

# Effect of Scalping on the Mechanical Behavior of Coarse Soils

Nadine Ali Hassan, Ngoc Son Nguyen, Didier Marot, Fateh Bendahmane

**Abstract**—This paper aims at presenting a study of the effect of scalping methods on the mechanical properties of coarse soils by resorting to numerical simulations based on the discrete element method (DEM) and experimental triaxial tests. Two reconstitution methods are used, designated as scalping method and substitution method. Triaxial compression tests are first simulated on a granular materials with a gap graded particle size distribution by using the DEM. We study the effect of these reconstitution methods on the stress-strain behavior of coarse soils with different fine contents and with different ways to control the densities of the scalped and substituted materials. Experimental triaxial tests are performed on original mixtures of sands and gravels with different fine contents and on their corresponding scalped and substituted samples. Numerical results are qualitatively compared to experimental ones. Agreements and discrepancies between these results are also discussed.

**Keywords**—Coarse soils, scalping, substitution, discrete element method, triaxial test.

## I. INTRODUCTION

**C**OARSE soils are natural materials often used as construction materials for dams, dikes, embankments. They are characterized by a wide grain size gradation where particle diameters vary largely from a few microns up to several decimeters. The mechanical characterization of these soils using the classical laboratory devices is difficult to achieve due to the presence of large elements that prevent or disturb the performance of the test. Hence, it is necessary to remove from the soil all these oversized particles by a scalping or substitution method. The scalping method consists in removing from the soil all the oversized particles and then testing the reconstituted soil. For the substitution method (scalping/replacement), the oversized particles are replaced by an equal mass of smaller ones. However, it is not clear yet how to choose the material for this replacement.

The results of experimental studies on the consequences of scalping on the shear strength of coarse soils are contradictory. Different ways for controlling the density of scalped and substituted samples were proposed. Reiffsteck et al. [12] and Holtz [18], [19] controlled the dry density  $\gamma_d$  of scalped and substituted soils to be equal to that of the original soil, while Torrey et al. [10] controlled the ratio of the dry density  $\gamma_d$  to the maximum dry density  $\gamma_{d,max}$  obtained by the Proctor compaction test for the original, scalped and substituted soils. Andrianatrehina et al. [17], Dupla et al. [16] and Dano [13] controlled the relative density ( $D_R$ ) for

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cohesionless soils, while El Dine [3] compacted the scalped soil in order to reach the void ratio  $e_{retained}$  of the retained fraction in the original soil, as well as the US army [9]. The conclusions about these studies are divergent. Some studies have shown a good estimation [14], [20], an over-estimation [13], [21], or an under-estimation [3] of shear strength while using the scalping method. The substitution method can also lead to a good estimation [11], an over-estimation [12] or an under-estimation [10], [15] of the shear strength. The divergence in these conclusions is related to the fact that the behavior of scalped and substituted soils depends on many factors such as the scalping technique used, the scalping diameter, the compaction parameter to be controlled and the material under consideration.

This paper presents a numerical study followed by an experimental one to get a better understanding of consequences of the scalping and substitution methods on the shear strength of coarse soils. First, triaxial compression tests were simulated on granular materials with gap-graded particle size distribution using the discrete element method (DEM). Both scalping methods mentioned above are used. It is also crucial to select the parameter to be controlled for the original sample and the scalped (or substituted) one so that they can be considered to be equivalent in terms of compactness. For the numerical study, we control three parameters: the void ratio of the retained fraction ( $e_{retained}$ ), the relative density ( $D_R$ ) and the global void ratio ( $e$ ).

This paper is organized as follows: the performed numerical simulations and numerical results are first presented in Section II. The experimental results are presented and compared to numerical results in Section III.

## II. NUMERICAL STUDY

The DEM based on the molecular dynamic (MD) approach is used in order to model a dry cohesionless granular soil which is implemented in the open-source software YADE [22]. The DEM uses Newton-Euler dynamic equations to describe the translational and rotational motions for each rigid particle. The interaction forces at the contact between two particles are calculated by using a contact model that consists of two linear springs in the normal and tangential directions with respective stiffnesses  $K_n$  and  $K_t$ . The contact normal and tangential stiffnesses are calculated from the respective particle stiffnesses,  $k_n$  and  $k_t$ , by assuming that the latter ones are connected in series in each direction. They are expressed as:

$$K_n = \frac{k_n^i k_n^j}{k_n^i + k_n^j} \quad \text{and} \quad K_t = \frac{k_t^i k_t^j}{k_t^i + k_t^j} \quad (1)$$

where the superscripts  $i$  and  $j$  denote two particles at the contact point. The tangential force  $f_t$  is limited by Coulomb friction law as  $|f_t| \leq f_n \tan(\varphi)$ , where  $f_n$  is the normal force and  $\varphi$  is the friction angle. The microscopic parameters used in our simulations are identical to those used in [1] where the normal particle stiffness  $k_n/D = 250$  MPa, stiffness ratio  $k_t/k_n = 0.5$ , friction angle  $\varphi = 35^\circ$  and mass density  $\rho = 2600$  kg/m<sup>3</sup>.

The simulated samples are mixtures of fine and coarse particles with a gap-graded particle size distribution with different fine contents  $f_f$ . Fig. 1 shows the particle size distribution (PSD) of the original soil with  $f_f = 30\%$  (black curve). The gap ratio  $G_r = D_{\min}/d_{\max}$  is chosen to be equal to 3 in order to keep the computation time reasonable because a higher value of  $G_r$  leads to a large number of particles and thus, a very long computation time. Each original soil is then scalped by removing all the particles of diameters greater than a scalping diameter  $d_{\text{scalping}}$  which depends in turn on the removed fraction defined as the ratio of the removed mass to the total mass of the original soil. In our simulations, all the soils are scalped to have a removed fraction of 35%. For the substituted soil, the removed mass is replaced by an equal mass of particles of diameters  $d$  between  $D_{\min}$  of the coarse fraction and  $d_{\text{scalping}}$ . The scalped and substituted PSDs are presented in Fig. 1 for the original soil of  $f_f = 30\%$ . It can be seen that the fine content  $f_f$  remains constant for the substitution method, while its value is increased to a value  $f'_f$  by the scalping method. The values of fine content  $f_f$  and  $D_{\max}$  for all simulated samples are presented in Table I.

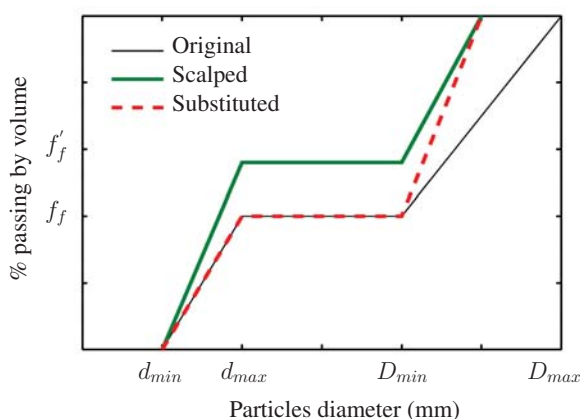


Fig. 1 Particle size distribution of simulated samples

Three density parameters are considered:

- (i) The global void ratio  $e$
- (ii) Void ratio  $e_{\text{retained}}$  of the retained fraction ( $d < d_{\text{scalping}}$ ) in the original soil

$$e_{\text{retained}} = \frac{V_v}{V_{s,\text{retained}}} = \frac{e}{f_{\text{retained}}}, \quad (2)$$

where  $V_v$  is the total void volume,  $V_{s,\text{retained}}$  is the solid volume of the retained fraction and  $f_{\text{retained}} = V_{s,\text{retained}}/V_s$  with total solid volume  $V_s$ .

TABLE I  
PARTICLE SIZE DISTRIBUTION CHARACTERISTICS FOR SIMULATED SAMPLES

Sample	$f_f$ (%)	$D_{\max}$ (mm)
Original	20	12
Scalped	30	9.375
Substituted	20	9.375
Original	30	12
Scalped	46	9
Substituted	30	9
Original	60	12
Scalped	95	6.75
Substituted	60	6.75

- (iii) The relative density  $D_R$  defined as

$$D_R = \frac{e_{\max} - e}{e_{\max} - e_{\min}}, \quad (3)$$

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

When a density parameter is chosen, its value for the scalped or substituted soil is controlled to be equal to the value for the original soil.

To study the behavior of a gap-graded soil, it is convenient to use two other void ratios: intergranular void ratio  $e_c$  for the coarse-grained fraction and the interfine void ratio  $e_f$  for the fine-grained fraction as proposed by [2]:

$$e_c = \frac{V_v + V_s^f}{V_s^c} = \frac{e + f_f}{1 - f_f} \quad \text{and} \quad e_f = \frac{V_v}{V_s^f} = \frac{e}{f_f}, \quad (4)$$

where  $V_s^f$  and  $V_s^c$  are the respective solid volumes of the fine and coarse fractions.

Particles are first generated into a cube composed of six rigid walls according to a given PSD. Particle diameters are first reduced by a factor of 2.0 and then progressively expanded to reach the target particle size distribution. After that, we reduced the box dimensions until the stresses  $\sigma_i$  ( $i = 1, 2, 3$ ) reach a target confining stress. This value of confining pressure is often used when performing experimental triaxial tests on granular soils such as [2], [25], [24] and [23]. To obtain the loosest state (maximum void ratio  $e_{\max}$ ), the friction angle between particles is set to the value of  $35^\circ$  used for the triaxial test and a small confining pressure of 1 kPa is applied. The densest state (minimum void ratio  $e_{\min}$ ) is obtained by setting the friction angle to zero value to facilitate rearrangement of particles and by applying a confining pressure of 100 kPa [1], [4], [5], [6], [7], [8]. At the end of the compaction process, the friction angle is then reset to its original value ( $35^\circ$ ) used for the triaxial test. It is worth mentioning that these numerical procedures to obtain  $e_{\min}$  and  $e_{\max}$  are different from the experimental ones for which particles are deposited under gravity from a given height to obtain the loosest state and then vibrated with a given frequency to reach the densest state. These standard procedures have been established for coarse soils. Moreover, particle

segregation might occur for strongly gap-graded soils when depositing particles under gravity or vibrating them. A target value of the global void ratio  $e$  can be also reached by setting the friction angle to zero value during the compaction to reach 98% of the target value of  $e$  and then setting it to the original value and continuing to compact the sample until reaching the confining pressure. Once the compaction finishes, triaxial compression tests are then performed by prescribing a small strain rate  $\dot{\epsilon}_1 = 0.01 \text{ s}^{-1}$  in direction (1), while keeping the lateral stresses  $\sigma_2$  and  $\sigma_3$  constant and equal to the confining pressure of 100 kPa. Each sample is loaded until the axial strain  $\epsilon_{11}$  reaches 10%.

In the following, the mechanical behavior of scalped and substituted soils is presented in comparison with the behavior of the original soils. The densities of scalped and substituted soils are controlled by considering the void ratio  $e_{\text{retained}}$  of the retained fraction, the relative density  $D_R$  and the global void ratio  $e$ .

1) *Controlling the Void Ratio  $e_{\text{retained}}$  of the Retained Fraction:* The original material with fine content of  $f_f = 60\%$  is scalped with 35% of the removed fraction and the global void ratio  $e$  of the scalped sample is controlled to be equal to the value of  $e_{\text{retained}}$  that the retained fraction has in the original sample. The original sample has  $e = 0.39$  and  $e_{\text{retained}} = 0.6$  so the void ratio  $e$  of the scalped sample is equal to 0.6. It should be noted that when the original sample is scalped, its fine content increases as shown in:

$$f'_f = \frac{V_f}{V'_s} = \frac{V_f}{V_s - V_{s,\text{removed}}} = \frac{V_f}{V_s - (1 - f_{\text{retained}}) \cdot V_s} = \frac{V_f}{f_{\text{retained}} \cdot V_s} = \frac{f_f}{f_{\text{retained}}}, \quad (5)$$

where symbol ( $'$ ) is used to depict characteristics for the scalped sample. However, by controlling  $e_{\text{retained}}$ , the interfine void ratio  $e_f$  is preserved as demonstrated in:

$$e'_f = \frac{e'}{f'_f} = \frac{e_{\text{retained}}}{f'_f} = \frac{e}{f_{\text{retained}} \cdot f'_f} = \frac{e}{f_f} = e_f \quad (6)$$

Fig. 2 presents the stress ratio  $q/p$  and the volumetric strain  $\epsilon_v$  versus the axial strain  $\epsilon_{11}$  for the original sample with  $f_f = 60\%$  and for the scalped sample. It can be seen that the shear resistance and the dilatancy of the scalped sample are significantly lower than those for the original soil. This result means that the scalping method leads to an under-estimation of the shear strength of coarse soils. This numerical result is in good agreement with the experimental finding presented in [3]. The reason for this under-estimation is that the shear strength of the original soil results from the contributions of the retained fraction, of the removed fraction and of the interface between them. When controlling the void ratio  $e_{\text{retained}}$  of the retained fraction, we preserve the contribution of the retained fraction. However, we lose the contributions of the removed fraction and the interface between the retained and removed fractions. Therefore, the shear strength of the scalped sample is lower than that of the original soil. The scalping method with  $e_{\text{retained}}$  controlled would work if the removed particles are fully dispersed by the retained particles and then have no significant contribution to the shear strength of the soil.

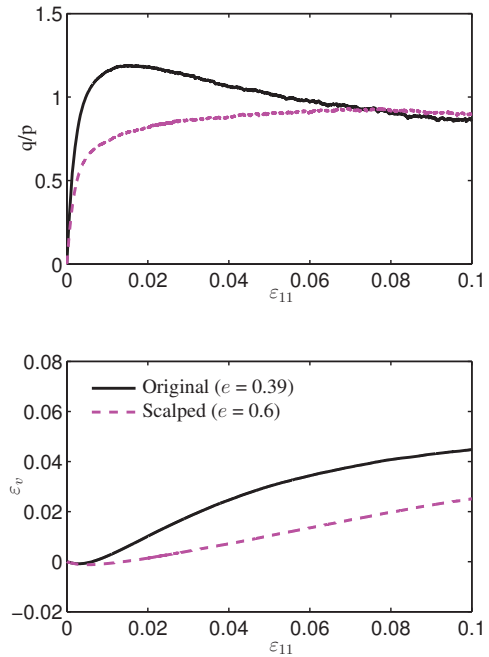


Fig. 2 Stress ratio  $q/p$  and volumetric strain  $\epsilon_v$  versus axial strain  $\epsilon_{11}$  for the original sample with  $f_f = 60\%$  and the scalped one. The void ratio  $e_{\text{retained}}$  of the retained fraction is controlled

2) *Controlling the Relative Density  $D_R$ :* Three original soils with fine contents  $f_f = 20\%$ ,  $30\%$  and  $60\%$  are scalped and substituted. The relative densities  $D_R$  for all the original, scalped and substituted samples are controlled to be equal to 50%. Table II presents some characteristics of these samples. Figs. 3-5 show the stress ratio  $q/p$  and the volumetric strain  $\epsilon_v$  versus the axial strain  $\epsilon_{11}$  for the original samples with the respective fine contents of 20%, 30% and 60% and for their corresponding scaled and substituted samples. As shown in Table II, the scalping method leads to a decrease in the void ratio  $e$  for the original fine content  $f_f = 20\%$  when the relative density  $D_R$  is controlled. As a result, the scalped sample becomes denser and stronger than the original one as shown in Fig. 3. It is clear that the scalping method greatly over-estimates the shear strength and dilativeness of the soil with  $f_f = 20\%$ . On the hand, the scalping method used for the soil with  $f_f = 30\%$  leads to an increase in void ratio  $e$ ; as a consequence the scalped sample is less resistant and less dilative than the original one as shown in Fig. 4. The same result is found for the fine content of 60%. For fine contents of 30% and 60%, the scalping method leads to an under-estimation of the shear strength of the original soils.

As mentioned previously, scalping a coarse soil causes an increase in the fine content  $f_f$  that can lead, in turn, to a change in the soil's microstructure and mechanical behavior. Taha et al. [1], [26] studied the role of fine content  $f_f$  on gap-graded materials by performing numerical simulations with the DEM. The numerical model and materials considered in this study are identical to those considered here. Gap-graded

TABLE II  
 FINE CONTENT  $f_f$ , VOID RATIOS  $e_{\max}$ ,  $e_{\min}$ ,  $e$ , MAXIMUM STRESS RATIO  $(q/p)_{\max}$  FOR ORIGINAL, SCALPED AND SUBSTITUTED SAMPLES

Sample	$f_c$	$e_{\max}$	$e_{\min}$	$e$	$e_f$	$e_c$	$(q/p)_{\max}$
Original	20%	0.46	0.33	0.39	1.93	0.73	1.04
Scalped	30%	0.36	0.29	0.32	1.03	0.9	1.44
Substituted	20%	0.46	0.32	0.39	1.94	0.74	1.02
Original	30%	0.34	0.28	0.3	1.02	0.86	1.43
Scalped	46%	0.41	0.35	0.37	0.81	1.55	1.25
Substituted	30%	0.37	0.3	0.33	1.09	0.89	1.4
Original	60%	0.46	0.39	0.42	0.69	2.5	1.17
Scalped	92%	0.64	0.54	0.58	0.63	19.5	1.0
Substituted	60%	0.49	0.41	0.45	0.74	2.6	1.04

samples with different fine contents were compacted to reach the densest state ( $D_R = 100\%$ ). Fig. 6 shows the dependence of the void ratio  $e$  and the maximum stress ratio  $(q/p)_{\max}$  upon fine content  $f_f$ . It can be seen that by increasing fine content  $f_f$ , the void ratio  $e$  decreases, reaches the lowest value at  $f_f = 30\%$  and then increases with fine content. Fine content of 30% is the optimum fine content at which the fine particles fill the best the void space between the coarse particles without separating the latter ones; therefore, the material density is highest. Lade et al. [27] found also an optimum fine content around 30% for mixtures of coarse and fine sands. It is clear from Fig. 6 (b) that when fine content is smaller than the optimum value of 30%, the shear strength increases with the fine content. The shear strength is the best at the optimum fine content. Above this optimum value, the shear strength decreases with fine content. By using these results, we can explain why the scalping method over-estimates the shear strength for  $f_f = 20\%$  but under-estimates for  $f_f = 30\%$  and 60% as shown in Table II. Indeed, scalping the soil with fine content of 20% causes an increase of its fine content to 30% which is the optimum fine content; therefore, the shear resistance is increased by scalping. Conversely, scalping the soils of  $f_f = 30\%$  and 60% displace fine content further away from the optimum fine content; as a result, the shear strength decreases. These results indicate that over-estimation or under-estimation of the scalping method depends on the value of fine content of the scalped soil in comparison with the optimum fine content. If the fine content gets closer to the optimum value, the scalping method over-estimates the shear strength. If the fine content moves further away from the optimum value, the shear strength is under-estimated.

Regarding the substitution method, it leads to a slight increase of  $e_{\min}$  and  $e_{\max}$  and then  $e$  in comparison with those of the original samples. As shown in Figs. 3-5, the substitution method leads to a good estimation of the shear strength of the original soil except for the sample with fine content of 60% for which the substituted sample has a lower shear strength than the original one. It is worth mentioning that the materials considered here are not widely graded. The substitution method might have stronger effect for more widely graded. Further study needs to be carried out to confirm the obtained results and to interpret them.

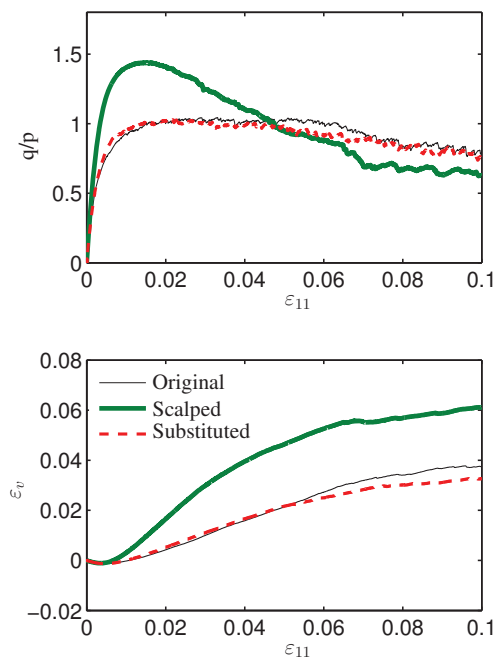


Fig. 3 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original  $f_f = 20\%$  and  $D_R = 50\%$

3) *Controlling the Global Void Ratio  $e$* : In this section, we analyze the behavior of scalped and substituted samples in comparison with that of the original one when the global void ratio  $e$  is controlled to be the same for all the samples. It should be noted that controlling the global void ratio  $e$  is equivalent to controlling the dry density  $\gamma_d$  of samples as proposed in [12], [19] if the solid density  $\gamma_s$  is the same for fine and coarse particles. The scalping method leads to an increase in fine content  $f_f$ , hence a decrease in interfine void ratio  $e_f$  but an increase in the intergranular void ratio  $e_c$ , while the substitution method preserves the latter ones. Table III shows the fine content  $f_f$ , the void ratios  $e$ ,  $e_f$  and  $e_c$  for original, scalped and substituted soils with an original fine content of 30%.

Figs. 7 and 8 show the stress ratio  $q/p$  and the volumetric



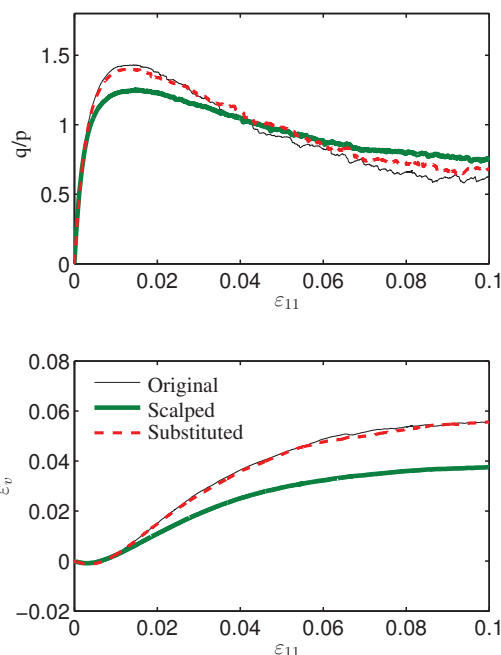


Fig. 4 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original  $f_f = 30\%$  and  $D_R = 50\%$

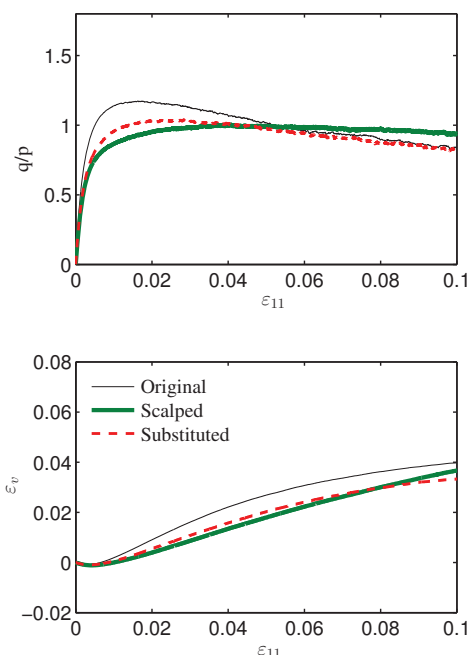


Fig. 5 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original  $f_f = 60\%$  and  $D_R = 50\%$

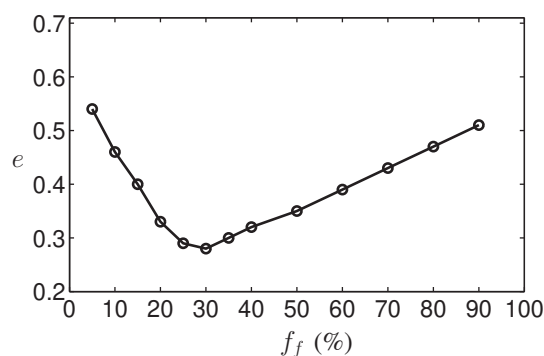
TABLE III  
 FINE CONTENT AND VOID RATIOS FOR ORIGINAL, SCALPED AND SUBSTITUTED SOILS FOR ORIGINAL FINE CONTENT OF 30%

Soil	$f_f$	$e$	$e_f$	$e_c$
Original	30	0.36	1.18	0.94
Scalped	46	0.36	0.79	1.54
Substituted	30	0.36	1.18	0.94

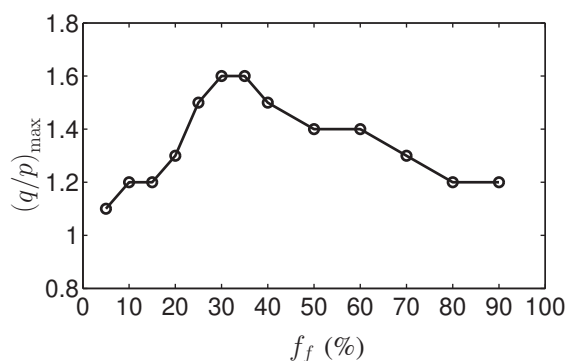
strain  $\varepsilon_v$  versus the axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original fine content  $f_f = 30\%$  with  $e$  controlled to be around 0.36 and  $f_f = 60\%$  with  $e$  controlled to be around 0.49. It is shown that for the original fine content  $f_f = 30\%$ , the scalped and substituted samples show much higher shear strength and dilativeness than those of the original sample, particularly for the scalped sample. For the original fine content of 60%, the scalped sample is much stronger than the original one, while the substitution method results in almost the same behavior as that of the original sample.

As mentioned previously, the scalping method results in primarily an increase in fine content and secondly in a reduction of the particle size gradation of the coarse fraction, while the substitution method results only in the second effect. In the following, we show how the fine content  $f_f$  and the particle size gradation of the coarse fraction influence the mechanical behavior of gap-graded soils when the global void ratio  $e$  is controlled. This understanding is needed to explain the consequences of the scalping and substitution methods shown above.

a) *Effect of Fine Content  $f_f$* : Let us analyze here the effect of the fine content on the mechanical behavior of mixtures of fine and coarse particles when their global void ratios are controlled to be the same. Two series of numerical simulations are performed on samples with gap-graded PSDs shown in Fig. 1. Fine content  $f_f$  is varied from 20% to 50%, and the global void ratio  $e$  is controlled to be around 0.32 for the first series, while  $f_f$  is varied from 50% to 75% and  $e$  is controlled to be around 0.47 for the second series (see Fig. 9). It is worth mentioning that as the maximum and minimum void ratios depend on the fine content, the global void ratio  $e$  cannot be controlled to be the same for all fine contents. Figure 10 presents the behavior of different mixtures with fine contents of 20, 30, 40 and 50%, and the maximum stress ratio  $(q/p)_{max}$  is plotted versus fine content  $f_f$  in Fig. 11 for the two series of tests. It can be seen that the effect of fine content  $f_f$  when  $e$  is controlled is opposite to that found when the relative density  $D_R$  is controlled (Fig. 6). Indeed, mixtures become stronger and more dilative with an increase in fine content  $f_f$  when  $f_f$  is smaller than the optimum value of 30%, but they become weaker and less dilative with an increase in fine content above 30%. At the optimum fine content of 30%, the shear resistance is the highest when the relative density  $D_R$  is controlled, while it is the lowest when the global void ratio  $e$  is controlled. This result can be explained by comparing value of  $e$  to that of the minimum void ratio  $e_{min}$  of each mixture in Fig. 9. At the same value of  $e$ , the mixture with the optimum fine content of 30% is quite far away from the densest state; as a result, it behaves as a loose material. On the contrary, the mixture



(a)



(b)

Fig. 6 (a) Void ratio  $e$  and (b) maximum stress ratio  $(q/p)_{\max}$  versus fine content  $f_f$  for gap-graded samples with  $D_R = 100\%$  [1], [27]

with  $f_f = 20\%$  is quite close to its densest state; therefore, it behaves as a dense material with a stronger dilativeness and higher resistance than those of the mixture with  $f_f = 30\%$ . The difference  $e - e_{\min}$  increases with fine content  $f_f < 30\%$  but decreases with fine content  $f_f > 30\%$ . This explains why the shear strength decreases with fine content  $f_f < 30\%$  but increases with fine content  $f_f > 30\%$ . Thevanayagam et al. [25] studied experimentally the effect of fine content on undrained shear strength of mixtures of silt and sand by controlling the global void ratio  $e$  as close to 0.6 as possible. The authors found that the undrained shear strength decreases with fine content  $< 25\%$  but increases with fine content  $> 25\%$ . The numerical result obtained in our study is in good agreement with the experimental finding of Thevanayagam et al. Moreover, this experimental study reveals that the optimum fine content for the considered silt-sand mixtures is around 30% (the value of 30% was not considered in this study).

*b) Effect of the Grain Size Gradation of the Coarse Fraction:* Three samples of fine content  $f_f$  of 30% were simulated with three different gradation ratios  $D_{\max}/D_{\min} = 1.5, 2$  and 3 for the coarse fraction. The values of  $e$  are controlled to be equal to 0.33 for all the samples as shown in Fig. 12. Fig. 13 shows the stress ratio  $q/p$  and the volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for these three samples. This figure shows clearly a decrease in the shear strength with an increase in the ratio  $D_{\max}/D_{\min}$  for the coarse fraction. This numerical result is in a good agreement with the experimental

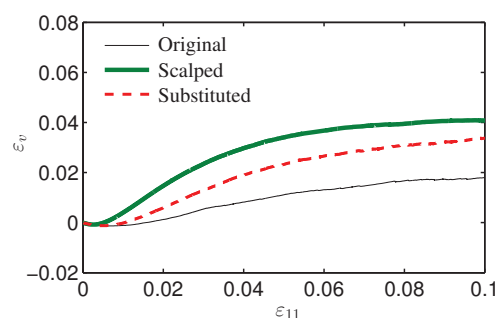
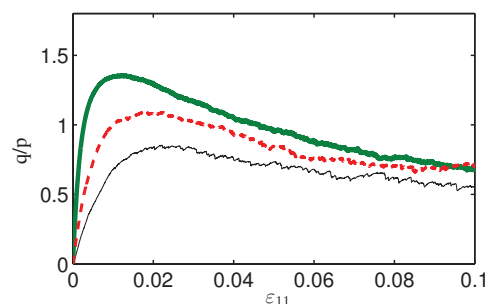


Fig. 7 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original  $f_f = 30\%$  and  $e = 0.44$

finding presented in [3], [28] where the shear strength of mixtures of sands and gravels of the same void ratio  $e$  was found to decrease as the gradation of the gravel fraction increases. The decrease of the shear strength with the ratio  $D_{\max}/D_{\min}$  can be attributed to a decrease of the minimum void ratio  $e_{\min}$  with  $D_{\max}/D_{\min}$  as shown in Fig. 12. Indeed, at the same value of  $e$ , the sample with  $D_{\max}/D_{\min} = 3$  is looser than that with  $D_{\max}/D_{\min} = 1.5$  in comparison with their respective values of  $e_{\min}$ . As a result, the former is less resistant and dilative than the latter.

Following the above numerical finding, the over-estimation of the shear strength of the original sample with  $f_f = 30\%$  by the substitution method when the global void ratio  $e$  is controlled is due to the fact that it reduces the particle size gradation of the coarse fraction. For the original sample with  $f_f = 60\%$ , as its microstructure is primarily governed by the fine fraction, a reduction in the gradation of the coarse fraction has little effect on its shear strength.

Regarding the scalping method, its over-estimation of the shear strength for the original samples with  $f_f = 30\%$  and 60% is primarily due to the increase in fine content  $f_f$  further away from the optimum value of 30% and secondly due to the reduction of the gradation of the coarse fraction. It could be expected that the scalping method leads to an under-estimation or good estimation of the shear strength for the original sample with  $f_f = 20\%$  as the increase in fine content  $f_f$  to 30% leads to the loss in shear strength which might be greater or equal to the gain in shear strength caused by the reduction of the gradation of the coarse fraction.

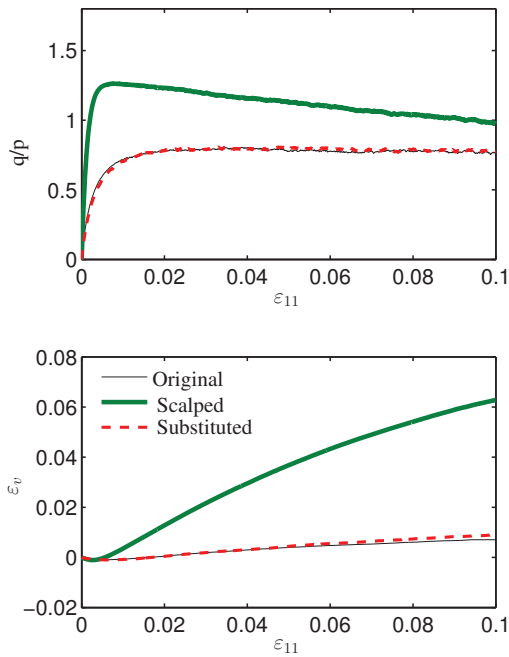


Fig. 8 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with an original  $f_f = 60\%$  and  $n = 0.32$

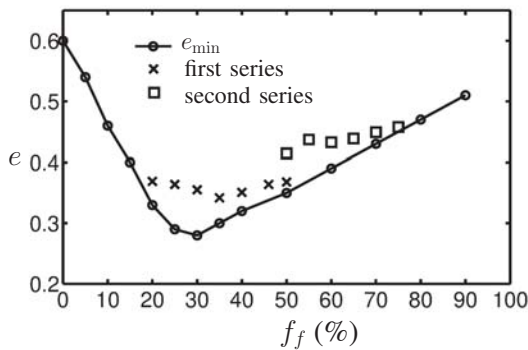


Fig. 9 Global void ratio  $e$  of mixtures for the first and second series of tests, in comparison with the minimum void ratio  $e_{min}$

#### A. Summary

A numerical study of consequences of the scalping and substitution methods on the shear strength of gap-graded materials has been presented. Three different parameters have been considered to control the compactness state of scalped and substituted samples in comparison with that of the original soil: the void ratio  $e_{retained}$  of the retained fraction, the relative density  $D_R$  and the global void ratio  $e$ . If  $e_{retained}$  is controlled, the scalping method under-estimates significantly the original shear strength. This method can either under-estimate or over-estimate the original shear strength when  $D_R$  or  $e$  is controlled depending on the original fine content in comparison with the optimum value. Regarding

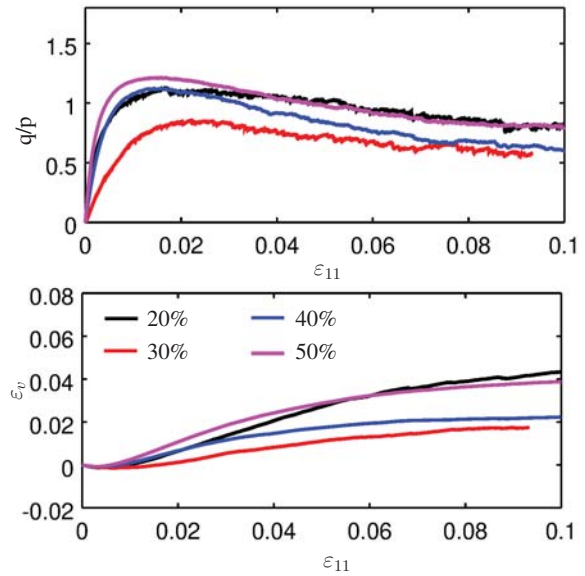


Fig. 10 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for different fine contents  $f_f$  when the global fine content  $e$  is controlled to be almost the same

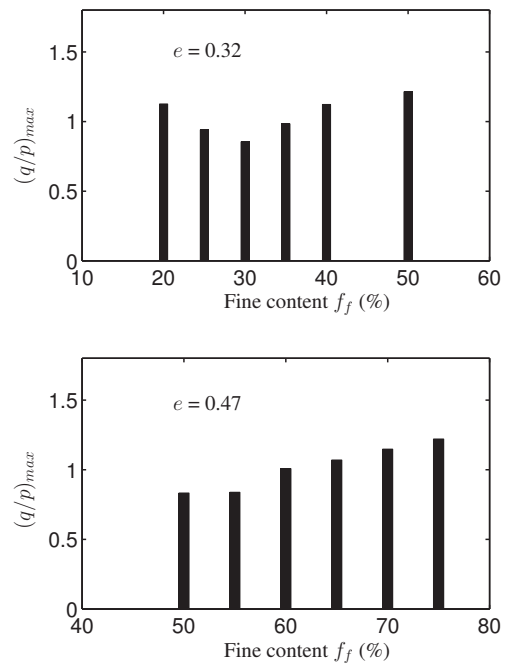


Fig. 11 Maximum stress ratio  $(q/p)_{max}$  versus fine content  $f_f$  when the global void ratio  $e$  is controlled

the substitution method, it could work if the relative density  $D_R$  is controlled. When the global void ratio  $e$  is controlled, it over-estimates the shear strength for original fine content  $f_f < 60\%$  and gives a good estimation for  $f_f > 60\%$ . It is worth mentioning that controlling the relative density  $D_R$  requires values of the maximum and minimum void

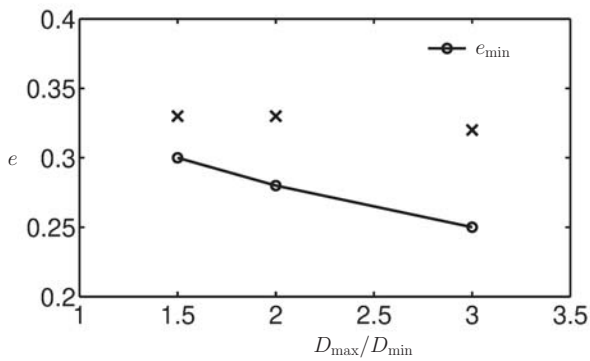


Fig. 12 Global void ratio  $e$  is controlled to be almost close to 0.33 for three mixtures of  $D_{max}/D_{min} = 1.5, 2$  and  $3$ , and with  $f_f = 30\%$ , in comparison with values of  $e_{min}$

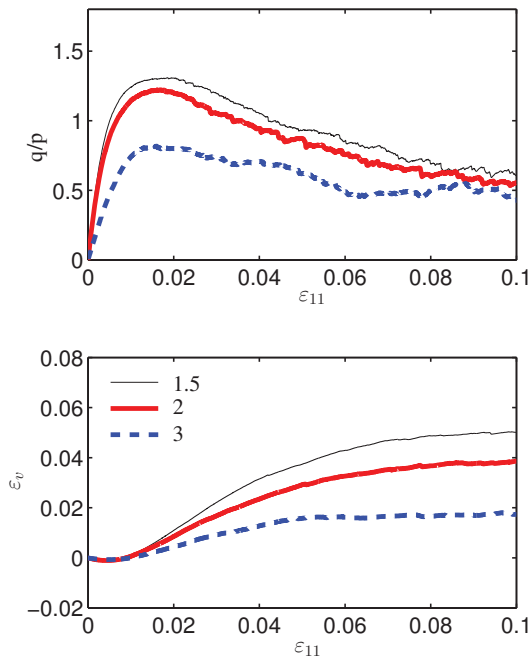


Fig. 13 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  with different grading  $D_{max}/D_{min}$  and  $f_f = 30\%$

ratios  $e_{max}$  and  $e_{min}$  for each original, scalped and substituted soil, which are difficult to obtain for coarse soils by using the experimental standard compaction procedures because of particle segregation. This is the reason why only the global void ratio  $e$  is controlled for the experimental study that will be presented in the following.

### III. EXPERIMENTAL STUDY

Experimental tests were carried out by using two triaxial devices with diameters  $\Phi 100$  mm and  $\Phi 50$  mm. The ratio  $\Phi/D_{max} = 10$  ( $D_{max}$  is the maximum particle diameter) is kept for all performed tests in order to respect experimental standards. Coarse soils considered in this study are mixtures

of Fontainebleau sand, representing the fine fraction, and Palvadeau and natural gravels, representing the coarse fraction. The names of Fontainebleau sand, Palvadeau and natural gravels are abbreviated as FS, PG and NG, respectively. Table IV presents some characteristics of these elementary materials. It should be noted that the internal friction angle of a soil depend on its void ratio  $e$ ; therefore, the values of the drained friction angle  $\varphi'$  shown in this table are only valid for the corresponding values of the void ratio  $e$ . As the coefficient of uniformity  $C_u$  and the void ratio  $e$  are almost the same for both Palvadeau and natural gravels, Palvadeau gravels appear to be more resistant than natural gravels. Two coarse soils with fine contents of 30% and 60%, namely FS30PG40NG30\_10 (30% Fontainebleau sand + 40% Palvadeau gravel + 30% natural gravel) and FS60PG10NG30\_10 (60% Fontainebleau sand + 10% Palvadeau gravel + 30% natural gravel), were used. Their samples have a diameter of 10 mm and they were tested by using the triaxial device of  $\Phi 100$  mm.

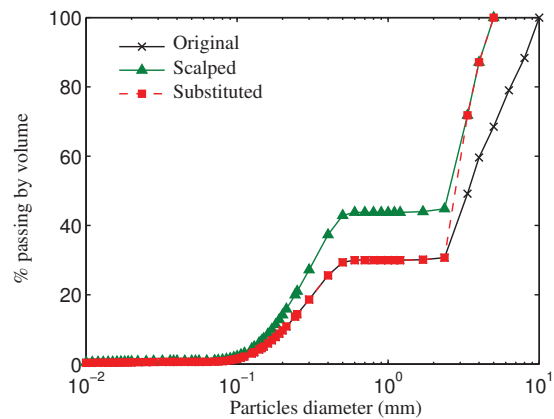


Fig. 14 PSDs for the original soil with  $f_f = 30\%$  and its scalped and substituted ones

Each original soil is then scalped at a particle diameter of 5 mm: the finer fraction (Fontainebleau sand and Palvadeau gravels) is retained, while the coarser fraction (natural gravels) is removed. The original soil is also substituted, where the fraction of natural gravels is removed and replaced by an equal mass of Palvadeau gravels. The particle size gradation of the replacement material is chosen to be the same as that of Palvadeau gravels in the original sample. Fig. 14 shows the PSDs of the original soil with fine content  $f_f$  of 30% and its corresponding the scalped and substituted soils. Scalped and substituted samples are named by the name of their corresponding original soil followed by letter S for scalping and SR for scalping/replacement, respectively, and the number 5 indicating their maximum particle diameter of 5 mm. For example, FS30PG40NG30\_S\_5 and FS30PG40NG30\_SR\_5 are the respective scalped and substituted samples of the original soil FS30PG40NG30\_10. The global void ratio  $e$  is controlled such that it is almost the same for all the original, scalped and substituted samples. Samples were compacted by the moist tamping to achieve the target void ratio and then saturated. Afterwards, they are consolidated and then sheared



TABLE IV  
 CHARACTERISTICS OF THE ELEMENTARY MATERIALS TO COMPOSE COARSE SOILS

Materials	Abbrev.	$d_{\min}$ (mm)	$d_{\max}$ (mm)	$C_u$	$e$	$\varphi'$
Fontainebleau Sand	FS	0.01	0.6	2.32	0.54	40.6°
Palvadeau Gravels	PG	1.6	5.0	1.57	0.54	42°
Natural Gravels	NG	5.0	10.0	1.45	0.55	47.8°

under drained conditions with an effective confining pressure of 100 kPa.

Table V shows the characteristics of the tested samples: composition of each sample, global, interfine and intercoarse void ratios  $e$ ,  $e_f$  and  $e_c$ , and the undrained friction angle  $\varphi'$  obtained from the triaxial test. Figs. 15 and 16 present the stress ratio  $q/p$  and the volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  for original, scalped and substituted samples with original fine contents of 30% and 60%, respectively. It can be seen that the scalping method results in a friction angle significantly higher than that of the original soil of  $f_f = 30\%$  (40.3° for the scalped sample compared to 37.4° for the original sample), while it gives a good friction angle for the original soil of  $f_f = 60\%$  (40.5° for the scalped sample compared to 40.7° for the original soil). Regarding the substitution method, it gives friction angles close to those of the original samples for both fine contents of 30% and 60%. One can also remark in Figs. 15 and 16 that it is difficult to get a clear effect of the scalping and substitution methods on the volumetric behavior of soils. El Dine et al. [28] also found that studying the volumetric behavior of gap-graded samples is particularly complicated as they are no longer homogeneous because of shear bands.

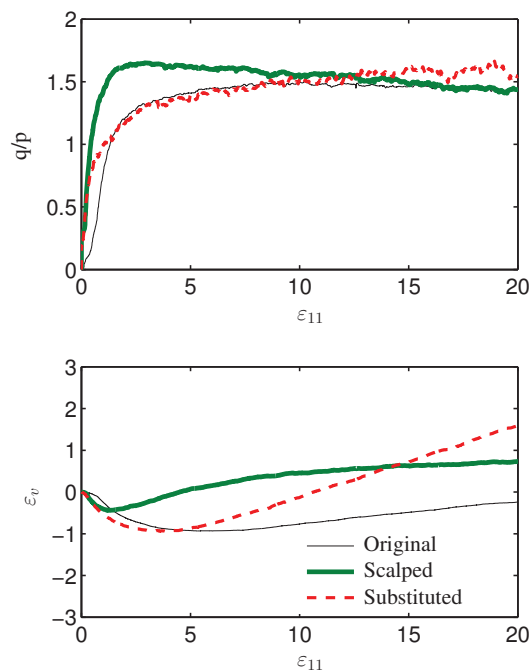


Fig. 15 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  with original  $f_f = 30\%$

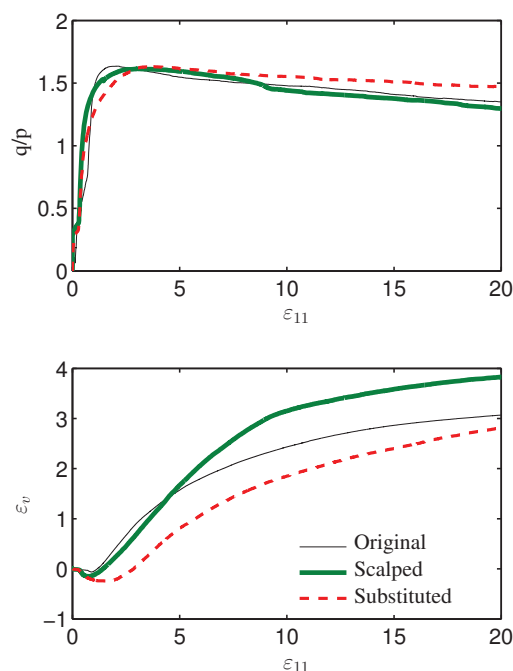


Fig. 16 Stress ratio  $q/p$  and volumetric strain  $\varepsilon_v$  versus axial strain  $\varepsilon_{11}$  with original  $f_f = 60\%$

By qualitatively comparing the numerical results presented previously to the experimental ones shown here, we find some agreements between them. Both studies show an over-estimation of the shear strength by the scalping method for the original soil with 30% of fine content, and a good estimation by the substitution method for original soils with 60% of fine content. However, we find some divergences between the numerical and experimental results. Firstly, the numerical simulation predicts an over-estimation of the shear strength by the scalping method for the original soil of 60% of fine content, while the experimental study shows a good estimation of the shear strength for this soil. Secondly, the substitution method over-estimates the shear strength of soil with 30% of fine content according to the numerical study, while it results in a good estimation according to the experimental study. These divergences are certainly due to the fact that the numerical simulations considered only spherical particles with the same surface friction angle so the effect of particle properties such as shape, roughness were not taken into consideration. For physical soils, particle properties of fine particles might be strongly different from those of coarse particles and these properties might be different for particles

TABLE V  
CHARACTERISTICS OF THE ORIGINAL COARSE SOILS AND THEIR CORRESPONDING SCALPED AND SUBSTITUTED SOILS

Soils	%FS	%PG	%NG	$e$	$e_f$	$e_c$	$\varphi'$ (°)
FS30PG40NG30_10	30	40	30	0.33	1.09	0.89	37.1
FS30PG40NG30_S_5	44	56	0	0.333	0.74	1.37	40.0
FS30PG40NG30_SR_5	30	70	0	0.32	1.08	0.89	37.95
FS60PG10NG30_10	60	10	30	0.39	0.65	2.48	40.35
FS60PG10NG30_S_5	84	16	0	0.39	0.47	7.70	40
FS60PG10NG30_SR_5	60	40	0	0.40	0.67	2.51	39.8

in the same fraction. For the soils tested in our experimental study, the coarse fraction (Palvadeau and natural gravels) is more resistant than the fine fraction (Fontainebleau sand). For the coarse fraction, natural gravels are more resistant than Palvadeau gravels as shown in Table IV. It should be noted that scalping a coarse soil leads to gain in shear resistance due to the increase in fine content but to a loss in shear resistance due to the decrease in coarse content. For numerical materials where the particle properties are the same for both fine and coarse fractions, the gain is bigger than the loss; therefore the scalping method over-estimates the shear resistance when the global void ratio  $e$  is controlled. However, for the considered physical coarse soils, the natural gravels are significantly stronger than Fontainebleau sands and Palvadeau gravels; as a result, removing them from the soils causes a significant loss in shear strength which might be equal to the gain. This would be the reason why the shear strength of the soils with 60% of fine content is well estimated by the scalping method. For the substitution method, we gain the shear resistance due to the reduction in particle size gradation of the coarse fraction but we gain or loss the shear resistance depending on the resistance of the replacement material compared to that of the replaced material. For numerical materials, there is no loss since the particle properties are the same for both replacement and replaced materials. For the considered physical soils, the replacement material (Palvadeau gravels) is less resistant than the replaced material (natural gravels), leading to a loss in the shear strength of the substituted soils; and this loss might be equal to the gain. This would be the reason why the substitution method gives a good estimation of the shear strength for the soils with 30% of fine content. Further numerical and experimental studies need to be carried out to understand the effect of particles properties when using the scalping and substitution methods.

#### IV. CONCLUSIONS

In this paper, we have presented a study on the effect of the scalping and substitution methods on the mechanical behavior of gap-graded soils by performing numerical simulations with the DEM and experimental triaxial tests. Numerical original samples are composed of fine and coarse spherical particles with different fine contents. They are scalped and substituted, and their compactness states are controlled by considering three different parameters: void ratio  $e_{\text{retained}}$  of the retained fraction, the relative density  $D_R$  and the global void ratio  $e$ . The numerical study has shown that the scalping method

leads to a significant under-estimation of the shear strength when  $e_{\text{retained}}$  is controlled. It can lead to an under-estimation or an over-estimation of the shear strength depending on whether  $D_R$  or  $e$  is controlled and on the original fine content with respect to the optimum fine content. Its consequences are mainly due to the increase in fine content. Whereas, the substitution method leads to an over-estimation of the shear strength for the soil with 30% of fine content if the global void ratio  $e$  is controlled to be the same for both original and substituted soils, but it gives a good estimation for the soil with 60% of fine content. Its consequences are mainly due to the reduction in the particle size grading of the coarse fraction. Coarse soils were composed of Fontainebleau sands, Palvadeau and natural gravels with different fine contents were considered in the experimental study. The global void ratio  $e$  was controlled to be the same for all original, scalped and substituted samples. It was found that the scalping method gives an over-estimation of the shear strength of the original soil with 30% of fine content but it gives a good estimation for the soil with 60% of fine content. The substitution method gives a good estimation of the shear strength for both soils. By a qualitative comparison between the numerical and experimental results, we found some agreements but also disagreements between these results. The disagreements are certainly due to the fact that particle properties such as shape and surface roughness were not taken into consideration in the numerical study. For physical coarse soils, particle properties have a great influence on the mechanical behavior of original, scalped and substituted soils. The influence of particle properties need to be addressed in the upcoming study.

LIST OF SYMBOLS

$f_f$	Fine content
$f_n, f_t$	Normal and tangential contact forces
$k_n, k_t$	Normal and tangential particle stiffnesses
$K_n, K_t$	Normal and tangential contact stiffnesses
$E_m$	Young's modulus of the particle material
$\varphi$	Contact friction angle
$D_{\min}, D_{\max}$	Minimum and maximum diameters of coarse particles
$d_{\min}, d_{\max}$	Minimum and maximum diameters of fine particles
$G_r$	Gap ratio
$e$	Global void ratio
$e_f$	Interfine void ratio
$e_c$	Intergranular void ratio
$e_{\text{retained}}$	Void ratio of retained particles
$D_R$	Relative density
$V_v, V_s$	Void and solid volumes
$\sigma$	Stress tensor
$p$	Mean stress
$q$	Deviatoric stress
$\varepsilon$	Strain tensor
$\varepsilon_{11}$	Axial strain
$\varepsilon_v$	Volumetric strain

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