JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
55, 2, pp. 523-533, Warsaw 2017
DOI: 10.15632/jtam-pl.55.2.523

EXPERIMENTAL STUDY OF THE SHEAR RESISTANCE OF GRANULAR MATERIAL: INFLUENCE OF INITIAL STATE

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The shear strength of sand and its mechanical properties can be affected by numerous parameters. This work presents an experimental investigation which aims to study the influence of the fines content, the depositional method and the grain size on the shear strength of Chlef sand. Tests were conducted with the shear box on two types of soil, the natural sand and the clean sand-silt mixture. Dense samples ($Dr = 88\%$) were reconstituted through dry deposition for each type of the material. An additional series of tests was carried out on a medium dense natural sand ($Dr = 52\%$) prepared by dry and wet ($w = 3\%$) deposition methods. All specimens were subjected to normal stresses of 100 kPa, 200 kPa and 300 kPa and there was no immersion of water. The tests results show that the behavior of sand can be affected by three parameters, the fines content, the deposition method and the particle size. The maximum shear stress and the friction angle decrease as the fines content increases, the initial water content increases, the effective grain size diameter decreases and the uniformity coefficient increases. The cohesion intercept increases with the increasing fines content and decreasing initial water content. Overall, the samples prepared by the dry deposition method show more resistance than those prepared by the wet deposition method. The results obtained are generally in agreement with the previous research on drained and undrained saturated sand in the literature.

Keywords: dry sand, fine content, water content, grain size, depositional method

1. Introduction

Soil of the Chlef region is vulnerable to earthquakes and its mechanical effects as the north of Algeria is a part of the African tectonic plate. On October 10th 1980, the Chlef region was hit by an earthquake of magnitude 7.3 [12], considered the strongest in its history. Much damage occurred due to landslides, pavement deformation and liquefaction [3]. Due to all these facts, the characterization of the mechanical behavior of soil of this region and especially the sand of Chlef river is of relevance to mitigate and prevent similar disaster in the future.

The shear strength of soil was studied through the direct shear test. The experiment showed that very similar shear strength results could be obtained on saturated sand and dry sand, provided that the sand remained saturated and that drainage took place freely during shear, and in both cases the effective stresses were equal to the total stresses (Head and Epps, 2011).

The behavior of saturated Chlef sand is the topic of study of many researchers, but studies conducted on the dry chlef sand are rare in the literature.

The objective of this research was to study the effect of the fines content, the deposition method and the particle size on the shear strength of the dry Chlef sand (without saturation by immersion in water) using the direct shear apparatus.

2. Literature review

The effect of the fines content and the sample preparation method on the liquefaction resistance of saturated soil was the subject of some controversial research, because no consensus could be found in the literature.

Researchers who studied the effect of the fines content on the resistance of saturated soils are divided into three groups; some say that an increase in the fines content increases the liquefaction resistance (Chang *et al.*, 1982; Amini and Qi, 2000), others say that it reduces the liquefaction resistance (Shen *et al.*, 1977; Troncosco and Verdugo, 1985; Finn *et al.*, 1994; Vaid, 1994; Zlatovic and Ishihara, 1997; Arab, 2009; Belkhatir *et al.*, 2013, 2014), while the third group of researchers conclude that the liquefaction resistance decreases with an increasing fines content to a minimum value, then it rises (Law and Ling, 1992; Koester, 1994; Bouferra and Shahrour, 2004).

The results obtained on the effect of the depositional method are not all in agreement, some authors found that the samples prepared by the sedimentation method present a higher resistance to liquefaction than the samples prepared by other methods such as the dry funnel pluviation and the wet deposition (Zlatovic and Ishihara, 1997); others found that the liquefaction resistance of the samples prepared by the wet deposition is larger than that of samples prepared by the dry funnel pluviation (Mulilis *et al.*, 1977; Yamamuro and Wood, 2004). Canou (1989), Ishihara (1993), Benahmed *et al.* (2004) found that the resistance of the samples prepared by the dry funnel pluviation is more elevated than by the wet deposition method. The tests performed by Della *et al.* (2009) on saturated Chlef sand confirmed this result, showing that the dry funnel pluviation method gives stable samples (dilating) while the wet deposition method encourages contractance.

It is known in the literature that the particle size significantly affects the resistance to soil liquefaction. Whether from studies conducted in the laboratory (Lee and Fitton, 1968) or in situ observations (Tsuchida, 1970; Seed and Idriss, 1971), many boundaries of particle size distribution curves have been proposed to identify liquefiable soils. To study the effect of grain size, a series of undrained tests were performed by Belkhatir *et al.* (2011). They found that the undrained shear strength at the peak and the undrained residual shear strength decreased as the coefficient of uniformity increased while the average diameter decreased and fines content increased up to 50%.

Due to the lack of studies conducted on the unsaturated sand of Chlef region (Northern Algeria), it was suggested to study the effect of the fines content, the deposition method and the particle size on the shear strength of the dry Chlef sand (without saturation by immersion in water) using the direct shear apparatus.

3. Material tested

The tests were realized on sand from the Chlef river (which crosses the city of Chlef to the west of Algiers). However, two types of the Chlef sand were used; the natural sand and the clean sand mixed with different fractions of silt (from 0% to 40%). The Chlef river silt shows low plasticity with a plasticity index equal to 5.81%. Figure 1 shows microphotographs of the natural and the clean sand. The properties of the natural sand, the clean sand-silt mixture and the silt used in this study are illustrated in Table 1. The grain size distribution curves of the tested soils are shown in Fig. 2.

Figure 3 shows the variation of the maximum and the minimum void ratio with the fines content. It is clear that both decrease with the increasing fines content (Fc) up to a value $Fc = 30\%$ beyond which they begin to increase following the same trend (similar observation were reported by Belkhatir *et al.* (2013)).

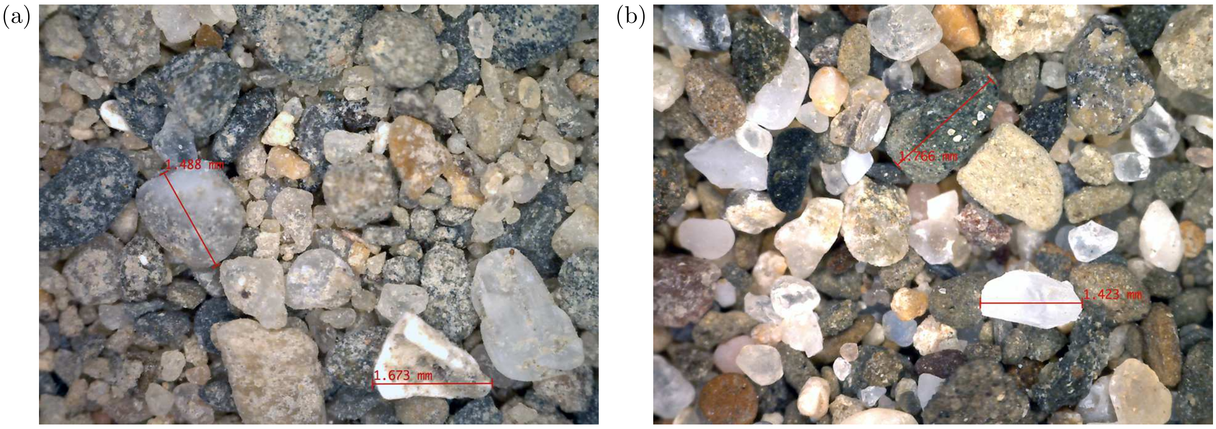

Fig. 1. Microphotographs: (a) Chlef natural and (b) Chlef clean sand (zoom 50x)

Table 1. Index properties of materials used

Material	Fc [%]	G_S [g/cm^3]	e_{min}	e_{max}	D_{10} [mm]	D_{30} [mm]	D_{50} [mm]	D_{60} [mm]	C_U	C_C
Natural sand	1	2.700	0.586	0.946	0.171	0.311	0.463	0.538	3.153	1.055
Clean sand	0	2.652	0.632	0.795	0.266	0.431	0.596	0.700	2.634	0.999
Silty sand	10	2.654	0.536	0.703	0.077	0.369	0.549	0.643	8.304	2.733
(clean sand	20	2.655	0.458	0.697	0.029	0.298	0.510	0.616	21.622	5.058
+ fines	30	2.657	0.449	0.687	0.017	0.087	0.420	0.535	30.630	0.811
content)	40	2.658	0.504	0.759	0.011	0.057	0.307	0.437	38.305	0.662
Silt	100	2.667	0.991	1.563	–	0.015	0.029	0.036	–	–

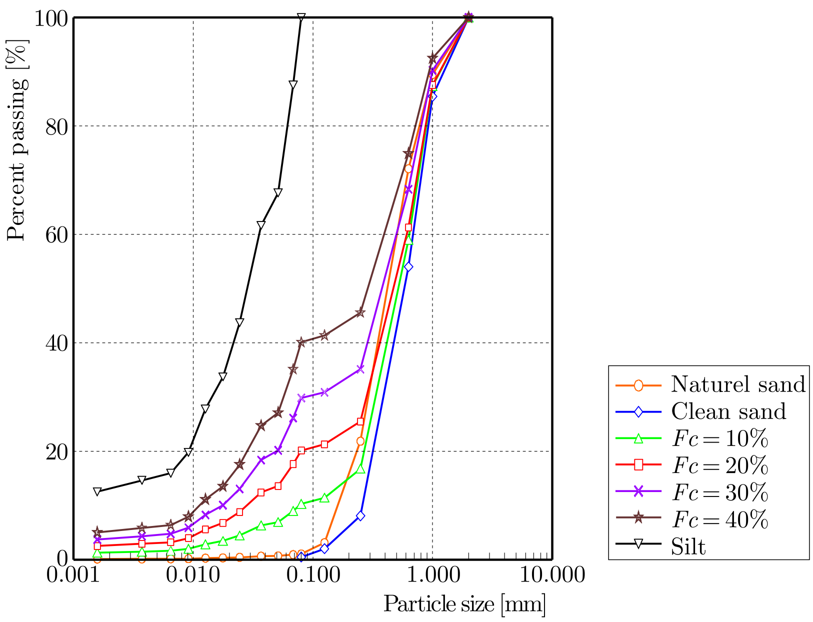

Fig. 2. Grain size distributed curves of the tested materials

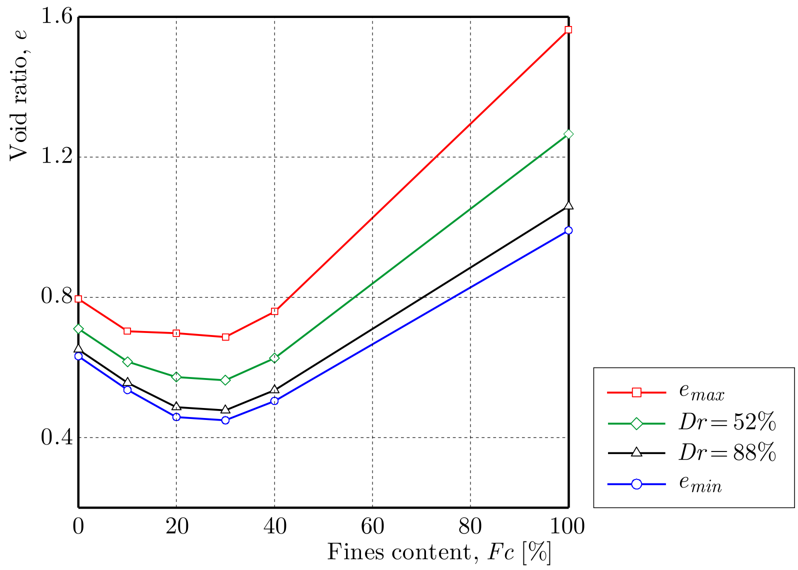

Fig. 3. Maximum and minimum void ratios versus fines content

4. Experimental program

In this study, a series of tests were performed on the natural sand and the clean sand-silt mixture for a relative density $Dr = 88\%$ (also $Dr = 52\%$ for some tests) under three normal stresses $\sigma_N = 100$ kPa, 200 kPa and 300 kPa. To study the effect of the depositional method, dry or wet, the initial water contents were set to $w = 0\%$ and 3%, respectively.

The tests were performed using a square direct shear box $60\times60\,\text{mm}^2$. The initial sample height was 25 mm. The test consisted in placing a sample in the shear box and subjecting it to a vertical load N that represented the normal stress applied (100 kPa, 200 kPa, 300 kPa) and a horizontal load T which was gradually increased. The direct shear test allowed measuring the peak and residual shear strength corresponding to every normal stress.

Two methods were used to set-up the sample, the dry deposition and the wet deposition methods. In the wet deposition method, the dry sand was mixed thoroughly with a small quantity of water (3%) until a homogeneous soil sample was obtained. In the dry deposition method, the sand was deposited in the dry state. To achieve the two relative densities, the sample was divided into three layers. Each layer was compacted to achieve the dense state ($Dr = 88\%$), however, no compaction was necessary to achieve the medium dense state ($Dr = 52\%$), so only the sample surface was leveled off. After the set-up, the samples were sheared at a constant speed (1 mm/min).

5. Test results

5.1. Effect of fines content

To study the effect of fines content on the shear strength of dry sand, five samples of sand-silt mixture ($Fc = 0\%$ to 40%) were tested under three normal stresses. Figure 4a shows the effect of the fines content on the shear stress of dry sand ($\sigma_N = 300$ kPa, $Dr = 88\%$). For samples with $Fc = 0\%$ to 20%, the mobilized shear stress increased with the increasing horizontal displacement to reach the maximum value (located between 2 and 3 mm) and then it gradually decreased; whereas the mobilized shear stress of samples with $Fc = 30\%$ and $Fc = 40\%$ did not show the peak value (Fig. 4a).

Figure 4b shows the Mohr-Coulomb failure envelope that represents the relationship between the maximum shear stress τ_{max} and the normal stress σ_N according to the following formula

$$\tau_{max} = C + \sigma_N \tan\varphi \tag{5.1}$$

where C and φ are the cohesion intercept and the friction angle, respectively.

Figure 4b shows clearly that the slope of the failure envelope decreases with the increasing fines content. The reliability of these results is high considering the limited spread obtained for each series of tests ($R^2 = 0.97 \sim 0.99$).

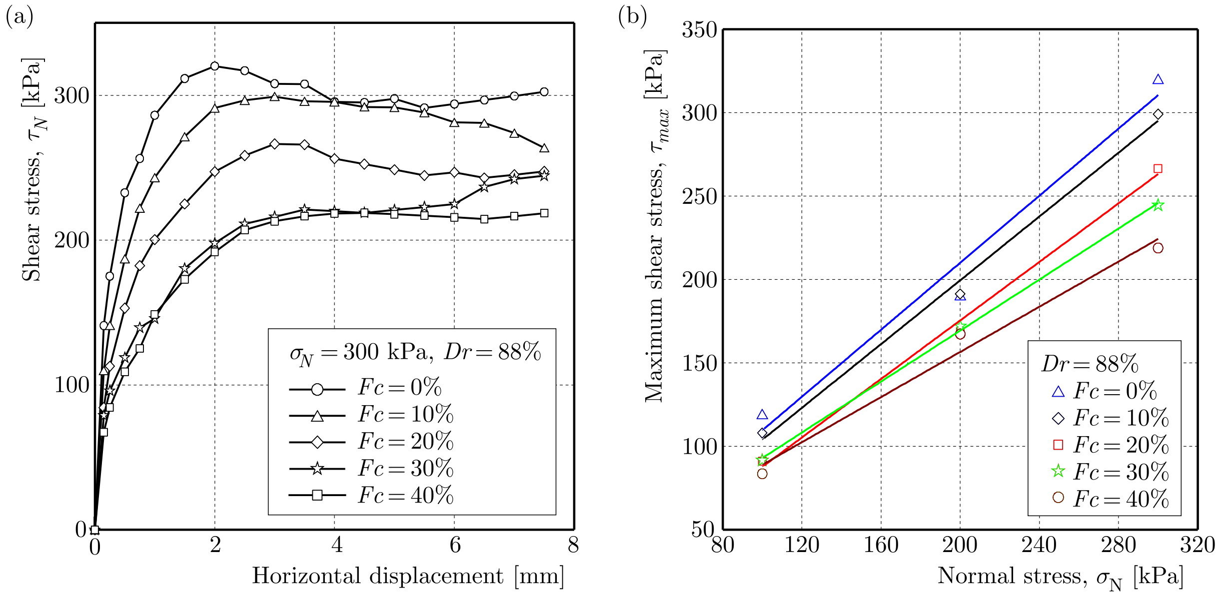

Fig. 4. Effect of the fines content on the strength: (a) shear stress versus horizontal displacement $\sigma_N = 300$ kPa, $Dr = 88\%$, (b) maximum shear stress versus normal stress

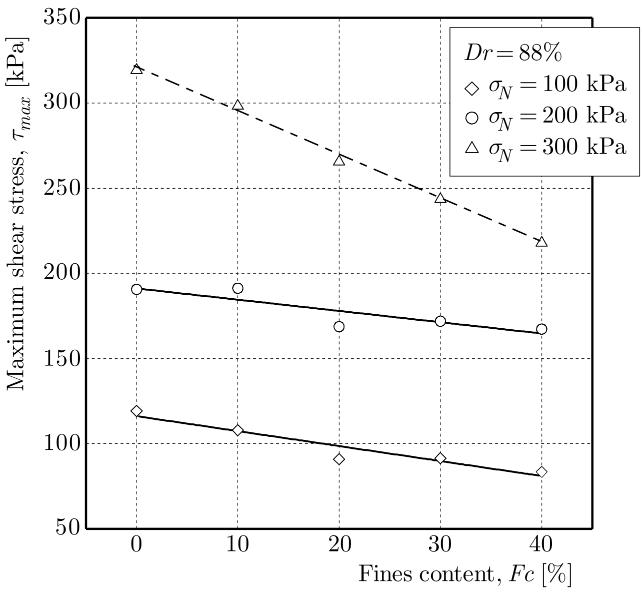

Fig. 5. Maximum shear stress (τ_{max}) versus fines content (Fc), $\sigma_N = 100$, 200, 300 kPa, $Dr = 88\%$

The development of the maximum shear stress with the fines content is shown in Fig. 5. It is clear from this figure that the maximum shear stress decreases with the increasing fines content for the three normal stresses ($\sigma_N = 100$, 200, 300 kPa), but the decrease is more pronounced for $\sigma_N = 300$ kPa.

Figure 6 shows the effect of the fines content on the mecanical properties (cohesion intercept and friction angle) of the sand-silt mixture for the dense state ($Dr = 88\%$). It can be seen that the cohesion increases with the increasing fines content (Fig. 6a). For the friction angle, it is clear that it decreases lineary with the increasing fines content (Fig. 6b). This decrease in the resistance is probably due to the presence of fine particles between grains of sand that promote reduction in the contact between sand particles. The same effect was found by Arab (2009) on the saturated sand.

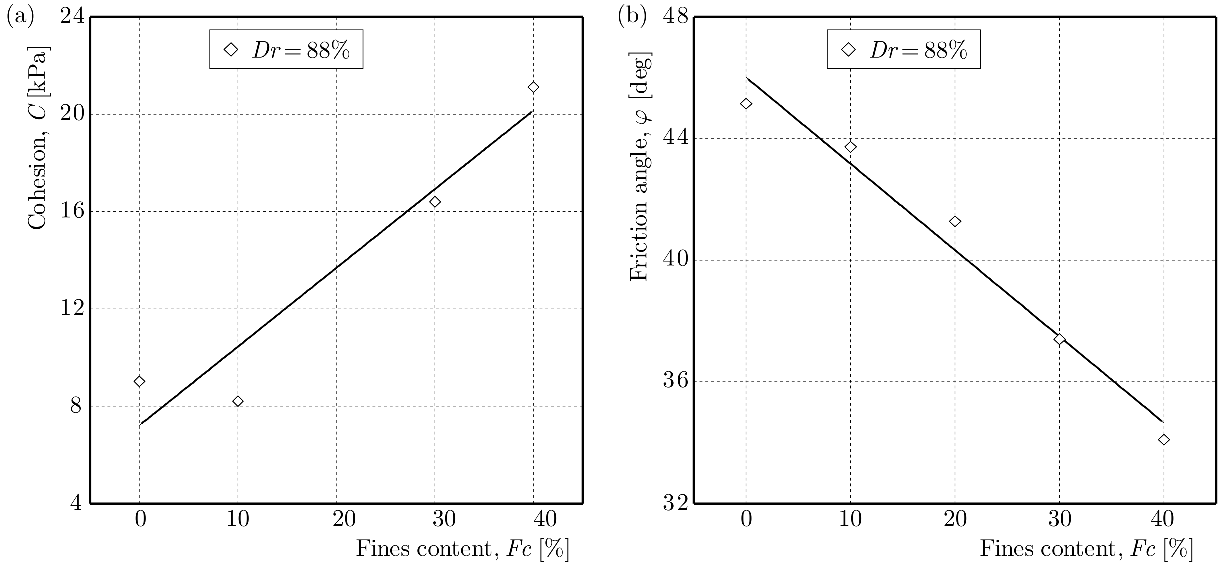

Fig. 6. Variation of mechanical properties with the fines content (Fc), $Dr = 88\%$: (a) cohesion versus fines content, (b) friction angle versus fines content

5.2. Effect of the mode of deposition

In order to study the effect of the depositional method (dry or wet), a series of tests were performed on the natural sand. Two values of initial water content were used; $w = 0\%$ for the dry case, and $w = 3\%$ for the wet case. Specimens at two relative densities were tested ($Dr = 52\%$, $Dr = 88\%$) subjected to three levels of normal stresses ($\sigma_N = 100$, 200 and 300 kPa).

The relationship between the mobilized shear stress and the horizontal displacement is shown in Fig. 7. For the medium dense state ($Dr = 52\%$), it is clear from Fig. 7a that the shear stress of the dry specimens rapidly increases until a horizontal displacement of about 3 mm occurs. Beyond that, the increase is less significant. The results on the specimens prepared by wet deposition show a mobilized shear stress that increases continuously with the increasing horizontal displacement. In the dense state ($Dr = 88\%$), Fig. 7b shows that the shear stress of the dry method rises to reach a peak value (between 3 mm and 6 mm), while the shear stress of the wet method keeps increasing with the horizontal displacement as in the medium dense specimens.

Figure 8 shows the variation of the maximum shear stress τ_{max} (deduced from Fig. 7) with the initial water content in the two states, the dense and the medium dense. It is clear that the maximum shear stress of the dry specimens is higher than that of the wet specimens. This result is in agreement with that obtained by Della *et al.* (2009) on the saturated sand. The difference in the resistance between the dry and wet deposition method is more pronounced in the dense

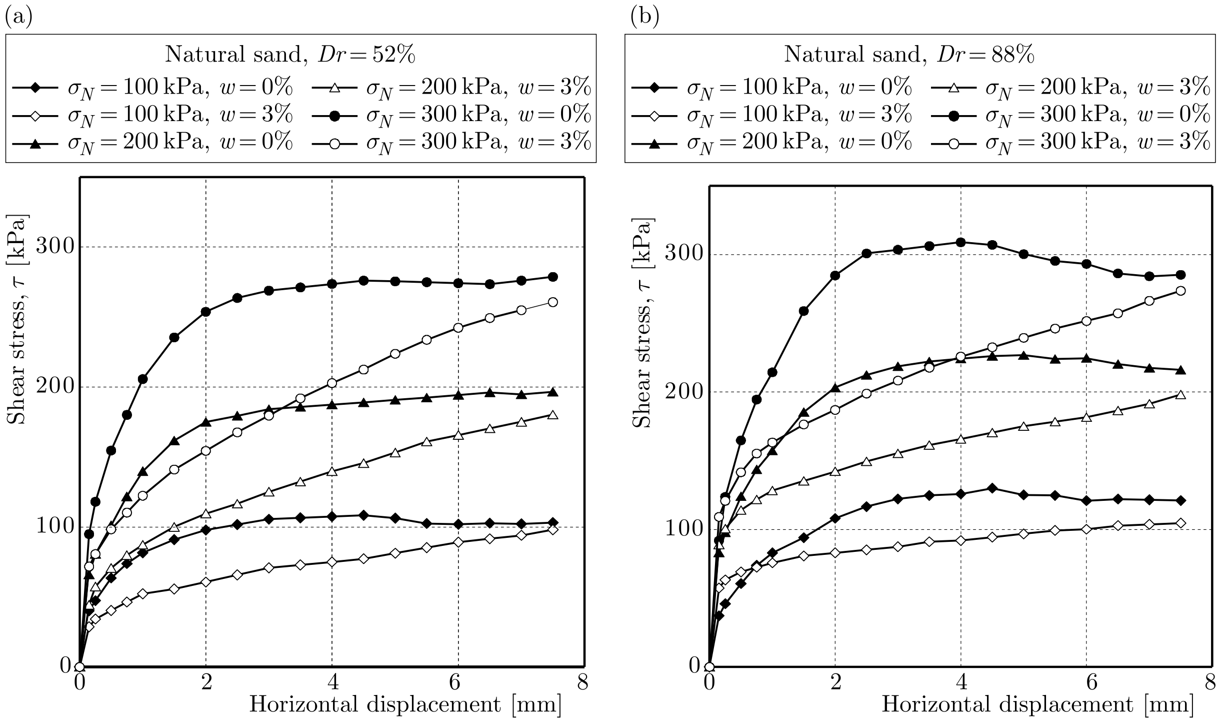

Fig. 7. Shear stress versus horizontal displacement, $\sigma_N = 100$, 200 and 300 kPa: (a) medium dense state ($Dr = 52\%$), (b) dense state ($Dr = 88\%$)

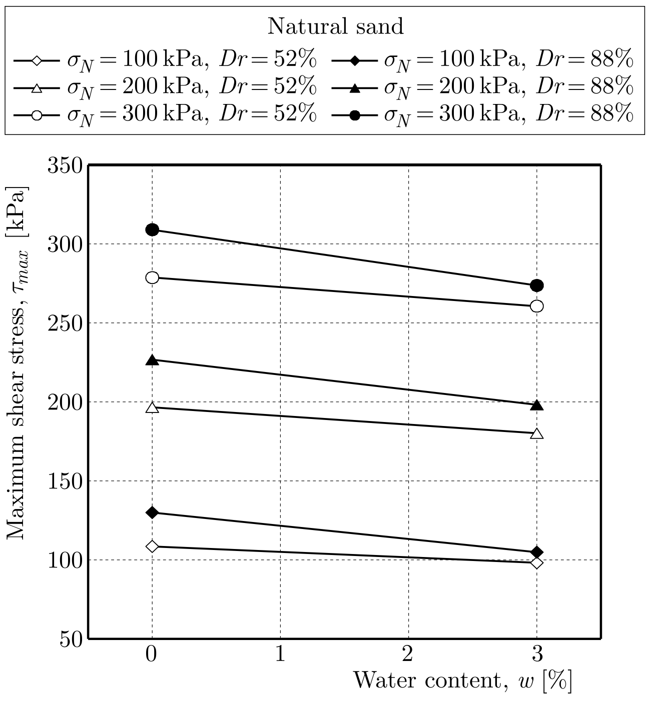

Fig. 8. Maximum shear stress (τ_{max}) versus water content (w), $\sigma_N = 100$, 200 and 300 kPa, $Dr = 52\%$ and 88%

state. Furthermore, the difference in the resistance between the dense state and the medium dense state is more apparent in the dry deposited samples than in the wet deposited samples.

The effect of the depositional method in terms of the initial water content on the mechanical properties of sand is shown in Fig. 9. It is clear that the cohesion intercept decreases with the increasing initial water content for both the dense and the medium dense state (Fig. 9a), but the trend of the decrease is more pronounced in the dense state. Concerning the friction angle, it can be seen from Fig. 9b that it also decreases with the increasing initial water content with the same trend for the two relative densities. This decrease in the friction angle confirms the previous result and allows saying that the dry samples are more resistant than the wet samples.

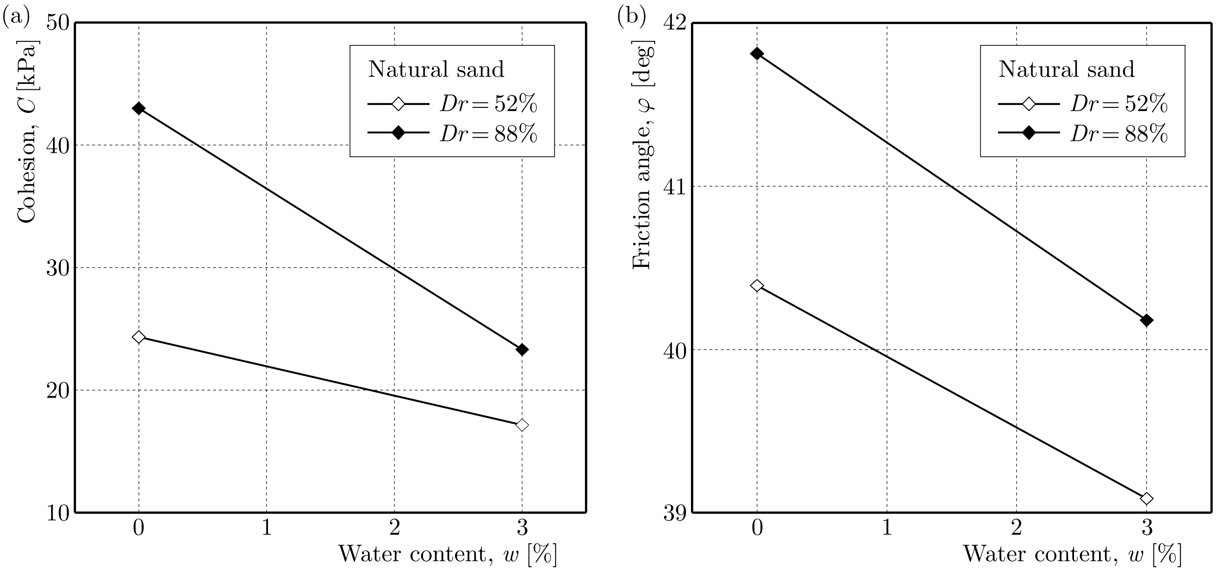

Fig. 9. Variation of the mechanical characteristics with the initial water content (w), $Dr = 52\%$ and 88%: (a) cohesion versus water content, (b) friction angle versus water content

5.3. Effect of the particle size

Only the effective grain size diameter D_{10} and the uniformity coefficient Cu were chosen as parameters to study the particle size effect on the shear stress and the friction angle of the sand-silt mixture. For each normal stress level ($\sigma_N = 100$, 200 and 300 kPa), it was found that the maximum shear stress increases according to a logarithmic trend with an increasing effective grain size diameter D_{10} (Fig. 10a). About the friction angle, Fig. 10b shows that it increases with the increasing effective grain size diameter and decreasing fines content.

As it is known, the uniformity coefficient (Cu) is a crude shape parameter (Holtz and Kovacs, 1981) and it represents the ratio of the 60% particle size (D_{60}) to the 10% particle size (D_{10}) (Head, 2006). Figure 11 shows the effect of the uniformity coefficient on the mechanical behavior of the sand-silt mixture. By increasing the fines content from 0% to 40%, the uniformity coefficient values range between 2.6 and 38.3, this is why Figs. 11a and 11b present similar tendencies and results with those of Figs. 5 and 6b, respectively showing that the maximum shear stress and the friction angle decrease linearly with the increasing uniformity coefficient. These findings are in agreement with those found by Belkhatir *et al.* (2011) on the saturated sand.

6. Conclusion

Results of experimental research on the influence of the fines content, the depositional method in terms of the initial water content and the grain size on the shear stress as well as the mechanical properties of Chlef river sand (natural and clean sand-silt mixture) have been presented.

Shear tests were performed in a direct shear apparatus. Two relative densities were evaluated $Dr = 52\%$ and 88% for the natural sand using two sample preparation methods, the dry deposition and the wet deposition, while only dense ($Dr = 88\%$) specimens of clean sand-silt mixture were tested using the dry deposition. The specimens were sheared dry without water immersion and they were subjected to three levels of normal stresses $\sigma_N = 100$, 200 and 300 kPa.

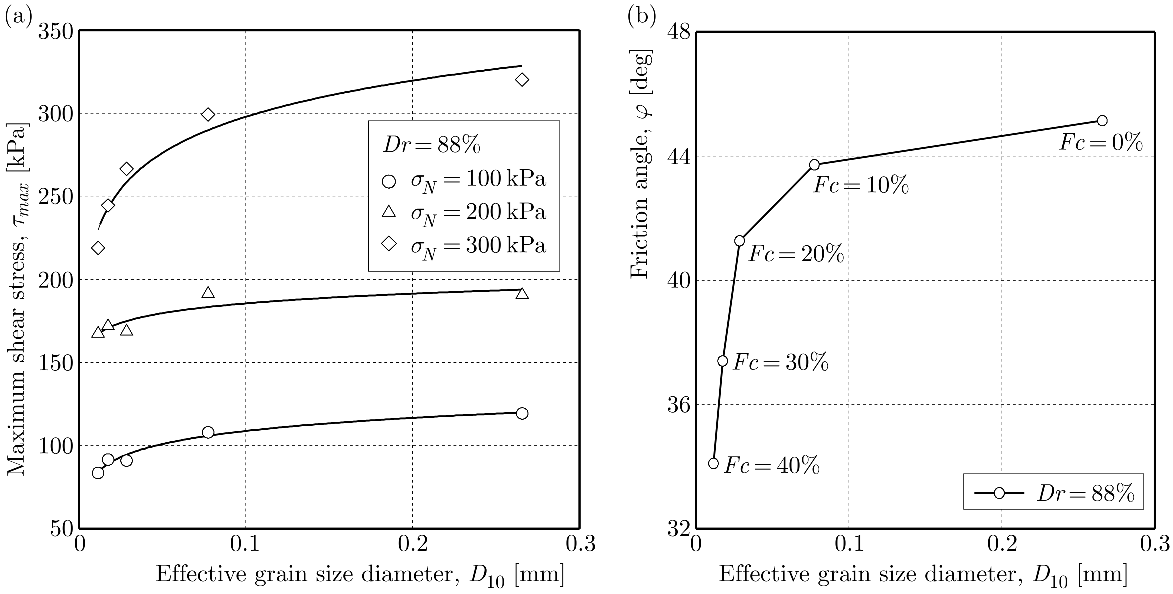

Fig. 10. Effect of the effective grain size diameter D_{10}: (a) maximum shear stress (τ_{max}) versus the effective grain size diameter, (b) friction angle versus the effective grain size diameter

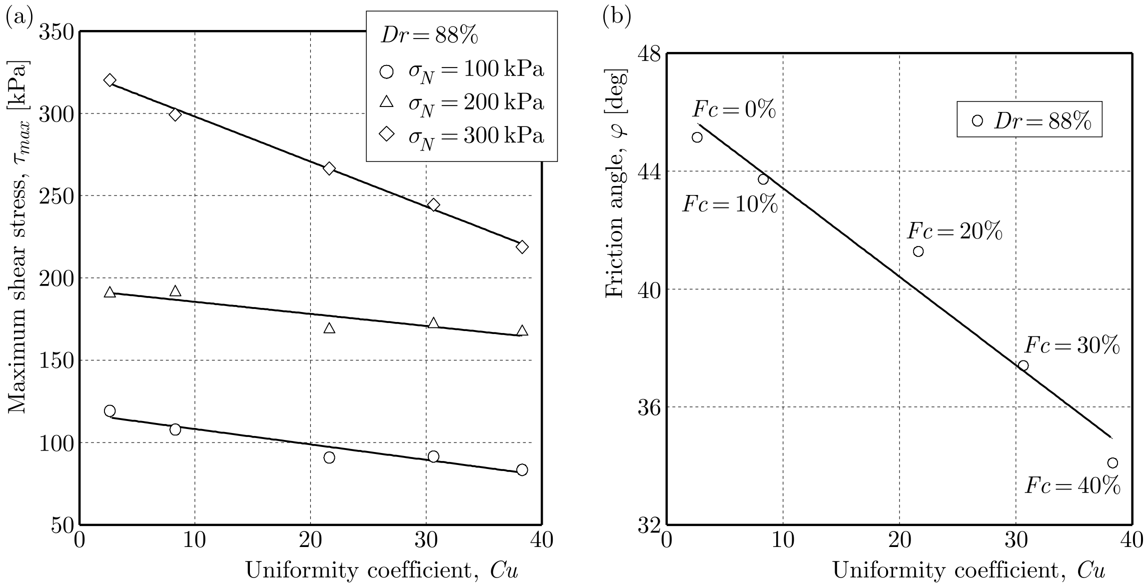

Fig. 11. Effect of the uniformity coefficient Cu: (a) maximum shear stress (τ_{max}) versus the uniformity coefficient, (b) friction angle versus the uniformity coefficient

Test results showed that the fines content, the depositional method and the grain size affect the strength of the dry sand. It was found that by increasing the fines content, the strength of the sand-silt mixture decreases, the friction angle decreases and the cohesion increases. Concerning the effect of the depositional method, it was shown that the maximum shear stress of the dry deposited specimens was higher than that of the wet deposited specimens. Also, the friction angle and the cohesion decreased with the increasing initial water content at deposition. About the effect of the grain size, the tests illustrated that the maximum shear stress and the friction angle increased with the increasing grain size diameter D_{10} and the decreasing fines content. Furthermore, the results showed that the maximum shear stress and the friction angle decreased linearly with the increasing uniformity coefficient and the fines content.

The results obtained from this study performed on the dry Chlef river sand are in agreement with those carried out on the saturated sand reported in the literature.

Acknowledgments
The testing was performed at the Laboratory of Material Sciences and Environment (LMSE) at Chlef University and The Institute of Mechanics, Materials, and Civil Engineering (iMMC) of the Université Catholique de Louvain (UCL). The authors express their gratitude to all who were assisting in the preparation of this paper.

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Manuscript received May 28, 2016; accepted for print October 14, 2016