Shear and interface shear strengths of calcareous sand

Résistance au cisaillement et à l'interface du sable calcaire

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ABSTRACT: The paper presents a brief summary of an experimental testing obtained by a direct shear box. In this study, two series of direct shear tests and interface shear tests are conducted to investigate the effects of grain size and gradation on the ratio of skin friction angle between soil and stainless steel to the internal friction angle of calcareous sand (δ/ϕ). The differences in stress – strain relationships for the samples obtained by both types of tests are identified. Although, the shear stress reaches a peak state at large shear strain, the interface shear stress reaches a peak value in an early state of shearing and then fluctuate harmonically until the end of shearing. The fluctuation is found greater for the samples loaded at higher applied normal stress. The results indicate that the ratio decreases with the increase in D_{50} and increases with an increasing uniformity coefficient (C_u). This tendency can clearly be seen in the samples tested at higher normal loads. For both effects, the ratio is found to vary in a rather limited range of 0.26-0.50 c orresponding to the range of interface friction angles of 11°-17°. These information may be useful and necessary at least for predicting the shaft bearing capacity of piles embedded in calcareous sand and for other practical applications in foundation design.

RÉSUMÉ : L 'article présente un résumé d' un essai expérimental obtenu par cisaillement direct. Dans cette étude, deux séries de tests de cisaillement direct et d'interface sont effectuées pour étudier les effets de la taille des grains et de la granulométrie sur le rapport de l'angle de frottement entre le sol et l'acier inoxydable et l'angle de frottement interne du sable calcaire (δ/ϕ). La différence des relations contrainte - déformation obtenue pour les échantillons au moyen des deux types d' essais est identifiée. Bien que la contrainte de cisaillement atteigne un pic en grande déformation, la contrainte de cisaillement d'interface atteint un pic dès le début du cisaillement, puis fluctue harmoniquement jusqu'à la fin du cisaillement. La fluctuation est plus grande pour les échantillons chargés à des contraintes normales plus élevées. Les résultats indiquent que le rapport diminue avec l'augmentation de D_{50} et augmente avec un coefficient d'uniformité croissant (C_u). Cette tendance peut être clairement observée dans les échantillons testés à des charges normales plus élevées. Pour les deux effets, le rapport varie entre 0.26 et 0.5, valeurs correspondant respectivement à des angles de frottement d'interface compris entre 11 et 17°. Ces informations peuvent être utiles et nécessaires pour prédire la capacité portante en frottement de pieux installés dans du sable calcaire et pour d'autres applications pratiques dans le dimensionnement de fondations.

KEYWORDS: calcareous sand, direct shear test, interface friction, grain size, uniformity coefficient.

1 INTRODUCTION

Calcareous sand plays an important role in the construction of coastal structures worldwide; it is composed of marine shells and other marine organisms (belemnite, corals, mollusks, etc.). The skeletal particles of calcareous sand vary largely in size and shapes. They are very angular and show a much higher void ratio than commonly measured in silica sand.

For civil engineering structures, soils are common in direct contact with the foundations of the structures. This contact causes the transmission of the force on the contact surface between the soils and foundations called skin friction or interface friction. Therefore, the interface shear strength plays a critical role in the capacity of in-ground structures (piping, linings, casings, and piles, etc.).

In laboratory testing, the direct shear tests are used usually to relate soil-structure interaction to the shear properties (shear strength and internal friction angle) of the soil. Many authors have investigated the interface shear tests. They performed the tests with various types of soils, scale sizes (Bałachowski 2006, Khan et al. 2014, Ebrahimian and Bauer 2015), and with different surface roughness between material-soil (Potyondy 1961, Tatsuoka and Haibara 1985, O'Rourke et al. 1990, Fioravante et al. 1999, Vangla and Latha 2015) together with other effects such as different densities, shear rates, and normal stresses to determine the relationship between the interface shear properties (strength and friction angle) and the shear properties of soils. However, the study on the effects of particle characteristics (size, shape) and gradation is limited, especially for calcareous sands.

Based on the literature, it can be clearly seen that the interface shear characteristics are the following. The interface friction angle (δ) increases with the increase in soil density and normal stress (O'Rourke et al. 1990, Khan et al 2014). A smooth surface shows a lower interface friction than a rougher surface (Potyondy 1961, Bosscher and Ortiz G 1988, McDowell and Bolton 2000). In addition, a good agreement on the test results was found between direct interface shear tests and axial model pipe tests performed on the same soil (Meyer et al. 2015). Recently, the interface shear strength was found independent of particle size at a specific void ratio, however, it was affected by the number of surface contacts (Vangla and Latha 2015).

The main purpose of this study is to investigate the shear strength and interface strength of calcareous sand by using direct shear tests and interface shear tests. The results of the tests are presented and the effects of grain size and gradation on the friction angle ratio, which is defined as the ratio of the skin friction (interface friction) angle between steel and sand to the internal friction angle of calcareous sand, are discussed.

2 TESTED MATERIALS AND METHODOLOGY

2.1. *Tested materials*

The calcareous sand, Sarb sand (S), used in this study was obtained from an artificial island in Abu Dhabi in the United Arab Emirates. To assess the grain size effect, the tests (series 1) are performed on four fraction sizes of S sand obtained from four sieves as follows: 160µm-250µm (S2), 500µm-630µm (S4), 0,63mm-1mm (S5), and 1mm-1,25mm (S6). Based on the targets of this study, all the particle fraction sizes of S sand is used to produce an artificial sand (S') with the difference in uniformity coefficient (C_u), therefore, the effect of uniformity coefficient can be performed, in which S, S5, and S' are considered as the same in D_{50} (series 2). The physical properties of the studied sand and artificial sands produced from Sarb sand are summarized in Table 1 and Table 2, and the grain size distribution (GSD) curves are shown in Figure 1.

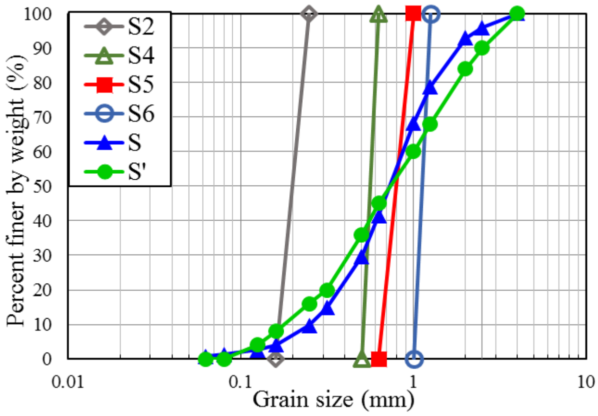


Figure 1. Grain size distribution curves of studied materials

Table 1. Physical properties of the studied materials

Name sand	S	S'
Specific gravity, G_s	2.787	2.787
Mean grain size, D_{50} (mm)	0.73	0.75
Uniformity coefficient, $C_u= D_{60}/D_{10}$	3.46	5.556
Curvature coefficient, $C_c=(D_{30})^2/(D_{10}*D_{60})$	1.12	1.051
Maximum void ratio, e_{max}	1.33	1.227
Minimum void ratio, e_{min}	0.903	0.754
Maximum dry density, $\rho_{d(max)}$ (gr/cm^3)	1.464	1.588
Minimum dry density, $\rho_{d(min)}$ (gr/cm^3)	1.196	1.251

Table 2. Physical properties of four fraction sizes of S sand

Name sand	S2	S4	S5	S6
Sieve size (mm)	0.16-0.25	0.5-0.63	0.63-1	1-1.25
e_{max}	1.376	1.556	1.752	1.835
e_{min}	0.933	1.042	1.172	1.224
$\rho_{d(max)}$ (gr/cm^3)	1.441	1.365	1.283	1.253
$\rho_{d(min)}$ (gr/cm^3)	1.173	1.09	1.013	0.983

2.2. *Methodology*

In this study, two types of tests are performed using a direct shear device (see Figure 2a) under saturated condition. However, for metal-soil interface tests, the stainless steel plate is placed on the bottom half of the shear box to investigate the steel-soil interface friction angle of the calcareous sand (Figure 2c,d). For this kind of test, a porous stone is placed at the top of the specimen to allow drainage. For direct shear tests, two porous stone are inserted at the top and bottom of the specimen to transfer horizontal shear stress. As presented in Figure 2a, the horizontal and vertical displacements are measured using displacement transducers, LVDT1 and LVDT3, respectively; and the shear force is measured indirectly by using a proving ring working as a load cell. The value of shear force can be converted from the displacement of LVDT2.

The test samples are prepared under vibrating compaction method, by hitting sideway of the box gently until the specimen get the target initial relative density of 40%.

All the samples molded into a metal shear box of 60x60 mm and 32.2 mm in height for direct shear tests and 22.66 mm in height for interface shear tests are consolidated at various normal stresses (50kPa, 100kPa, 200kPa) and sheared at a constant strain rate of 0.07815 (mm/min). Due to the limit of horizontal displacement, all the tests are sheared up to a shear strain of 10%, which is considered as their residual shear strengths. After testing, all the samples are dried for sieve analysis.

In this study, the Mohr-Coulomb failure criterion is used to obtain the residual shear strength and friction angle for both types of tests.

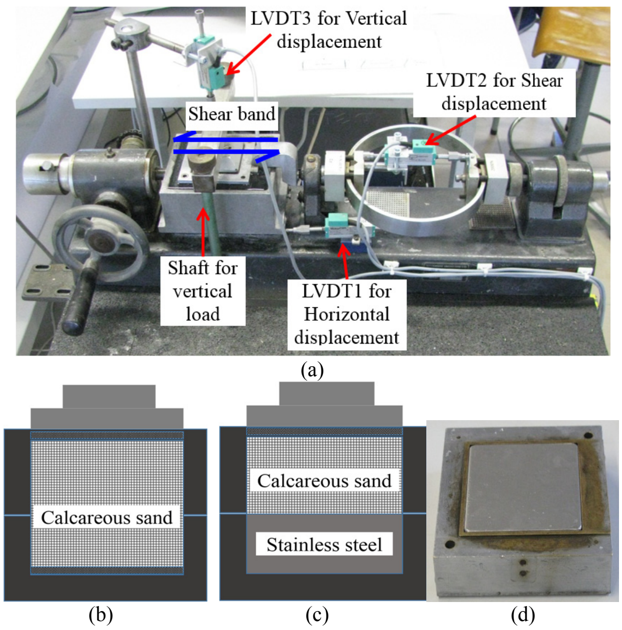
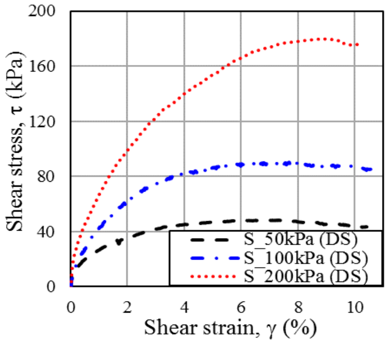


Figure 2. Direct shear device (a), direct shear test (b), steel-soil interface shear test (c), view of the bottom part of steel-soil interface test device (d).

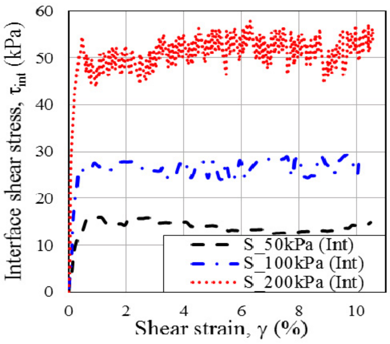
3 RESULTS AND DISCUSSION

After sieving, it is clear to indicate that there is no crushing after shearing in all the tested samples; therefore, the effect of crushing is not taken into account for this study.

Figure 3 exhibits stress-strain relationships of S samples conducted by both types of tests at various applied normal stresses. As expected, the increase in normal load leads to an increase in the shear stress in both types of tests. Especially, while the shear stress reaches a peak state at large shear strain, the interface shear stress reaches a peak state at small shear strain in an early state of shearing and then fluctuate harmonically. The fluctuation becomes much greater at higher normal stress. This behavior of the interface shear stresses is likely corresponding to the process of particle moving or re-arrangement during shearing. Therefore, the residual shear stress is calculated by the average values of stress fluctuation.



(a) Direct shear test results



(b) Interface test results

Figure 3. Shear stress versus shear strain of S samples.

The results of direct shear tests (DS) and interface shear tests (Int) performed at the applied normal loads of 50kPa, 100kPa, and 200kPa are summarized in Table 3, Table 4, and Table 5, respectively. In these tables, the residual shear strengths and friction angles of calcareous sandy samples are much higher than the interface shear strengths and interface friction angles at residual state, respectively. It can be seen that that the residual shear strength and friction angle of calcareous sand depend on its grain size. The residual shear strength and friction angle increases with mean grain size. As expected, the values of shear strength and friction angle at the residual state of well-graded sand are higher than those of poorly-graded sand. The increase in shear strength is primarily due to a better density. From this point, this may seem that relative density in this study is not a reliable parameter for the comparison of the sands different from C_u.

Table 3. Test results of the samples loaded at 50kPa

Materials	D_{50} (mm)	C_u	Residual shear strength (kPa)		Residual friction angle (°)		δ/ϕ
			τ	τ_{int}	ϕ	δ	
S	0.73	3.46	43.85	14.00	41.25	15.64	0.38
S2	0.205	1.265	27.49	11.34	28.81	12.78	0.44
S4	0.408	1.127	29.17	10.60	30.26	11.97	0.40
S5	0.815	1.274	32.86	12.00	33.31	13.50	0.41
S6	1.135	1.122	36.89	10.25	36.42	11.59	0.32
S'	0.75	5.556	46.58	15.22	42.97	16.93	0.39

Table 4. Test results of the samples loaded at 100kPa

Materials	D_{50} (mm)	C_u	Residual shear strength (kPa)		Residual friction angle (°)		δ/ϕ
			τ	τ_{int}	ϕ	δ	
S	0.73	3.46	86.96	26.74	41.01	14.97	0.37
S2	0.205	1.265	62.63	29.03	32.06	16.19	0.50
S4	0.408	1.127	70.35	21.00	35.12	11.86	0.34
S5	0.815	1.274	77.24	22.10	37.68	12.46	0.33
S6	1.135	1.122	88.8	20.90	41.60	11.80	0.28
S'	0.75	5.556	93.9	29.80	43.20	16.59	0.38

Table 5. Test results of the samples loaded at 200kPa

Materials	D_{50} (mm)	C_u	Residual shear strength (kPa)		Residual friction angle (°)		δ/ϕ
			τ	τ_{int}	ϕ	δ	
S	0.73	3.46	175.65	49.42	60.35	14.58	0.35
S2	0.205	1.265	142.47	60.31	54.94	16.78	0.47
S4	0.408	1.127	145.87	48.00	55.57	13.50	0.37
S5	0.815	1.274	163	46.90	58.47	13.20	0.34
S6	1.135	1.122	181.43	39.16	61.14	11.08	0.26
S'	0.75	5.556	179.43	53.20	60.87	16.49	0.39

The residual shear stresses of both types of tests are normalized due to the difference in applied normal loads. The dependences of normalized interface shear stress and friction angle ratio on mean grain size (D_{50}) and on uniformity coefficient (C_u) are plotted in Figure 4-Figure 7.

For the effect of D_{50}, the normalized interface shear stress, τ_{int}/σ'_v, is found to decrease with increasing mean grain size (D_{50}) (Figure 4) . The tendency is more evident at higher apllied load. The same trend is also seen in the relationship between friction angle ratio, δ/ϕ, and mean grain size (Figure 5) . This means that the contact number of particles, hence, contact surface between steel and sand increases with decreasing mean particle size. Therefore, the increase of contact surface in the samples with smaller particle size causes the increase in interface shear strength as well as in interface friction angle. In contrast, for C_u effect, the normalized interface shear stress and friction angle ratio increase with the increase in C_u as expected (Figure 6, Figure 7), however, at the low aplied normal load of 50kPa the ratio, δ/ϕ, is not evident. For both effects, the ratio is found to vary in a rather limited range of 0.26-0.5 correspoding to the range of interface friction angles of 11°-17°. This range of ratio values is smaller than the range of 0.5-0.65 obtained by other authors (Potyondy 1961, O'Rourke et al. 1990) on other different types of soils.

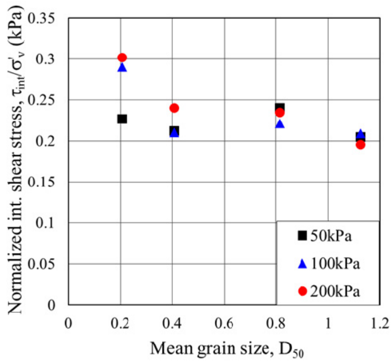
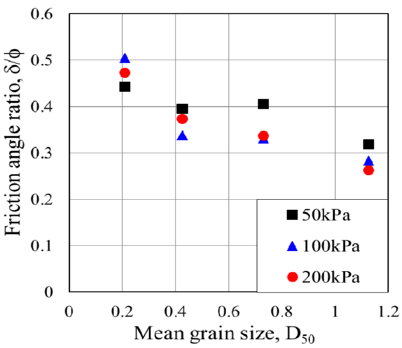


Figure 4. Dependence of normalized interface shear stress on mean grain size (D_{50}) of calcareous sand.



(b)

Figure 5. Dependence of friction angle ratio on mean grain size (D_{50}) of calcareous sand.

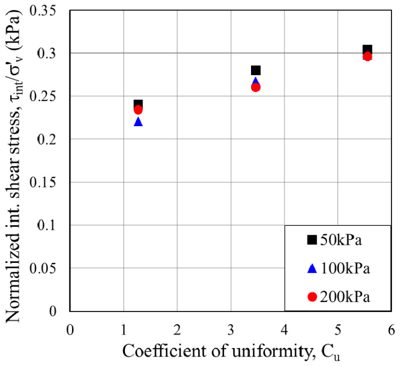
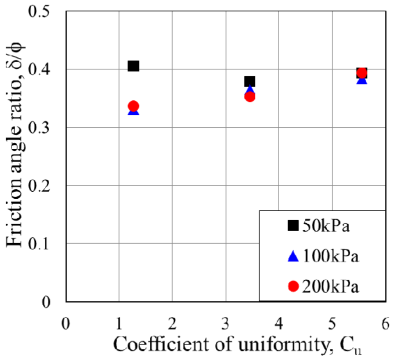


Figure 6. Dependence of normalized interface shear stress on uniformity coefficient (C_u) of calcareous sand.



(b)

Figure 7. Dependence of friction angle ratio on uniformity coefficient (C_u) of calcareous sand.

4 CONCLUSIONS

Steel-sand interface tests are performed on the reconstructed medium dense samples of the calcareous sands. From the current study, the following conclusions are observed as follows:

- The difference in stress-strain curves are identified for both kinds of tests. With the tests performed in the same initial conditions, the shear stress reaches a peak state at large shear strain, but the interface shear stress reaches a peak state in an early state of shearing, and then fluctuate harmonically. The fluctuation is greater for the samples loaded at higher applied normal stress.
- The interface shear strength and friction angle of steel - calcareous sands increases strongly with increasing uniformity coefficient (C_u) and decreases with increasing grain size (D_{50}) due to the change in contact surface. This tendency can be clearly seen in the samples applied at higher normal loads. For C_u effect, the well-graded samples owning better packing density with less void ratio (more number contact) show greater interface friction than the poorly-graded samples. Hence, the friction angle ratio (δ/ϕ) is found to increase with the increase in uniformity coefficient and decrease with the increase in grain size.

The information can be useful and necessary at least for predicting the shaft bearing capacity of piles embedded in calcareous sand and for other practical applications in foundation design.

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