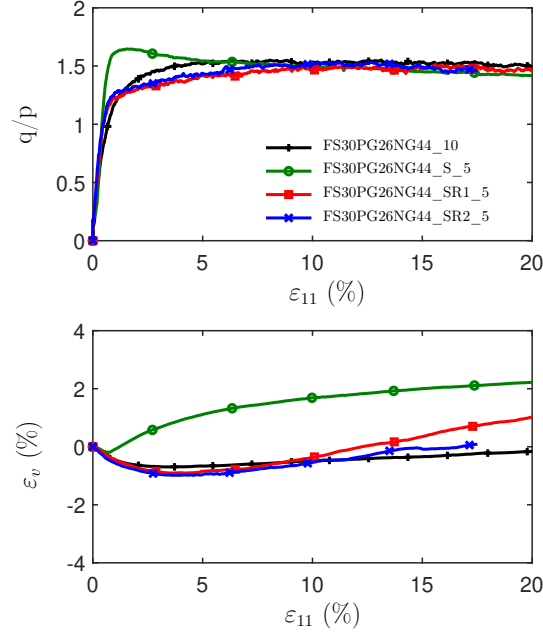


Figure 9: Behavior of the scalped and scalped/replaced soils in comparison with that of the original soil FS30PG26NG44_10

546 As pointed out in Section 2.5, a reduction in the GSD of the coarse fraction could result in an
 547 increase in the shear strength of gap-graded soils under the condition that the global void ratio
 548 e is controlled to be the same. It is thus reasonable to infer that the scalping/replacement leads
 549 to an overestimation of the shear strength of coarse-grained soils as it reduces the coarse GSD.
 550 Ali Hassan et al. (2021) showed actually in their numerical study that the scalped/replaced soils
 551 have higher shear strengths than that of the original soil with 30% of fine content. However, it
 552 is not the case for the soils tested in the current study as shown above. It should be noted that
 553 for the studied soils, the natural gravel (NG), which is highly resistant to shearing, is replaced
 554 by Palvadeau gravel (PG) which is less resistant to shearing. The former and latter are called as
 555 *replaced* and *replacement* materials, respectively. The two following hypotheses can be made to
 556 explain this experimental finding.

557 (i) The effect of the reduction in the coarse GSD is small as the grading parameter d_{\max}^c/d_{\min}^c

558 is only reduced by a factor of 2 by the scalping/replacement; or

559 (ii) The increase in the shear strength caused by a reduction in the coarse GSD is erased by a
560 decrease in the shear strength due to the fact that the replacement material is less resistant
561 than the replaced one.

562 The first hypothesis is reasonable for the original soil FS60PG10NG30_10 with 60% of fine
563 content. For such a high fine content, the coarse particles are strongly dispersed by the fine
564 particles. As a result, a change in the coarse GSD has a little influence on the shear strength of
565 the soil provided that the coarse content is preserved. Ali Hassan et al. (2021) showed actually
566 that the scalping/replacement used for the soil with 60% of fine content gives a good estimation
567 of the original shear strength. For lower fine content, the mechanical behavior of gap-graded soils
568 would be more sensitive to a change in the coarse GSD, particularly for a fine content around the
569 optimum fine content of 30% as shown by Ali Hassan et al. (2021). It is not well understood yet
570 why a change in the coarse GSD caused by the scalping/replacement does not lead to a change
571 in the shear strength of the tested soil with 30% of fine content. More studies need to be carried
572 out to understand the effect of the particle properties of the replacement material (in comparison
573 with those of the replaced material) and the effect of the reduction in the coarse GSD for higher
574 values of the ratio $d_{\max}/d_{\text{scalp}}$ on the mechanical behavior of the scalped/replaced material.

575 5 Conclusions

576 This paper presented an experimental study on the scalping and scalping/replacement methods
577 used to evaluate the mechanical properties of coarse-grained soils. Original soils with gap-graded
578 particle size distributions are composed of mixtures of fine and coarse particles with different fine
579 contents and different materials: Fontainebleau sand and glass beads for the fine fraction, and
580 Palvadeau and natural gravels for the coarse fraction. Small and medium triaxial devices with
581 specimen diameters of 50 and 100 mm were used to evaluate the shear strength of original, scalped
582 and scalped/replaced soils. Two different methods for the scalping/replacement were studied:
583 the whole fraction of retained coarse particles is used for the scalping/replacement 1, while only
584 the class of particles closest to the removed fraction is used for the scalping/replacement 2. In

585 addition, two different compactness parameters were controlled for scalped and scalped/replaced
586 soils: the global void ratio e and the void ratio e_{retained} of the retained fraction in the original
587 soil. The following results were obtained:

- 588 • Consequences of the scalping method are mainly due to an increase in fine content. When
589 e is controlled, it leads to either an underestimation or an overestimation of the shear
590 strength depending on the original fine content. The shear strength is overestimated if
591 the original fine content is equal or bigger than the optimum value of about 30%. This
592 overestimation is observed even when the fine fraction is significantly less resistant than the
593 coarse one. Nevertheless, for soils with high fine contents ($\geq 60\%$), the scalping method
594 gives a good estimation of the original shear strength.
- 595 • When e_{retained} is controlled, the scalping leads to a significant underestimation of the shear
596 strength if an important fraction of coarse particles is removed.
- 597 • The scalping/replacement procedures allow us to preserve the key parameters of a gap-
598 graded soil such as fine content f_f , intergranular and interfine void ratios e_c and e_f when
599 the global void ratio e is controlled. However, they induce a reduction in the coarse GSD,
600 which might lead, in turn, to an increase in the shear strength of scalped/replaced soils.
601 In addition, the difference in the particle properties between the replacement and replaced
602 materials might have an effect on their shear strength. These two effects induced by
603 the scalping/replacement are not visible for the soils studied here with $d_{\text{max}}/d_{\text{scalp}} = 2$
604 for which the replacement material is less resistant than the replaced one. Indeed, the
605 scalping/replacement procedure 1 gives a good estimation of the shear strength of the
606 original soils with different fine contents.
- 607 • Unlike the scalping/replacement procedure 1, the consequences of the procedure 2 are not
608 well understood yet: it gives a good estimation or an overestimation of the shear strength
609 depending on the soil under consideration. This scalping/replacement procedure should
610 not be used according to the recommendations of U.S Army Corps of Engineers (1970)
611 that require the whole admissible coarse fraction to be used for the replacement (procedure
612 1).

613 In summary, the scalping procedure should not be used for gap-graded soils. On the contrary,
614 the scalping/replacement procedure 1 with a control of the global void ratio e shows a great
615 interest for this kind of soils. Our future studies will focus on the consequences of this procedure
616 for soils with higher values of $d_{\max}/d_{\text{scalp}}$. In addition, the effect of the particle properties
617 of the replacement material in comparison with those of the replaced material will be further
618 investigated.

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