Investigation of soil-steel interface behavior of Iraqi soil by direct shear apparatus

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Abstract. Soil – structure interaction is an important theme observed in many civil engineering structures like foundations. The interface shear strength plays a significant role in the analysis and design of many structures constructed above or under the ground. In this study, a total of 28 specimens were tested at vertical stresses of 100, 200, and 400 kPa using direct shear apparatus under consolidated drained condition. A silty sand soil, as per USCS classification system was prepared in the laboratory at different water contents (4.5%, 8.8%, and 12.5%) and voids ratios (0.4, 0.6, 0.8, and 1). The frictional resistance of this soil was measured. The soil samples were also sheared against three steel surfaces of different textures (smooth, moderate-rough, and rough). The experimental results showed that the steel surface texture is an effective factor in soil-steel interface shear strength. The interface shear strength of the rough steel surface was found higher than smooth and semi-rough steel surfaces. In addition to the surface roughness, the water content and void ratio also play important roles in interface shear strength.

1 Introduction

The interface is usually defined as a contact zone between two bodies. The serviceability of the geotechnical structures is highly dependent on the behaviour of the layer of soil forming close to the structure surface (i.e. interface layer). Numerous previous studies reported the crucial role of the interface behaviour in analysis of the some geotechnical problems like a retaining wall and the skin friction along a pile shaft. Briaud et al. [6] indicated that 43% of the resistance along a rigid concrete pile shaft embedded in stiff clay is provided by skin friction. Whereas, Smith and Ray [7] reported that the frictional resistance generated along a concrete pile shaft contributed about 84% of the total soil resistance subjected to a lateral loading. Extensive researches have been performed to investigate the interface shear strength behaviour between soil and different types of materials under different test conditions (dry and saturated) [2, 9, 1, 4, 3, 5, 10, 11] using a variety of equipment, e.g., direct shear [2, 8], annular shear device [9], Ring torsion apparatus [4], and simple shear [3]. Their outcomes revealed that the interface shear strength depends on different factors like structure interface condition (i.e. rough, intermediate and smooth), type of construction materials (i.e. concrete, steel, wood and geotextile), moisture content, grain size distribution, different types of soil (i.e. clay, sand and silt), void ratio and normal stress. Potyondy [2] has performed earlier soil structure interface research.

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He performed numerous laboratory interface direct shear tests to find out the value of frictional resistance between soil and several types of materials (steel, concrete, and wood). The experimental results showed that the angle of internal friction and cohesion should be considered in calculating of skin friction of cohesive soils. He also indicated that the most important factors influencing on the interface shear strength are surface roughness, applied vertical stress, water content, soil composition, and solid material roughness. Kulhawy and Peterson [12] conducted a series of direct shear tests between sand and various surface roughness of concrete to evaluate the influence of surface roughness on the interface shear strength. They pointed out that the surface roughness has a significant impact on the interface shear strength and that the interface friction angle increased with increasing of surface roughness. Their results showed that the angle of friction of soil is greater than the interface friction angle of both smooth and rough surfaces. In another work, Desai et al., [8] studied the properties of sand against concrete interface with different densities, postulating that the interface behaviour greatly influenced by relative density of sand, magnitude of vertical stress, and rate of shear displacement.

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Tsubakihara and Kishida [14] conducted laboratory tests on friction between cohesive soils and moderate steel using two types of apparatuses : a direct shear apparatus and a simple shear apparatus. Different types of soils were examined in this study, clay and sand-clay mixtures. They stated that there was little difference in the maximum friction coefficient between the tests with different mixture ratios of sand. Paikowsky et al., [15] indicated a series of laboratory tests using a modified direct shear apparatus and a modified simple shear apparatus. The test results showed that at a given applied vertical stress level, the major parameters which controlling the interface shear strength behaviour are particles shape and surface roughness. Recently, the influence of surface roughness on the shear strength behaviour of an interface between silty sand and a cement grout surface by means of direct shear apparatus is investigated by Chu and Yin [16]. Their results indicated that the soil-interface shearing resistance depends primarily on the surface roughness, water content of soil, and magnitude of the applied stress. The influence of soil water content, surface roughness and normal stress on the relationship between shear stress versus horizontal displacement was investigated by Shakir and Zhu [17] using simple shear apparatus. In their study, different concrete surface roughness's (smooth and rough) were used. Clay specimens were compacted at the same dry density with different water content ratios. They stated that the interface shear behaviour for both rough and smooth concrete surfaces governed by the interface sliding occurred within the interface layer between soil and concrete for all specimens except when the water content of specimen is greater than 16% for the case of rough concrete surface where the shear failure occurs within the soil body. Recently, Fleigh et al. [18] classified the interface friction behaviour into three failure modes, namely full sliding at the interface, shear failure within the soil and mixed behaviour where interface sliding and shear deformation of soil specimen proceed simultaneously. In their work, they performed a series of interface direct shear tests to study the effect of surface roughness and texture models on the friction angle between cohesive soils and steel.

2 Research Objectives

To the author's knowledge, there is inadequate literature available about the behaviour of interface shear strength of Iraqi soils. Hence, the aim of the present paper is to examine the influence of three major parameters namely surface roughness, soil water content and void ratio on the interface shear strength behaviour between silty sand soil and steel surface using direct shear apparatus.

3 Laboratory testing

3.1 Material

To achieve the goal of this research, synthetic soil specimens were prepared from sandy soil and kaolin

since it could not be possible to find natural soil specimens from Iraq. The soil is prepared in the laboratory according to sieve analysis test results of soil obtained from AL-Rashedia site located in Nineveh governorate (495 km north of Baghdad) and published in a journal paper achieved by Khattab et al., [22]. Standard tests were carried out to determine the engineering properties of the prepared soil. Details are given in Table 1. According to the Unified Soil Classification System (USCS), the soil used in the investigation was classified as silty sand or SM. Fig. 1 shows particle-size distribution curves of the original and prepared soils, which indicate that the soil is composed of 73% sand, 19% silt, and 8% clay. Moreover, a standard compaction test was performed according to (ASTM D1577-02) by using a 2.5 kg rammer and a mould of 1000 cm³. Fig. 2 shows the relationship between the dry unit weight and water content of the soil used. The obtained maximum dry density is 20.20 kN/m³ with an optimum moisture content of 8.8%.

Fig. 1. Particle-size distribution curve of the soil

Fig. 2. Dry density versus water content curve for prepared soil

3.2 Sample preparation

In this research, the soil specimen used in the direct shear test was prepared in the laboratory and placed in the oven at a temperature of 105 °C for 24 hours. Then, the desired quantity of soil was taken and appropriate amount of water was added to the target water content.

The wet soil was wrapped in anti-evaporation plastic bags and stored in containers for 72 hours for water content equalization. For soil to soil specimen, the soil was compacted inside a square mould having inner dimensions of 60 mm by 60 mm and a height of 20 mm. The soil was compacted in four layers of 5 mm thickness of each inside steel mould to the required density. The compaction was done by using a tamping rod. Finally, the mould with the specimen was placed over the upper half of shear box and the specimen pushed slowly inside the shear box until the specimen attached with the lower porous stone. The above procedure was adopted in preparing soil against steel direct shear specimen except that the wet soil was compacted in two layers of 5 mm each. Total number and types of tests performed for this study are presented in Table 2.

Table 1. Index properties of prepared soil

Soil property	Unit	Value
Specific gravity (Gs)	-----	2.74
Liquid limit (L.L.)	%	21
Plastic limit (P.L.)	%	20
Plasticity index (P.I)	%	1
Gravel	%	0
Sand	%	73
Silt	%	19
Clay	%	8
Standard maximum dry density	kN/m ³	20.20
Optimum water content	%	8.8
D ₆₀	mm	0.35
D ₅₀	mm	0.25
D ₃₀	mm	0.075
D ₁₀	mm	0.004
Soil classification (USCS)	-----	SM

Table 2. Total number and types of tests conducted for this study

Parameter	Interface	Applied vertical stress (kPa)			Test condition
		100	200	400	
e = 0.4	Soil	x	x	x	Consolidated drained
	Smooth	x	x	x	
	Moderat	x	x	x	
	Rough	x	x	x	
e = 0.6	Soil	x	x	x	Consolidated drained
	Smooth	x	x	x	
	Moderat	x	x	x	
	Rough	x	x	x	
e = 0.8	Soil	x	x	x	Consolidated drained
	Smooth	x	x	x	
	Moderat	x	x	x	
	Rough	x	x	x	
e = 1	Soil	x	x	x	Consolidated drained
	Smooth	x	x	x	

$\omega = 4.5\%$	Moderat	x	x	x	Consolidated drained
	Rough	x	x	x	
	Soil	x	x	x	
	Smooth	x	x	x	
$\omega = 8.8\%$	Moderat	x	x	x	Consolidated drained
	Rough	x	x	x	
	Soil	x	x	x	
	Smooth	x	x	x	
$\omega = 12.5\%$	Moderat	x	x	x	Consolidated drained
	Rough	x	x	x	
	Soil	x	x	x	
	Smooth	x	x	x	

3.3 Counterface

In order to investigate the influence of surface roughness on the interface shear stress between soil and structures, three steel plates prepared from a steel sheet were used in this study as a counterface. All steel plates were manufactured having the same dimensions of 100*100*10 mm, which is exactly the same as the size of lower half of shear box. Three different surfaces roughness (smooth, semi-rough, and rough) were performed as shown in Fig. 3. The completely smooth surface polished by fine sandpaper [2]. A value of 0.0025mm was used as a peak to valley height for smooth steel plate [25]. Uesugi and Kishida [3] defined the normalized surface roughness, R_n as a maximum peak to valley height, R_{max} divided by grain size diameter corresponding to 50% finer, D_{50} . Based on the particle-size analysis curve, the normalized surface roughness of smooth, moderate and rough steel plates were equal to 0.01, 4, and 8 respectively.

Fig. 3. Surface geometry of (a) semi-rough: and (b) rough

4 Soil testing method

A fully automated commercially direct shear apparatus was used in this study. All tests were performed according to (ASTM D3080-04). The test procedure consists of three stages :- saturation, consolidation and shearing stages. After placing the soil specimen inside the shear box, the specimen was soaked in water for 24 hours to ensure that the voids are completely filled with water. After saturation, the specimen was consolidated under three applied vertical stresses of 100, 200 and 400 kPa. The consolidation process continues until the

vertical deformation versus horizontal displacement curve is levelled off. After consolidation attained, a shearing stage was performed under drained condition with a constant horizontal shearing rate of 0.06 mm/min for all specimens (i.e. soil versus soil and soil versus interface).

5 Test results and analysis

5.1 Test results of soil to soil specimens

Single stage direct shear tests were performed on initially saturated soil to soil specimens under different applied vertical stresses of 100, 200 and 400 kPa. The effect of different water content and void ratio on the shear strength behaviour of compacted silty sand soil are presented and discussed in the following sections.

5.1.1 Influence of water content on shear strength behaviour

Typical direct shear test results are presented in terms of shear stress versus horizontal shear stress displacement curves for soil specimens tested at different water contents (4.5%, 8.8% and 12.5%) under 100, 200 and 400 kPa applied vertical stress respectively are shown in Fig. 4a-c. Soil specimens of dry and wet side of optimum were compacted at same dry density (19.2 kN/m^3) with different water content (4.5% and 12.5%). As expected, all specimens exhibited a hardening behaviour at beginning of shearing stage until peak shear stress followed by different patterns of shear behaviours (softening and/or hardening). These figures also illustrated that the shear strength increased with the increasing of applied vertical stress. Regardless of the value of vertical stress, specimens compacted at dry side of optimum exhibited higher shear stress compared with those tested at wet side of optimum. These findings coincide with the findings reported by Tiwari and Al-Adhahd, [11]. Fig. 4 also indicates that clear peak shear stress and softening behaviour are obvious for specimens carried out under 400 kPa vertical stress. Fig. 5 depicts Mohr-Coulomb shear envelopes obtained from the three different types of tests. As expected, specimens compacted at optimum water content had higher shear strength compared to those tested at dry and wet side of optimum for all vertical stresses. However, dry side of optimum specimens showed higher shear strength than those compacted at wet side of optimum. Vanapalli et al., [19] and Cokca et al., [20] found the same results. The shear strength parameters along with the water content are summarized in Table 3. As can be seen in Table 3, a significant reduction was observed in the effective cohesion with an increase in water content. In addition, effective friction angle decreased as water content decreased. For example, friction angle decreased from 30° to 29° when water content increased from 4.5% at dry side to 12.5% at wet side of optimum.

Fig. 4. Direct shear test results for soil to soil specimens compacted at different water content (a) dry; (b) optimum; and (c) wet

Fig. 5. Failure envelopes corresponding to different water content

Table 3. Shear strength parameters from different water content tests

Water content (%)	ϕ' (deg)	c' (kPa)
Dry side = 4.5	30	10
Optimum = 8.8	31.5	21
Wet side = 12.5	29	4

5.1.2 Influence of void ratio on shear strength behaviour

Twelve consolidated drained direct shear tests were carried out on the saturated silty sand under three vertical stresses and four different void ratios. Fig. 6a-d shows shear stress versus horizontal displacement curves for soil specimens performed at different void ratios (0.4, 0.6, 0.8, and 1) and water content equal to 7%. It can be seen from Figure 6 that the shear stress decreased with increasing of void ratio for all applied vertical stresses. As can be observed, the maximum shear stress increases as the vertical stress increases for all void ratios. It can be also noticed that the dense specimens (low void ratio) exhibited peak shear stress more clearly than the loose specimens (high void ratio). The values of maximum shear stress from all tests are plotted against applied vertical stress in Fig. 7. The shear strength envelopes for various void ratios are approximately linear. Moreover, the shear strength parameters ϕ' and c' decrease with an increasing of void ratio as shown in Table 4. The experimental shear strength result agrees with the findings reported by Tiwari and Al-Adhahd [11].

Fig. 6. Direct shear test results for soil to soil specimens compacted at different void ratios (a) 0.4; (b) 0.6; (c) 0.8; and (d) 1

Fig. 7. Failure envelopes corresponding to different void ratios

Table 4. Shear strength parameters from different void ratio tests

Void ratio	ϕ' (deg)	c' (kPa)
0.4	29	20
0.6	28.5	19
0.8	26.5	15
1	24	0

5.2 Interface shear tests

This study is set out with the aim of assessing the importance of surface roughness on the shear strength of soil. To do this, a series of interface direct shear tests were carried out to examine the effect of three types of steel surface roughness on the interface shear strength at different void ratios and water content. Curves of shear stress versus horizontal shear displacement for different water content (4.5% and 12.5%) sheared against smooth, semi-rough, and rough steel surfaces under applied vertical stress of 400 kPa are plotted in Fig. 8a-b. Similar behaviour was observed while the specimens were examined under other vertical stresses. It is interesting to note that the shear stress increased with an increase in the surface roughness increases for both dry and wet side of optimum conditions. As can be observed from Figure 8a-b that the interface shear strength of specimen with rough steel significantly increased approximately by 1.5 folds and 2 folds for specimens with 4.5% and 12.5% water content, respectively. It can be also observed that the curves for rough surface exhibited peak shear stress followed by softening behaviour. As opposed to the rough interface, curves of smooth interface showing no peak shear stress followed by steady state condition. The failure envelopes for soil-steel interfaces performed under different water content are shown in Fig. 9a-b. The failure envelopes are found to be linear. It can be also noticed that there was a remarkable reduction in the interface shear strength compared to the shear strength of soil. The highest reduction was observed for soil sheared against smooth interface compared to the specimens sheared against semi-rough and rough interfaces. This trend was observed for all water content values.

Fig. 8 Direct shear test results for soil to interface specimens compacted at different water content (a) dry; (b) wet

Fig. 9. Failure envelopes for the soil to soil and soil to interface for specimens compacted at different water content (a) dry; and (b) wet

These results are consistent with those reported by [21]. The shear strength parameters along with the water content are summarized in Table 5.

Table 5. Shear strength parameters from different water content tests

Interface	Water content (%)	ϕ' (deg)	c' (kPa)
Soil	4.5	30.5	10
Smooth		18.5	6
Semi-smooth		26.5	7.5
Rough		28.5	12
Soil	12.5	29	6
Smooth		15.5	4
Semi-smooth		25	0
Rough		27	5

Likewise, the results of interface direct shear tests for the soil specimens with 0.4 and 1 void ratio are presented in Figure 10a-b tested under applied vertical stress of 400 kPa. Similar behaviour was observed while the specimens were carried out under other applied vertical stresses. As evident, there is a consistent increase in the

interface shear stress with an increase in the surface roughness irrespective of whether the void ratio was 0.4 or 1. As could be observed from Fig. 10a-b that the interface shear strength of specimen with rough steel significantly increased approximately by 3 folds and 1.6 folds for specimens with 0.4 and 1 void ratios respectively. It can be also noticed that the curves for rough surface exhibited peak shear stress followed by softening behaviour. As opposed to the rough interface, curves of smooth interface showing no peak shear stress followed by steady state condition. In general, it is observable that the void ratio has a remarkable influence on the interface shear stress. For example, the maximum shear stress for rough interface decreased by 28% when the void ratio increased from 0.4 to 1. The presented findings seem to be consistent with the results observed by previous researchers such as [2, 12, 10, 21]. The values of peak shear stress from all tests are plotted against the vertical stress in Fig. 11a-b, for different void ratios. The interface failure envelopes for various interfaces roughness are approximately linear. Similar to interface direct shear results under different water content, a significant reduction in the interface shearing resistance compared to the shearing resistance of soil. The highest reduction was observed for soil sheared against smooth interface compared to the specimens sheared against semi-rough and rough interfaces. The shear strength parameters along with the void ratios are tabulated in Table 6. In addition, Figure 12a-b illustrates the influence of surface roughness on the interface angle of friction.

Fig. 10. Direct shear tests results for soil to interface specimens compacted at different void ratios (a) 0.4; (b) 1

Table 6. Shear strength parameters of soil and interfaces

Interface	Void ratio	ϕ' (deg)	c' (kPa)
Soil	0.4	30.5	17
Smooth		20	8
Semi-rough		24	13
Rough		30	16
Soil	1	24	7
Smooth		5.5	23
Semi-rough		19	0
Rough		22.5	5

Fig. 11. Failure envelopes for the soil to soil and soil to interface for specimens compacted at different void ratios (a) 0.4; and (b) 1

Fig. 12. Influence of surface roughness on the interface friction angle

6 Conclusions

Consolidated drained direct shear tests were carried out to investigate the influence of water content, void ratio, and surface roughness on the interface shear strength between silty sand and steel plate. Three types of surface roughness (smooth, semi-rough, and rough) were used. The specimens were compacted at different water contents (4.5%, 8.8%, and 12.5%) and void ratio (0.4, 0.6, 0.8, and 1). Based on the results obtained the following conclusions are summarized.

1. The shear strength of soil increases with decreasing both water content and void ratio.
2. Soil shear strength increased with increasing of applied vertical stress. Based on the presented results, it can be seen that soil shear strength was higher than the interface shear strength of smooth, semi-rough and rough interfaces.
3. The interface shear stress increases with increasing the surface roughness. Therefore, from the geotechnical point of view, rough steel surface can be used to increase the interface shear strength of some geotechnical structures such as steel pile foundation and offshore structures.
4. The interface friction angle of different surface roughness increases as the surface roughness increases. Interface friction angle increased by 50% when the surface roughness changed from the smooth to the rough surface for specimens compacted at dry side of optimum.
5. Based on the results, void ratio and water content had an obvious influence on the interface friction angle between soil and steel plates. Referring to the results, high water content and low void ratio produced small friction angle.

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