Effects of Moisture on the Mechanical Behavior of Sand–Geogrid: An Experimental Investigation

Amir Mostafa Namjoo[1] · **Fazlollah Soltani**[1] · **Vahid Toufigh**[1]

Abstract

Soil–geosynthetic interaction is a key factor for designing and analyzing reinforced soil structures. In this investigation, the effect of different moisture content on the behavior of soil–geogrid interfaces is evaluated using direct shear and pullout tests. The results are presented and discussed in terms of direct shear and interface shear behavior, the frictional resistance of interfaces, efficiency factor, pullout resistance, pullout behavior, and apparent friction coefficient. The results revealed that a decrease in moisture content resulted in an increase in the both interface friction angle and adhesion of specimens. Moreover, the interface friction angle of sand–geogrid specimens in pullout tests was higher than that of direct shear tests. According to interface shear results, the efficiency factors ranged from 0.87 to 0.99. Based on pullout results, the apparent friction coefficient was found to be in the range of 0.77–1.72.

Introduction

Most of the structures are in contact with soil and its stability is one of the most significant concerns of geotechnical engineers. Researches have shown that although soil has relatively high compressive strength, its tensile strength is low. Different methods of reinforcement have been used to solve such shortcomings. These days, geogrid is widely used to enhance the mechanical properties of soil. Using this type of geosynthetics increases the strength of soil mass through the mobilization of the tensile strength of this element. This mobilization can contribute to decrease horizontal deformations and increase the stability of soil structures. To understand the interaction between soil–geosynthetics, various experimental methods have been used and developed, including interface shear tests and pullout tests [1–5].

The interaction between soil and reinforcement elements is based on two main failure mechanisms as shown in Fig. 1. In region A, sliding between the soil mass and reinforcement may occur. Therefore, the direct shear test can be used to determine the interface properties. In region

B, the reinforcement can be pulled out; thus, the pullout test can simulate this situation [6, 7]. Note that all these tests have limitations, and they cannot fully simulate the field conditions.

Bergado et al. [8] examined the interface between clay and geomembrane using interface shear tests in dry and wet conditions. To prepare moist specimens, the specimens were soaked in the water and then the interface shear test was performed. Results showed that the interface peak friction angle under dry condition was 22% higher than that under wet condition.

Abu-Farsakh et al. [9] evaluated the interface behavior of different soils (including one sand and three clays with different plasticity) and four types of geosynthetics under different dry densities and moisture conditions, using interface shear tests. Their observation showed that multiple factors such as soil types, geosynthetics types, and moisture content had a significant influence on the interface behavior of soil–geosynthetics. Based on their assertion, an increment in both moisture content and dry density of soil plays an effective role in the interface shear strength of sand–geosynthetic specimens.

Ferreira et al. [3] studied the influence of moisture condition and dry unit weight of sand, and type of geosynthetic (uniaxial and biaxial geogrids and high-strength geotextile) on the sand–geosynthetic interface properties through interface

✉ Amir Mostafa Namjoo
  amirnamjoo2018@gmail.com

1 Faculty of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran
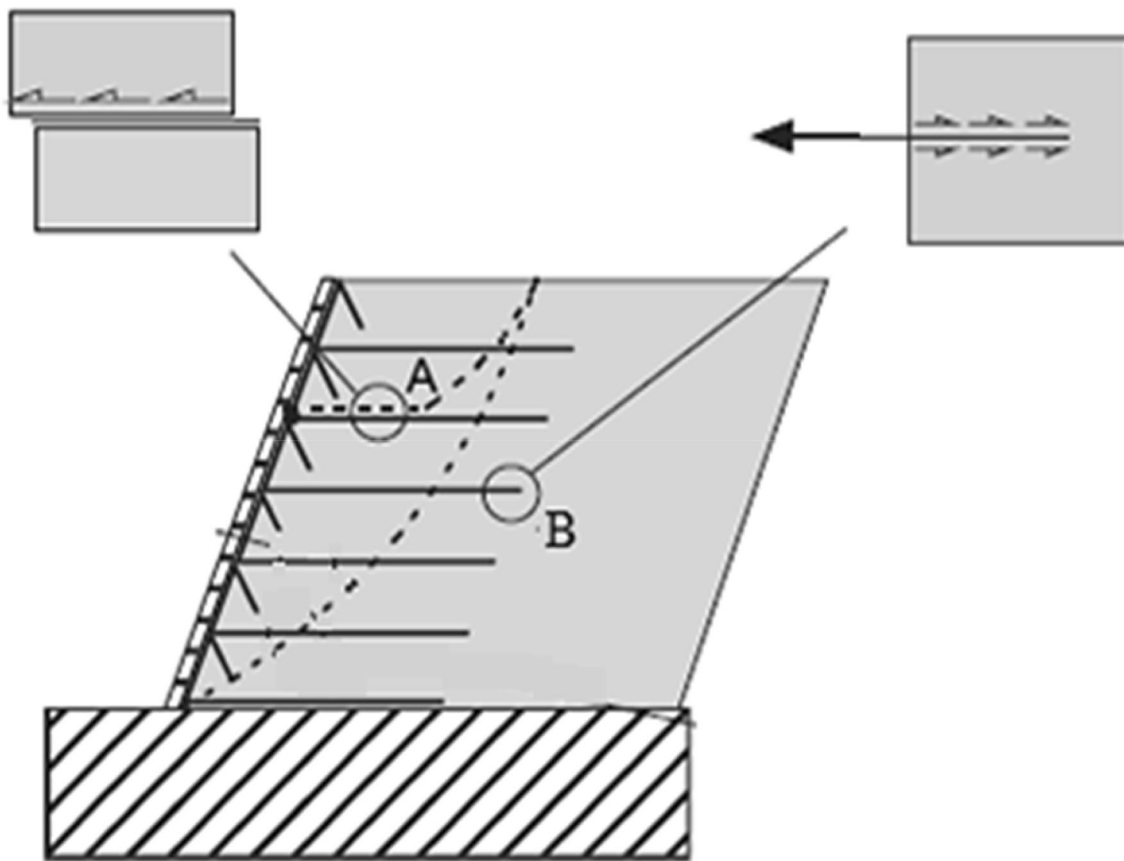
Fig. 1 Interaction mechanisms of reinforced soil wall (modified from Palmeira [7])

shear tests. Based on their results, the moisture content and soil density had a considerable effect on interface shear properties. They concluded that the biaxial geogrid in the direct shear mechanism among the different types of geosynthetics had the best performance for residual soil from granite.

Although many researchers investigated the effect of moisture content on the interface properties of soil–geotextile [10–12], a few studies have been investigated the effect of moisture on the interface properties of soil–geogrid. The general objective of this study is to investigate the effect of moisture on the interface behavior of silty sand-geogrid using direct shear and pullout tests. To achieve such purpose, the effect of five moisture content (dry, half of the optimum moisture content (0.5 OMC), optimum moisture content (OMC), optimum plus half of the optimum moisture content (1.5 OMC) and saturated) on the sand–geogrid interface were investigated and discussed.

Table 1 Mechanical and physical properties of silty sand

Water content (%)	0
D_{10}(mm)	0.09
D_{30}(mm)	0.33
D_{60}(mm)	1.91
D_{max}(mm)	2.76
Uniformity coefficient (C_u)	21.1
Coefficient of curvature (C_c)	0.6
Optimum moisture content (%)	10.5
Dry unit weight (kN/m^3)	19.3
Specific gravity of solid particles (G_s)	2.67
Maximum void ratio (e_{max})	0.78
Minimum void ratio (e_{min})	0.52
Angle of friction (ϕ)	35.69°

Materials

Sand

The sand used in this study was collected from Ekhtiarabad road in Kerman province, Iran. This sand is abundantly available in this region. Table 1 presents the primary physical and mechanical properties of selected sand. Based on the unified soil classification system (USCS), this sand was classified as silty sand (SM). The internal friction angle (ϕ) and cohesion (c) of sand were specified, according to ASTM D3080 [13]. The water content of the sand particles was determined according to ASTM D2216 [14].

Geogrid

In this study, the biaxial woven geogrid, which is produced from high modulus polyester (PET), was used as reinforcement element (Fig. 2). The geogrid has a rectangular aperture with a dimension of 9×8 mm and a thickness of 1.2 mm according to EN ISO 9863-1:2016 [15]. The mass per unit area and tensile properties of geogrid were specified according to EN ISO 9864:2005 [16] and EN ISO 10319:2008 [17], respectively. Table 2 provides the physical and mechanical features of this reinforcement.

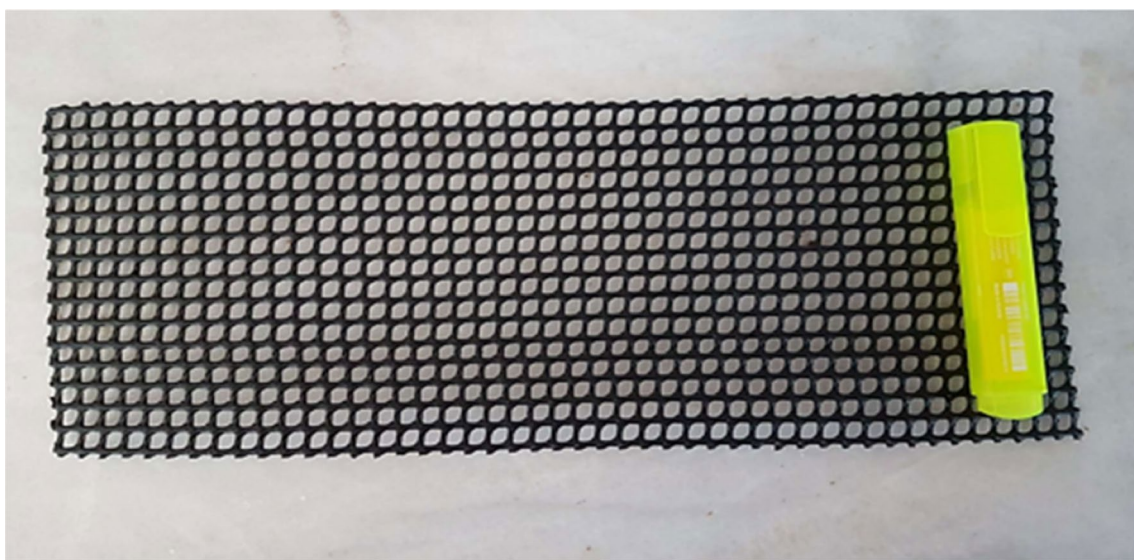**Table 2** High modulus polyester (PET) properties

Parameter	Standard	Values
Raw material	–	PET
Aperture size (mm×mm)	–	9×8
Thickness* (mm)	EN ISO 9863-1:2016 [15]	1.2
Mass per unit area* (g/m^2)	EN ISO 9864:2005 [16]	380
Tensile strength (T_{ult})* (kN/m)	EN ISO 10319:2008 [17]	58
Tensile stiffness* (kN/m)	EN ISO 10319:2008 [17]	417
Longitudinal strain at T_{ult}* (%)	EN ISO 10319:2008 [17]	11
Percent open area* (%)	–	60

*Provided by the supplier

Test Equipment

Direct Shear Device

A conventional direct shear box with a dimension of 10×10 cm was used to evaluate the frictional behavior of sand–geogrid. The direct shear tests and modified shear tests were performed on sand and sand–geogrid, in accordance with ASTM D3080 [13] and ASTM D5321 [18], respectively. The modification was to fill the lower shear box with a geogrid which was placed on granite stone block using epoxy resin, in accordance with Namjoo et al. [5]. The use of a similar rigid block was practiced by previous researchers [5, 19, 20]. The height of the granite block was specified in such that the geogrid was accurately placed in the interspace of the two halves of the shear box. The sand was compacted in the upper half of the shear box at 70% relative density,

Fig. 2 High modulus polyester (PET)

according to ASTM D698 [21]. The direct shear and interface shear tests were carried out using normal stresses of 25, 50, and 100 kPa. In shear tests, constant vertical stress was applied, and horizontal displacement was recorded. A shear displacement rate of 1.0 mm/min was used in all interface testes in this investigation.

Pullout Device

The modified pullout test device was used to perform pullout tests according to ASTM D6706 [22]. To assemble the pull-out device, a combination of triaxial loading and direct shear devices were used to apply normal loads and pullout forces, respectively. The normal stresses were uniformly transferred to soil through a steel plate, covering the whole surface area of the pullout box, and the direct shear device was used to apply the horizontal (pullout) forces with a constant rate.

According to ASTM D6706 [22], the length of the box should be five times larger than the maximum size of the geogrid apertures, which was 9 mm. Therefore, dimensions of the pullout box were $20 \times 20 \times 20$ cm, as shown in Fig. 3.

The use of similar small pullout box (with dimensions equal or less than $30 \times 30 \times 30$ cm) was practiced by previous researchers [2, 23, 24]. The pullout box has a 10-mm-thick horizontal slot to place the geogrid specimen in the sand.

Testing Program

As mentioned earlier, five different moisture content, including dry, 0.5 OMC, OMC, 1.5 OMC, and saturated, were selected to examine the interaction between sand and geogrid specimens. To prepare dry specimens, the air-dried sand in the shear box was compacted to reach $= D_r$ 70% (dense sand). To prepare 0.5 OMC, OMC (optimum moisture content) and 1.5 OMC specimens, 5.25%, 10.5% (optimum moisture content), and 15.75% water were added to the dry soil, respectively. After that, the soil and required water were mixed and then compacted in the shear box to reach 70% relative density ($D_r = 70\%$). For providing saturated specimens, the amount of water required to achieve the full degree of saturation was calculated and mixed with dry sand. The mixture was then poured into the shear box
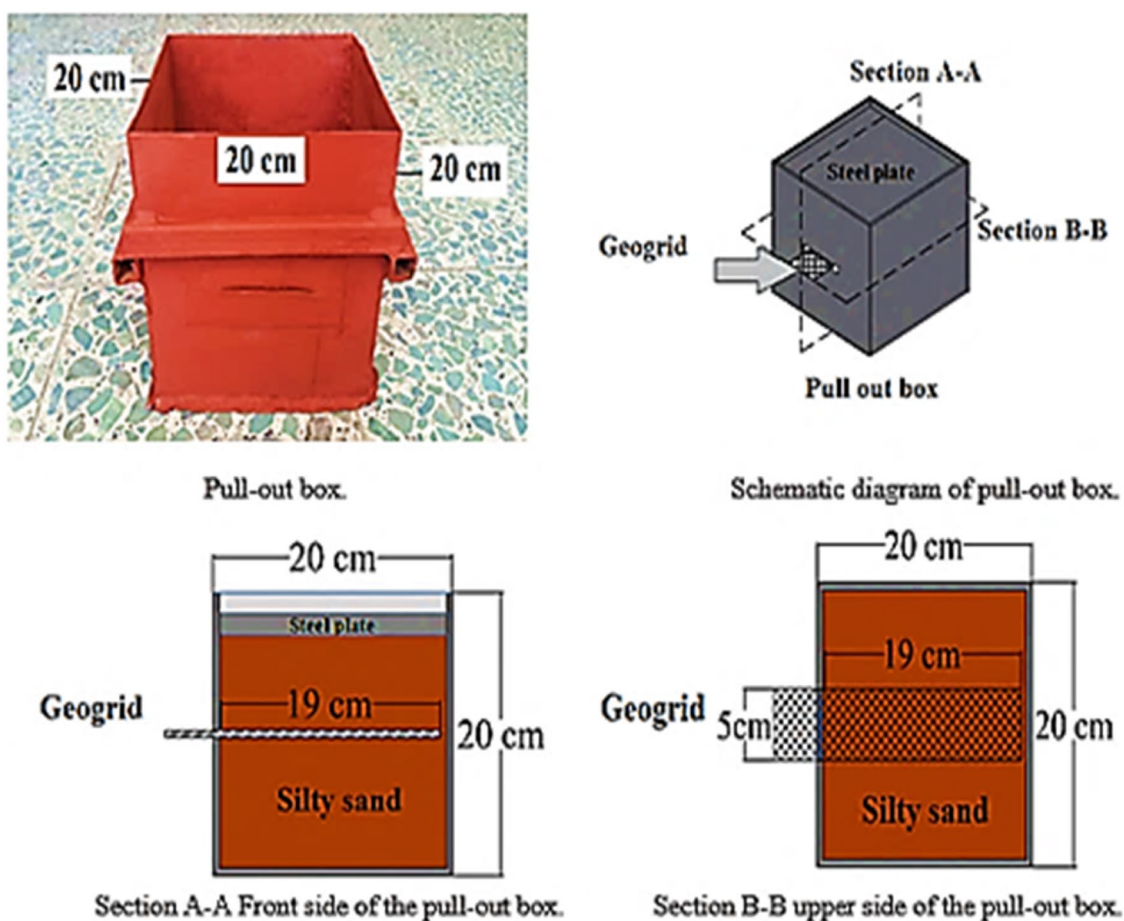

Fig. 3 Pullout box

and compacted to reach D_r=70%. To prepare sand–geogrid specimens, at first, a layer of geogrid with dimensions of 10×10 cm was prepared. A geogrid was attached to a granite stone using epoxy resin and placed in the bottom half of the shear box. Then, the soil and moisture required for each moisture condition were mixed and placed in the top half of the shear box and compacted. Then specimens were tested based on the ASTM D5321 [18].

For pullout specimens, a geogrid specimen with dimensions of 5×20 cm was used. At first, the soil was compacted under required moisture content, in four layers of 2.5 cm with D_r=70%, based on ASTM D698 [21]. Afterward, the geogrid was attached to the clamp and was placed on the soil, followed by releasing the clamp from the groove. The sand was then compacted in four layers of 2.5 cm, under required moisture content with D_r=70%, to reach 20 cm. The released clamp was attached to the hook, which was attached to the direct shear device. The direct shear device applied the pullout force, while the triaxial loading device applied normal stress. The measurements were continued up to horizontal displacement reached 15 mm, in which the maximum pullout resistance of specimens occurred. It should be noted that the test results could be affected by scale effects due to the use of small size apparatus.

Results and Discussion

Direct Shear Tests on Soil

Variations of shear strength–horizontal displacement for sand in different moisture contents are presented in Fig. 4. Results indicated that the maximum shear strength of specimens with lower moisture content mobilized at smaller shear displacements. Moreover, the shear strength significantly decreased by increasing the moisture content. As can be seen in Fig. 4a, the curve reduced with a steep slope under dry condition when shear strength reached an ultimate value, which represented an effective interlocking between sand particles in dense sand. Figure 4c presents the results of sand specimens under optimum moisture content (OMC). It can be observed that the ultimate shear strength increased significantly by increasing the normal stress. Moreover, it can be deduced that at low normal stresses, the ultimate shear strength took place at lower horizontal displacement. Based on the results of sand specimens under saturated condition (Fig. 4e), a remarkable drop in interface strength was observed, resulting in a considerable reduction in the value of the internal friction angle of saturated sand (ϕ) in comparison with other conditions.

The comparison between Fig. 4a–c illustrated that the peak shear strength of the dry specimen declined by 18% and

24% by increasing moisture content to 0.5 OMC and OMC, respectively. Figure 5 shows the peak strength envelopes of sand. According to this figure, the correlation between shear strength and moisture content observed and the highest internal friction angle ($\phi = 40.85°$) was related to dry sand. Table 3 illustrates the values of the internal friction angle (ϕ) and cohesion (c) of sand. According to this table, the internal friction angle of dry sand was 9.5%, 14.5%, 44%, and 64.3% higher than that of 0.5 OMC, OMC, 1.5 OMC, and saturated specimens, respectively. Steady state is an area in sand that interfaces shear takes place continuously without any further change in stress state and void ratio.

Based on results for dry and 0.5 OMC, the peak frictional angle was 34.5% and 9.8% higher than that of steady state, respectively. On the other hand, for sand specimens with moisture content more than 0.5 OMC, no tangible reduction in shear strength after peak point observed and specimens reached to their steady state (i.e. $= \phi_{\text{steady state}} \phi_{\text{Peak}}$). Moreover, based on Table 3, the results showed a relationship between moisture content and cohesion, which dropped by increasing moisture content.

Sand–Geogrid Interface Shear Tests

The shear strength–horizontal displacement behavior of the sand–geogrid interface under different moisture conditions are plotted in Fig. 6. The results showed that the interface shear strength of sand–geogrid tended to decrease by increasing in moisture content. Considering Fig. 6, hardening and softening behavior before and after the peak shear strength was observed under dry condition, whereas the strain softening for the interfaces with moist sand–geogrid specimens was mobilized and remained relatively constant, which indicated ductile behavior.

Results obtained under the dry condition and with moisture content equal to 0.5 OMC at maximum normal stress (100 kPa) showed that an increment in moisture content between the aforementioned values resulted in a significant drop in the maximum shear strength (by 17%). Moreover, an increment in moisture content from dry condition to 0.5 OMC led to a decrease in the interface friction angle about 9%. In comparison with 0.5 OMC specimens, the maximum interface shear strength of OMC specimens fell by 5%. Moreover, the interface friction angle decreased by 22% when the moisture content varied from OMC to 1.5 OMC. Moreover, the interface friction angle under the saturated condition was close to its value for specimens with moisture content equal 1.5 OMC.

The relationship between maximum shear strength versus normal stress of all five moisture contents is presented in Fig. 7. Based on this figure, the interface friction angle of sand-geogrid decreased from 38.52°, for dry specimens, to

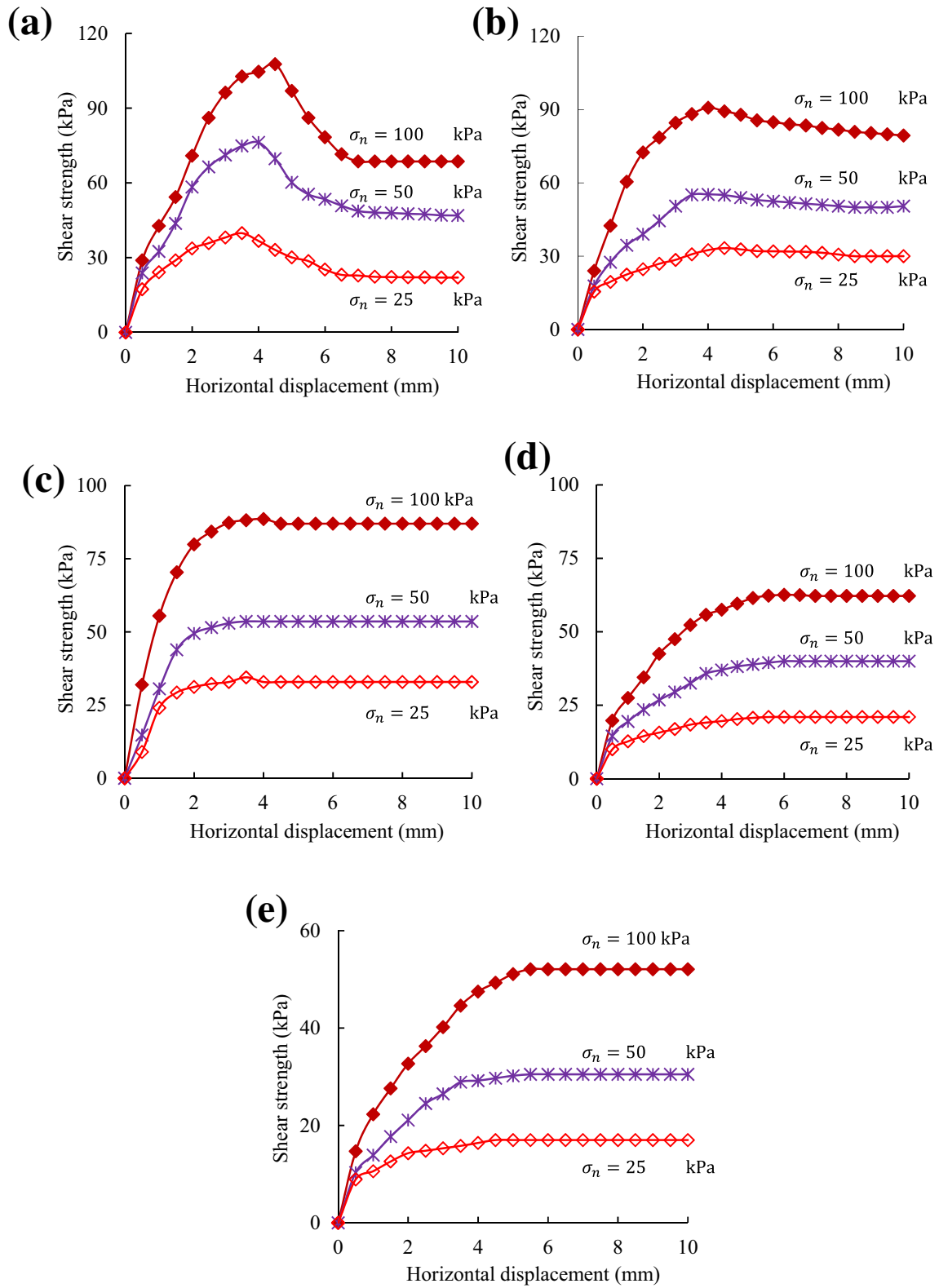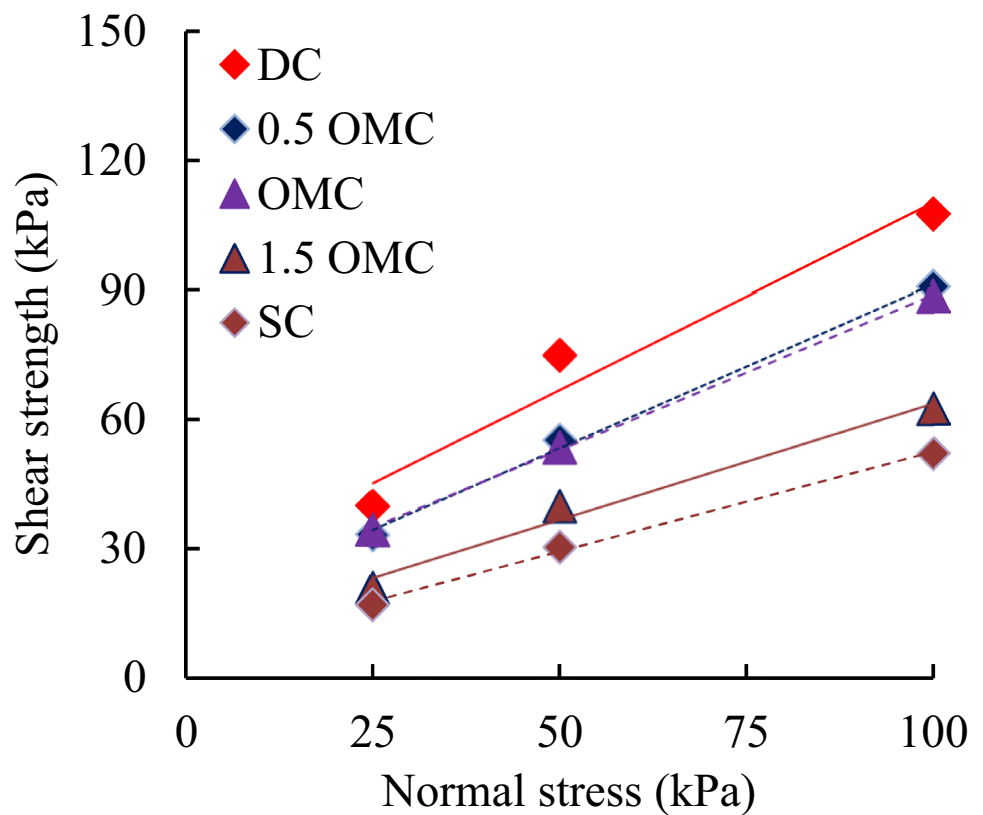**Fig. 4** Shear strength—horizontal displacement for sand specimens **a** dry; **b** 0.5 OMC; **c** OMC; **d** 1.5 OMC; **e** saturate

Fig. 5 Variations of maximum shear strength versus normal stress for sand specimens

Table 3 Soil shear strength parameters

Soil condition	Sand		Sand
ω	$\phi_{internal\ (Peak)}(°)$	c(kPa)	$\phi_{interal\ (steady-state)}(°)$
DRy	40.85	18.1	30.26
0.5 OMC	37.2	15.4	33.9
OMC	35.7	10.8	35.44
1.5 OMC	28.4	7.4	27.41
Saturated	24.87	4.8	24.69

22.41°, related to saturated specimens. This value for sand-geogrid under 0.5 OMC, OMC, and 1.5 OMC was 36.5°, 33.45°, and 26.18°, respectively. It can be concluded that an increase in moisture content led to a decrease in the interface friction angle by 42%. The maximum interface adhesion was 17.3 kPa, related to dry sand-geogrid specimens, whereas the minimum adhesion was 3.7 kPa, found for saturated sand-geogrid specimens. These results are in accordance with previous observations for sand-biaxial geogrid ([3] and [9]).

Efficiency Factors

The significance of using the "efficiency factor" or "coefficient of interaction," C_i or E_ϕ, is an essential design parameter in the reinforced soil structures, as discussed in the literature [1, 3–5, 9, 25]. Efficiency factor (E_ϕ) is specified as the ratio of maximum interface strength in interface shear test to the maximum shear strength in a direct shear test on soil under the same normal stress (σ_n).

$$E_\phi = \frac{c_a + \sigma_n \tan\phi_{int}}{c + \sigma_n \tan\phi}, \tag{1}$$

where c is sand cohesion, c_a is sand-geogrid cohesion, σ_n is the normal stress, ϕ is the internal friction angle of sand and ϕ_{int} is the interface friction angle between sand and geogrid in interface shear test. Table 4 presents the values of the efficiency factor for various moisture contents for different vertical stresses (50 and 100 kPa). The range of efficiency factors was from 0.86 to 0.99 (0.86 for the saturated condition and 0.99 for the optimum moisture content). Results showed that, in comparison with sand, the interaction between sand and geogrid was lower. Moreover, it can be inferred that increase in moisture content until OMC led to an increase in the efficiency factor; however, reverse behavior was observed for specimens with higher moisture content than OMC. A similar observation was reported by other researchers. Furthermore, Liu et al. [1] expressed that the values of an efficiency factor for soil–PET geogrid was 0.89–1.01. Ferreira et al. [3] represented efficiency factors
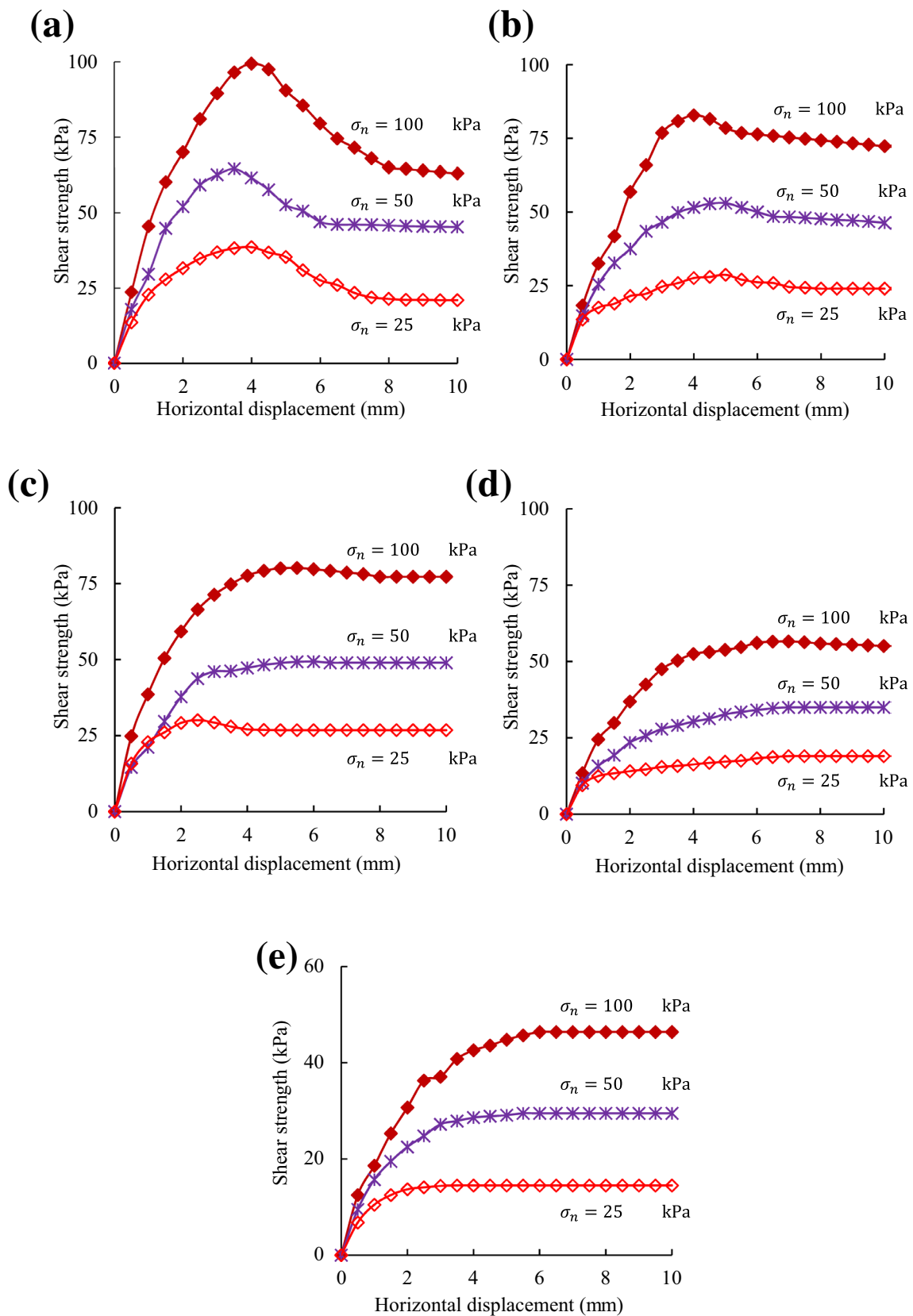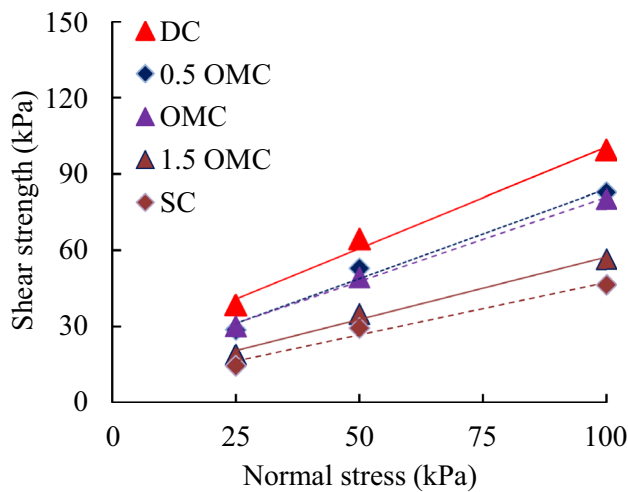
Fig. 6 Shear strength—horizontal displacement for sand-geogrid specimens **a** dry; **b** 0.5 OMC; **c** OMC; **d** 1.5 OMC; **e** saturate

Fig. 7 Variations of maximum shear strength versus normal stress for sand-geogrid specimens

for different moisture conditions for different types of geosynthetics. They demonstrated that the efficiency factor increased in the lower soil density by increasing moisture content until OMC. The range of efficiency factor for sand-biaxial geogrid was 0.81–0.99.

Pullout Results

Results of the pullout test as variations of pullout resistance versus pullout displacements for the sand-geogrid specimens are presented in Fig. 8 and analyzed in the following section. It can be inferred that the pullout resistance of sand-geogrid specimens was gradually mobilized by increasing in pullout displacements. The maximum pullout resistance occurred after 11.5–13.5 mm pullout displacement in a dry situation and remained relatively constant thereafter (see Fig. 8a). Furthermore, there is considerable variation of peak pullout resistance with a change in normal stress. An increase in the normal stress from 25 to 50 kPa resulted in a 36% increase in the peak pullout resistance. The pullout resistance is equal to 76.3 kPa for specimens with the normal stress of 50 kPa, whereas this value is 122 kPa for normal stress of 100 kPa, which is approximately 60% higher than the value obtained from the normal

stress of 50 kPa. Figure 8b presents the effect of normal stress on pullout resistance of the sand-geogrid specimens under 0.5 OMC. According to this figure, with increasing in moisture content, the maximum pullout resistance occurred in lower pullout displacement in comparison with a dry situation. For OMC, specimens reached their maximum pullout resistance after 11–12 mm pullout displacement and remained relatively constant after that. In addition, by increasing the moisture content (0.5 OMC to OMC), it can be seen that the maximum pullout resistance reduced and occurred at relatively lower pullout displacement.

The variations of the maximum pullout resistance of sand-geogrid specimens as a function of normal stress under different moisture conditions are shown in Fig. 9. The interface friction angle for dry specimens was 41.65°, whereas the lowest interface friction angle was 28.75°, related to the saturated specimen.

The summary results of direct shear and pullout tests for the interface of sand and sand-geogrid are given in Fig. 10. According to this figure, it can be inferred that increasing moisture content for sand-geogrid specimens in both direct shear test and pullout test led to decreasing in interface friction angle, which was 42% and 31%, respectively.

An increase in pullout resistance is mainly due to the existence of transverse members in the geogrid. In front of these members, passive soil resistance increased until the soil near the reinforcement reached a state of failure. The proportion of passive resistance in front of geogrid transverse members under pullout mood was larger than the friction resistance along the geogrid, which was consistent with observations presented by Palmeira [7]. Under dry condition and OMC, the friction angles at the interface of pullout tests for sand-geogrid specimens was approximately 8% and 19.5% higher than the direct shear tests. In saturated situation, the angle of friction at the interface of pullout tests was 28.3% higher than of direct shear tests.

Apparent Friction Coefficient

The pullout resistance in the pullout test is presented by:

Table 4 The efficiency factor of soil–geogrid interfaces

Soil condition	Sand				Normal stress (kPa)	
ω	$\phi_{internal}$(°)	c(kPa)	$\phi_{interface}$(°)	c_a(kPa)	50	100
Dry	40.85	18.1	38.52	17.3	0.93	0.93
0.5 OMC	37.2	15.4	35.1	12.9	0.92	0.92
OMC	35.7	10.8	33.45	13.7	0.99	0.96
1.5 OMC	28.4	7.4	26.2	6.3	0.89	0.9
Saturated	24.87	4.8	22.4	3.7	0.87	0.86
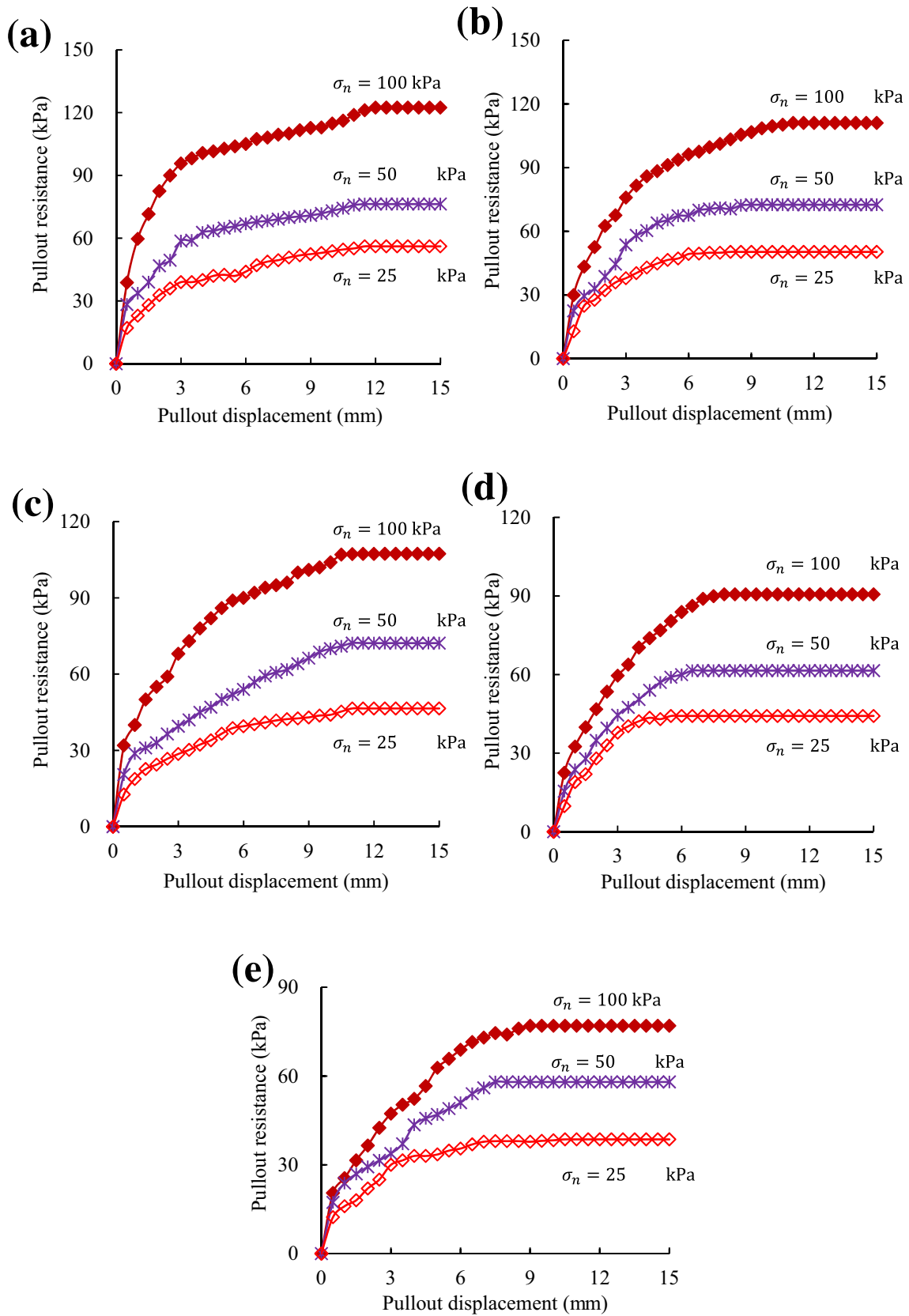
Fig. 8 Variations of pullout resistance—pullout displacement for sand-geogrid specimens under **a** dry; **b** 0.5 OMC; **c** OMC; **d** 1.5 OMC; **e** saturate
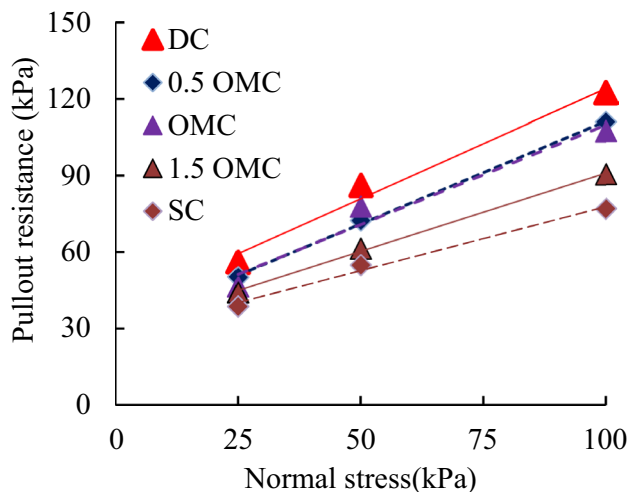
Fig. 9 Variation of maximum pullout resistance—normal stress for sand-geogrid specimens

$$P_R = 2L\sigma_n f_b \tan\phi = 2L\sigma_n f^*, \tag{2}$$

where P_R is pullout resistance (per unit width), L is the reinforcement length in the anchorage zone, σ_n is normal stress, f_b is pullout interaction coefficient, ϕ is the soil friction angle, and f^* is the apparent friction coefficient at the soil–reinforcement interface [26]. Results of the pullout tests can be demonstrated in terms of apparent friction coefficient (f^*) without having f_b and ϕ, depending on the normal stress. The value of f^* can be drawn from he following equation:

$$f^* = \frac{\tau_{max}}{\sigma_n}, \tag{3}$$

where τ_{max} is maximum pullout resistance and σ_n is normal stress. Table 5 presents the maximum pullout resistance (τ_{max}), and apparent friction coefficient (f^*), attained for all pullout tests under normal stresses equal to 50 and 100 kPa in the modified pullout test setup. Maximum pullout resistance and the apparent friction coefficient values were dependent on normal stress and moisture content as shown in this table. An apparent friction coefficient values were observed to be within the range of 0.77–1.72. Similar values were reported by other researchers. Prashanth et al. [27] reported values of apparent friction coefficient for sand–geosynthetic interfaces. These values for sand-geogrid (1.24–1.69) were much higher than the measured values for sand-geotextile (0.55–1.03). Mirzaalimohammadi et al. [24] showed that values of apparent friction coefficient varied from 0.64 to 1.43 for soil/PET–yarn geogrid interfaces. The apparent friction coefficient at the wet side of optimum moisture content showed lower values than the dry side of it; the lowest value was related to saturated sand at 100 kPa normal stress. Furthermore, the friction coefficient is

Fig. 10 Summary results of interface tests
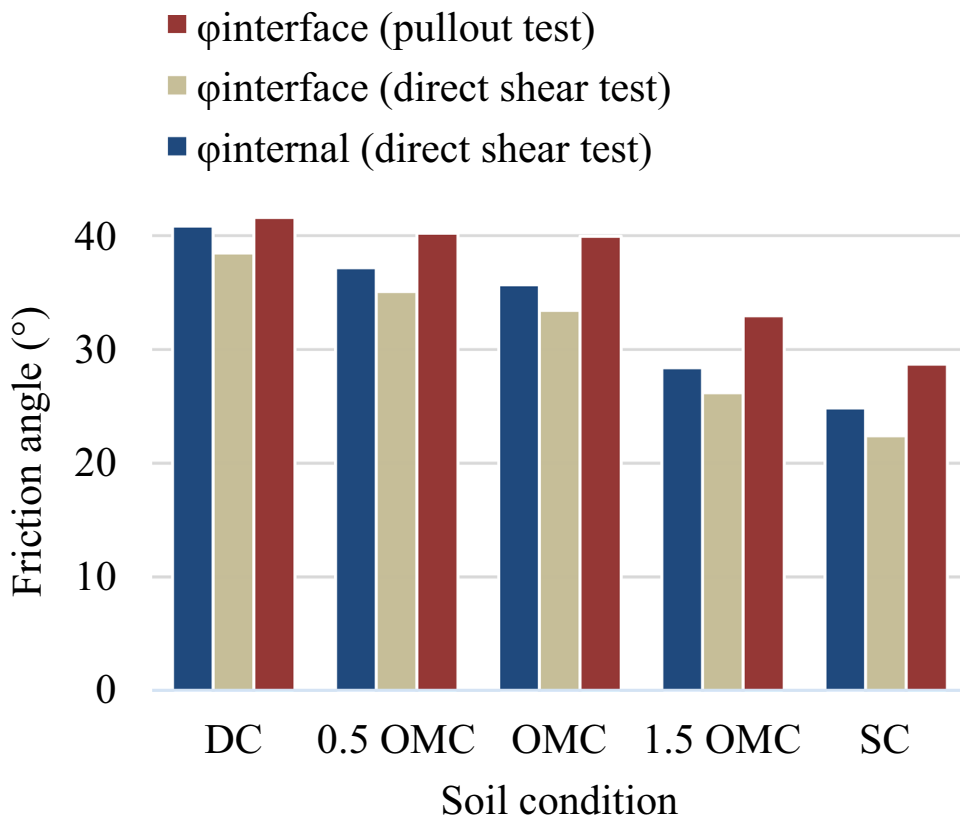
Table 5 Pullout apparent coefficient values

Soil condition ω	Normal stress (σ_n) (kPa)	Maximum pullout resistance (τ_{max}) (kPa)	Apparent friction coefficient (f^*)
Dry	50	86.3	1.72
	100	122.5	1.22
0.5 OMC	50	72.5	1.45
	100	111	1.11
OMC	50	78	1.56
	100	108	1.08
1.5 OMC	50	61.5	1.23
	100	90.6	0.91
Saturated	50	58	1.16
	100	77	0.77

reduced by an increase in moisture content. In other words, the pullout behavior was affected by the applied normal stress and moisture content.

Conclusions

This study focused on the influence of different moisture content on the sand-geogrid interface shear strength and pullout resistance using silty sand and geogrid. Some of the outcomes of this investigation are summarized below:

- The shear strength between sand and geogrid was the result of interlocking of sand aggregates within geogrid apertures under direct shear test. Apertures prevent the sliding of sand particle; therefore, the interface friction angle increased.
- Maximum internal friction angles under dry condition were 10%, 14.5%, 43.8%, and 64% higher than the internal friction angle of 0.5 OMC, OMC, 1.5 OMC, and saturated, respectively. There was an obvious reduction in the internal friction angle by increasing moisture content.
- The increase of soil moisture content led to a decline in the interface friction angle for sand-geogrid. The interface shear strength reduced up to 42% from dry to saturated condition. Results indicated that interface shear strength between sand and geogrid was lower than the internal shear strength of comparable sand. The range of efficiency factors varied from 0.86 to 0.99.
- Unlike the direct shear tests, pullout resistance of sand reinforced specimens gently mobilized by increasing in pullout displacements of the geogrid in pullout tests. It was also shown that the pullout resistance or maximum shear strength increased by increasing the normal stress of reinforced specimens in both cases of the pullout and direct shear tests.

- Maximum pullout resistances under dry condition were 4.5% and 45.5% higher than the pullout resistance of OMC and saturated situation, respectively. The interface friction angle of reinforced specimens reduced considerably with an increase in moisture (dry condition to saturate condition) in both pullout and direct shear mechanisms.
- The apparent friction coefficient values determined from various tests were placed within the range of 0.77–1.72.

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