



# A comparative study on the undrained shear strength results of fall cone and vane shear tests in sand–clay mixtures

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## Abstract

This paper presents an intensive series of laboratory testing results from vane shear and fall cone tests that were conducted on various clay–sand mixtures to understand the link between these methods which are often used for determining the undrained shear strength ( $s_u$ ). Three different gradations (2.0–1.0 mm, 1.0–0.6 mm, and 0.6–0.3 mm) of rounded and angular sands were mixed with low-plasticity clay at ratios of 0%, 10%, 20%, 30%, 40%, and 50%. The results of the tests demonstrated that the  $s_u$  values obtained from the vane shear tests were found to be always higher than those obtained from the fall cone tests. It was shown that the sand content used in the mixtures changed the  $s_u$  parameters of the specimens significantly. The results indicated that the  $s_u$  values were significantly influenced by grading characteristics of the sands ( $d_{10}$ ,  $d_{20}$ ,  $d_{30}$ ,  $d_{50}$ ,  $d_{60}$ ,  $c_u$ ,  $c_c$ ). The values of  $s_u$  were lower for the samples that had a larger size of sand grains. Finally, shape characteristics of the sand grains were found to be effective on the results. The samples with angular sand grains have higher  $s_u$  values than the samples with rounded sand grains, for all gradations employed in the present study.

**Keywords** Sand · Clay · Undrained shear strength · Fall cone · Vane shear

## Introduction

Most of the experimental researches for determining the engineering characteristics of cohesive soils focused on the behavior of clean clay specimens. However, site investigations reveal that the cohesive soils may contain different amounts of silt and/or sand grains with different physical properties (shape, gradation). The silt and sand grains in clay should be expected to influence the undrained shear strength of clay samples. It is of great importance to identify the undrained shear strength ( $s_u$ ) of such soils in order to make an accurate stability analysis. Two widely used methods for identifying the undrained shear strength are vane shear test and fall cone test. Undrained shear strength, liquid limit, and sensitivity of

soils were previously studied using the fall cone test (Terzaghi 1927; Hansbo 1957; Houlsby 1982; Wood 1982, 1985; Leroueil and Le Bihan 1996; Feng 2000; Claveau-Mallet et al. 2012; Westerberg et al. 2015; Cabalar and Mustafa 2015). The principle of this experiment is that a cone with a certain tip angle and weight is released into a soil sample and the penetration depth is measured. An equation that shows the change of undrained shear strength ( $s_u$ ) of clay during the penetration of the cone which has a mass of  $m$  was given by Hansbo (1957) in Eq. 1 as follows:

$$s_u = k \frac{mg}{d^2} \quad (1)$$

In the above equation,  $k$  is constant and is determined by the angle of cone. In a 30° British cone, this value is 0.85 (Wood 1985). Undrained shear strength studies have also been performed using vane shear tests by many researchers (Flaate 1966; Menzies and Merrifield 1980; Mohsen and Ullrich 1985; Seah et al. 2004; Larsson et al. 2009; Wang et al. 2013). Conventionally, the vane shear test is carried out using a four-bladed vane with four different sizes which have the ratio of height/diameter = 2. A torque is applied to the torque rod then to the vane at a rate of about 6°/min, preferably by a geared drive until the specimen fails. The undrained shear

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strength of a specimen is calculated in compliance with the standard equations (ASTM D 2573-94 2013) given below (Eqs. 2 and 3).

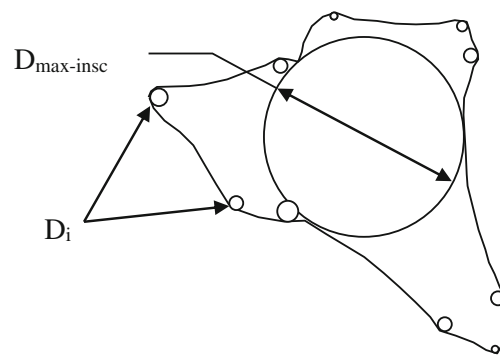
$$s_u = \frac{T}{K} \quad (2)$$

$$K = \frac{\pi D^2 H}{2} \times \left[ 1 + \frac{D}{3H} \right] \quad (3)$$

Where,  $T$  is torque,  $K$  is a coefficient related to dimensions and geometry of the vane,  $D$  is diameter of vane, and  $H$  is height of vane.

It is understood nowadays that grain shape properties and gradation can change the soils' engineering properties (Terzaghi 1925; Gilboy 1928; Lees 1964, Olson and Mesri 1970; Abbireddy et al. 2009; Clayton et al. 2009; Goktepe and Sezer 2010; Cabalar et al. 2013; Cabalar and Hasan 2013; Cabalar 2018). When looked in the literature, Terzaghi investigated shape characteristics of soil grains and he was one of the first to make such extensive experiments on soils (Terzaghi 1925). Around the same time, Gilboy (1928) also had performed experiments and concluded that any analysis without regard to the shape of the soil would be false and incomplete. It was also shown by Holubec and D'Appolonia (1973) that the grain shape played a role in dynamic penetration test results. Holtz and Kovacks (1981) presented a relationship between the internal friction angle ( $\varphi$ ) and the shape of the grains. Later, Cedergen (1989) showed that the shape of the grains can also affect their permeability. Wadell (1932), Krumbein (1941), Powers (1953), Holubec and D'Appolonia (1973), Youd (1973), and Cho et al. (2006) have done experiments related with grain shapes and shown the relation to the soil properties. The soil grain shape can be characterized simply by two parameters, namely (i) roundness, a parameter which defines the curvature or sharpness of the corners of a grain; (ii) sphericity which defines the more general form of the grain and how it approaches the shape of a sphere. Wadell gave the definition of sphericity ( $D_{\max\text{-insec}}/D_{\min\text{-circ}}$ ), to be the ratio of maximum inscribed circle to the minimum sphere circumscribing the shape. The definition of roundness ( $R$ ) given by Wadell (1932) is the ratio of the average diameter of the inscribed circles drawn on the corners to the diameter of the maximum inscribed circle ( $D_{i\text{-ave}}/D_{\max\text{-insec}}$ ). Figures 1, 2, and 3 present a chart that is still used today to determine  $R$  and  $S$  values (Krumbein 1941; Powers 1953).

Researchers have been studying undrained shear strength in laboratory, but it has been noted that there is no information available on the experimental study of sand–clay mixtures through both the fall cone and the laboratory vane shear tests. The fundamental relationships between the clay with sands at different physical characteristics and undrained shear strength that characterizes the sands have not been understood and quantified very well. Hence, this investigation reports what



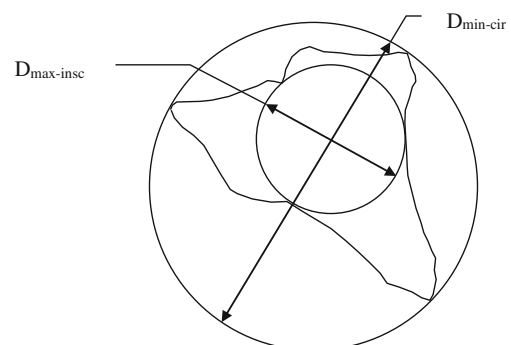
**Fig. 1** Graphical representation of roundness,  $R$  (redrawn from Muszynski and Stanley 2012)

is thought to be the first paper ever done to figure out the (i) effects of physical characteristics (shape and gradation) of sand grains; (ii) fine (clay) content; and (iii) amount of water in various sand–clay mixtures on the undrained shear strength results using both fall cone and vane shear tests. The objective of the present investigation was partly scientific curiosity, but moreso to quantify decisive undrained shear strength values of various sand–clay mixtures around many geotechnical applications. In order to conduct such an experimental work, a large number of both fall cone and vane shear tests were undertaken on the sand grains having distinct sizes/shapes mixed with clay at various contents ranging from 0 to 50%. Consequently, series of correlations among the undrained shear strength, size/shape of sand grains, amount of fine (clay), and testing approach were proposed in order to use for further studies.

## Experimental study

### Materials

Table 1 gives a summary of the testing program followed in the experimental studies. The undrained shear strength ( $s_u$ ) of sand–clay mixtures are usually calculated using either vane



**Fig. 2** Graphical representation of sphericity,  $S$  (redrawn from Muszynski and Stanley, 2012)

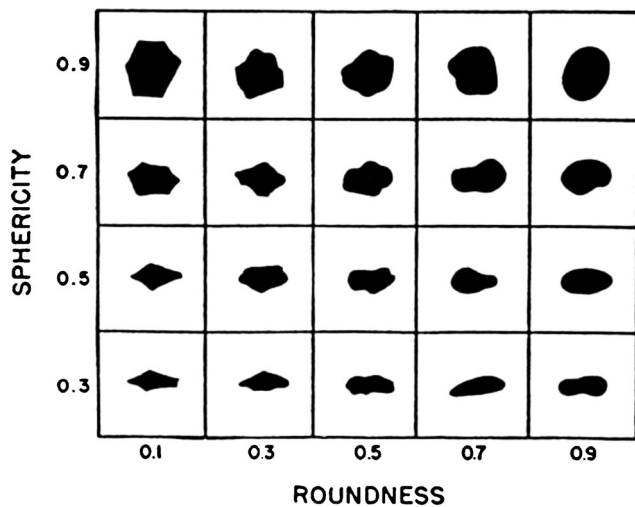


Fig. 3 Comparison chart (Krumbein and Sloss 1963)

shear or fall cone tests. These tests were conducted on the samples to understand the relationship between the two kinds of tests. Rounded and angular sands having three different gradations (2.0–1.0 mm, 1.0–0.6 mm, and 0.6–0.3 mm) were mixed with clay having a low plasticity at ratios that ranged from 0 to 50% (by increments, 10%) by weight. The geomaterials used during these tests were Narli Sand (NS) representing round-shaped sand grains, Crushed Stone Sand (CSS) representing angular-shaped sand grains, and a CL-type clay.

The NS is a naturally available river sand obtained from Aksu River in the southern part of Turkey. The CSS sand was

supplied from a local mining plant in the same region. The specific gravity ( $G_s$ ) of the sand grains was calculated to be 2.65 for the NS, and 2.68 for the CSS grains. Three different gradations of the samples falling between 2.0 mm and 1.0 mm, 1.0 mm and 0.6 mm, and 0.6 mm and 0.3 mm were artificially selected (Fig. 4). From the study by Muszynski and Vitton (2012), roundness ( $R$ ) and sphericity ( $S$ ) estimates were found to be respectively 0.43 and 0.67 for the NS, and 0.16 and 0.55 for the CSS grains. The clay was obtained from the campus of the University of Gaziantep. The PL of clay is 23 and LL value is 49. The specific gravity of the clay sample is calculated to be 2.61. Figure 5 shows the scanning electron micrograph (SEM) photographs of the NS, CSS, and clay samples.

### Testing apparatuses and specimen preparation

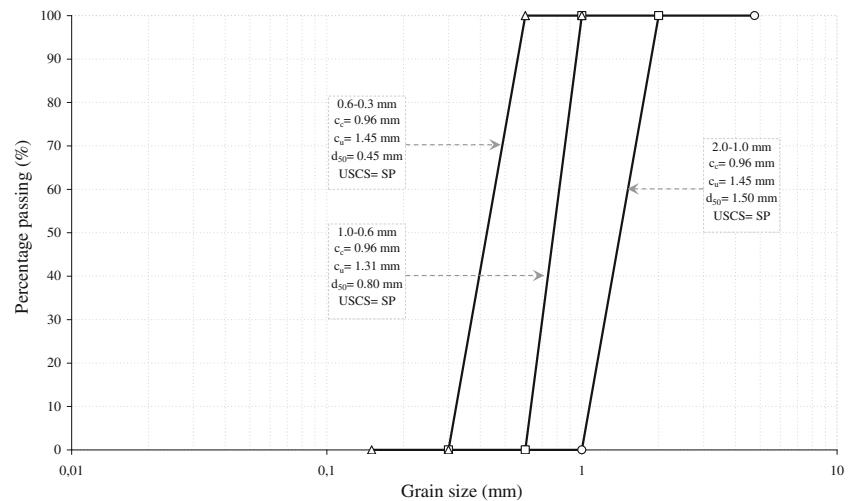
The tests were conducted in British fall cone and vane shear apparatuses, confirming to BS 1377, whose manufacturer is Wykeham Farrance. The fall cone apparatus has a cone that weighs 0.785 N with a 30° tip angle, and a cup to hold the specimens that is 55 mm in diameter and 40 mm in height. The vane shear apparatus has blades with the size of 12.5 mm in diameter, 25 mm in height, and 0.01 mm in thickness.

The sand and clay grains were first oven-dried, and de-aired water was added at specified percentages in order to have 20 mm penetration of cone. The mixtures were then left to cure for a time period of 24 h so that they will be saturated

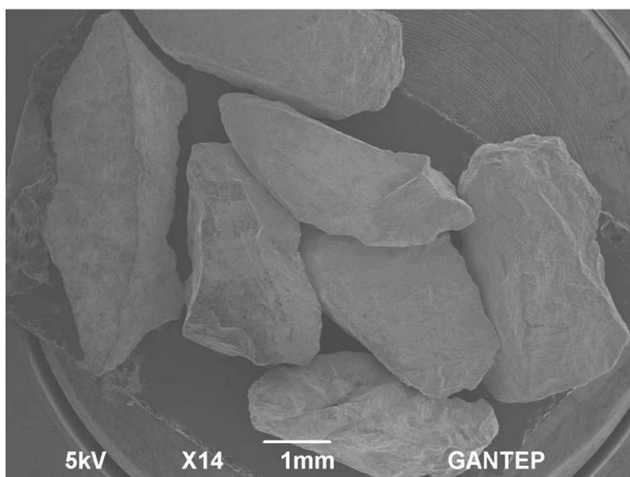
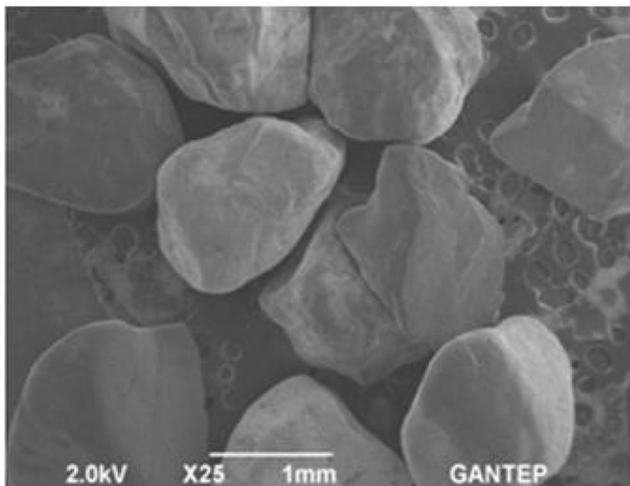
Table 1 Test scheme

Test type	Sand type	Gradation	Sand content (%)	Water content (%)
(i). Fall cone test	(i). Rounded sand	(i). 2.0–1.0 mm	10	28
				30
(ii). Vane shear test	(ii). Angular sand	(ii). 1.0–0.6 mm (iii). 0.6–0.3 mm	20	32
				34
				26
				28
				30
				32
				30
				24
				26
				28
(ii). Vane shear test	(ii). Angular sand	(ii). 1.0–0.6 mm (iii). 0.6–0.3 mm	40	30
				22
				24
				26
				28
				30
(ii). Vane shear test	(ii). Angular sand	(ii). 1.0–0.6 mm (iii). 0.6–0.3 mm	50	18
				20
				22
				24

**Fig. 4** Sieve analysis for the materials used



completely before the actual tests. Both of the methods will result in the various soil plasticity due to the five different water contents employed. The sand–clay mixture was prepared and inserted into the cup of the equipment while making



**Fig. 5** SEM pictures of the (top) NS and (bottom) CSS used during the experimental study

sure not to trap air. The top part of the cup was leveled to make its surface smooth. Later, the specimen was then mounted on the fall cone and vane shear equipment while making sure that the blades are only touching the surface. At the end of 5 s, the penetration reading from the fall cone was taken. In the vane shear test, the rate of rotation of the blades was constant. At each 5° of rotation, the spring deflections are recorded until the maximum rotation degree of 180 was reached. The experiments were conducted again several times to reproduce similar results. Water content measurements were taken at the end of each test. The testing procedures were repeated with varying water contents.

## Results and discussion

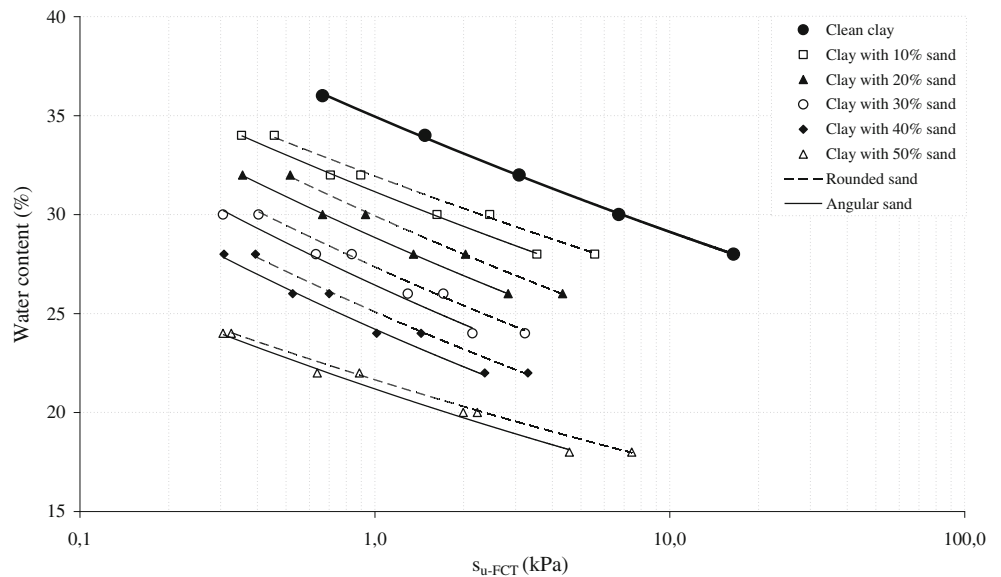
The summary of the test results is given in Table 2, in which a total of 125 fall cone tests and 125 vane shear tests were performed for various cases as shown.

To study the influence of the shape characteristics, changes in undrained shear strength ( $s_u$ ) with fall cone and vane shear tests for each of the mixtures with sizes 2.0–1.0 mm, 1.0–0.6 mm, and 0.6–0.3 mm of rounded sands and angular sands are shown in the Figs. 6 and 7. As can be seen from Fig. 6, the  $s_u$  parameters obtained through the fall cone tests ( $s_{u-FCT}$ ) reduce as the water content (%) in the sand–clay mixtures increases. In order to interpret the results of the fall cone test that was conducted, water contents of the mixtures corresponding to 20 mm penetration were observed. In Fig. 6, it can be seen that more sand content causes the  $s_{u-FCT}$  and corresponding water content to decrease. This is a result of the fact that a decrease in the clay content in a sand–clay mixture causes its liquid limit to also decrease, as shown by Nagaraj et al. (1987), Tan et al. (1994), and Cabalar and Mustafa (2015). The fall cone tests showed that the undrained shear strength is affected significantly by the shape of sand particles. It is seen from Fig.

**Table 2** Testing results

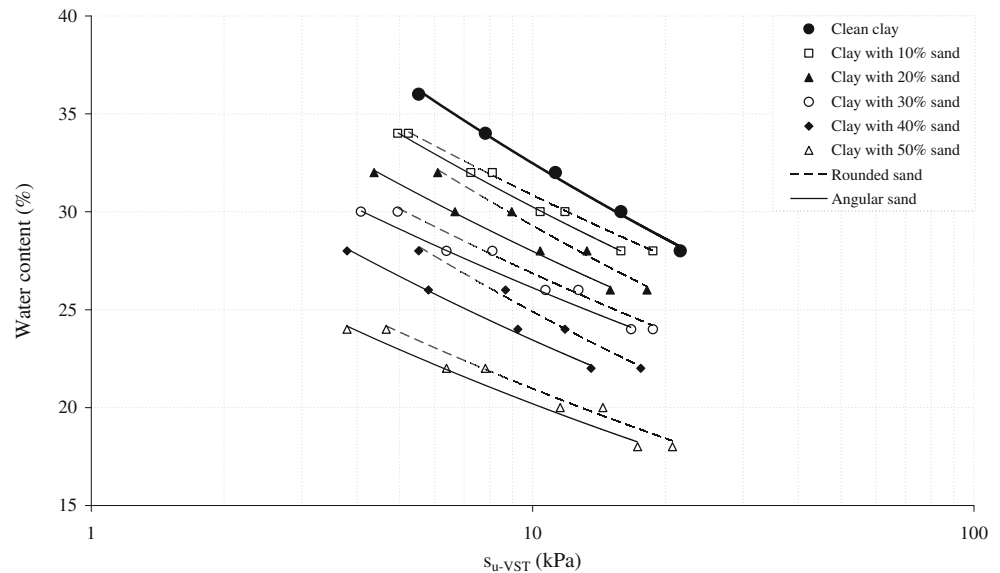
Sand content (%)	Water content (%)	Angular sand						Rounded sand					
		0.6–0.3 mm		1.0–0.6 mm		2.0–1.0 mm		0.6–0.3 mm		1.0–0.6 mm		2.0–1.0 mm	
		$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)	$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)	$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)	$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)	$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)	$s_{u-VST}$ (kPa)	$s_{u-FCT}$ (kPa)
0	28	21.61	16.44	21.61	16.44	21.61	16.44	21.61	16.44	21.61	16.44	21.61	16.44
	30	15.87	6.72	15.87	6.72	15.87	6.72	15.87	6.72	15.87	6.72	15.87	6.72
	32	11.27	3.09	11.27	3.09	11.27	3.09	11.27	3.09	11.27	3.09	11.27	3.09
	34	7.82	1.48	7.82	1.48	7.82	1.48	7.82	1.48	7.82	1.48	7.82	1.48
	36	5.52	0.66	5.52	0.66	5.52	0.66	5.52	0.66	5.52	0.66	5.52	0.66
10	28	15.87	4.96	15.58	4.01	15.29	3.54	18.74	7.43	17.59	6.95	16.73	5.57
	30	10.41	2.45	10.12	1.80	9.55	1.63	11.84	2.66	11.27	2.60	10.98	2.45
	32	7.25	1.05	6.96	0.78	6.38	0.71	8.11	1.16	7.53	1.08	7.25	0.90
	34	4.95	0.56	4.37	0.37	3.80	0.35	5.24	0.61	4.95	0.48	4.66	0.46
20	26	15.01	3.54	14.72	3.16	14.14	2.83	18.17	5.74	17.30	4.96	16.15	4.33
	28	10.41	1.65	10.12	1.46	9.83	1.35	13.28	2.66	12.42	2.40	11.27	2.03
	30	6.67	0.84	6.38	0.76	6.10	0.66	8.97	1.22	8.40	1.11	7.82	0.93
	32	4.37	0.46	4.09	0.39	3.80	0.36	6.10	0.61	5.52	0.57	5.24	0.52
30	24	16.73	2.83	16.44	2.45	16.15	2.14	18.74	4.69	17.88	4.22	17.30	3.23
	26	10.69	1.53	10.12	1.44	9.26	1.29	12.71	2.14	11.84	1.96	10.69	1.71
	28	6.38	0.75	6.10	0.69	5.81	0.63	8.11	0.94	7.53	0.91	6.96	0.84
	30	4.09	0.38	3.80	0.33	3.51	0.31	4.95	0.47	4.66	0.42	4.09	0.40
40	22	13.57	2.83	12.99	2.66	12.71	2.36	17.59	4.82	16.73	4.01	15.29	3.30
	24	9.26	1.19	8.40	1.10	8.11	1.01	11.84	2.14	11.56	1.80	10.69	1.44
	26	5.81	0.62	5.24	0.56	4.95	0.53	8.68	0.95	7.82	0.86	6.67	0.70
	28	3.80	0.35	3.51	0.34	3.22	0.31	5.52	0.54	4.95	0.46	4.37	0.39
50	18	17.30	6.30	16.73	5.25	16.15	4.57	20.75	11.82	19.89	10.42	18.74	7.43
	20	11.56	2.60	10.98	2.23	10.69	1.99	14.43	3.46	13.86	3.16	13.28	2.23
	22	6.38	0.87	6.10	0.67	5.81	0.64	7.82	1.17	7.53	1.00	7.53	0.89
	24	3.80	0.43	3.51	0.34	3.22	0.31	4.66	0.46	4.66	0.38	4.09	0.33

**Fig. 6** Relationship between  $s_{u-FCT}$  and water content for the clay with sands of 2.0–1.0 mm grain size





**Fig. 7** Relationship between  $s_{u-VST}$  and water content for the clay with sands of 0.6–0.3 mm grain size



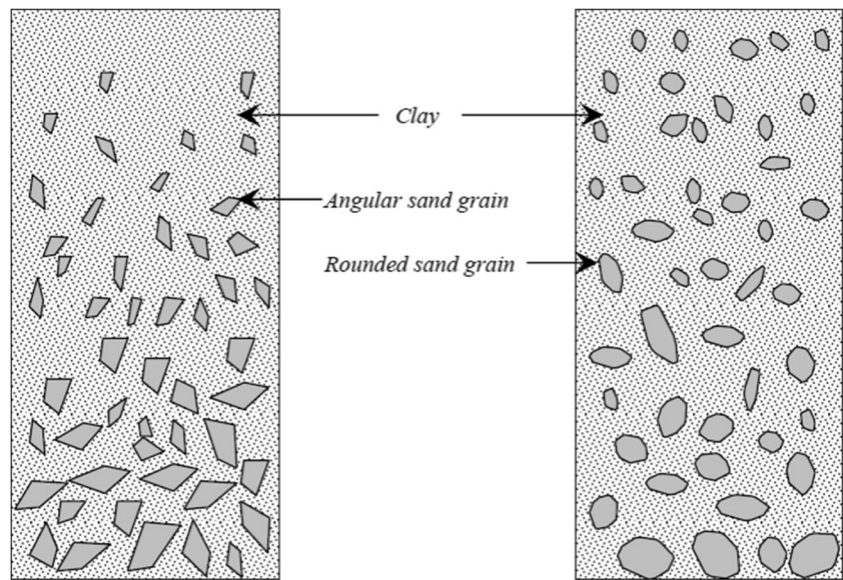
6 that the sand grains with an angular shape have higher  $s_{u-FCT}$  values for all sand and water contents. Hence, it is likely because of (i) open fabric structure in specimens with angular sand grains, and (ii) higher  $G_s$  values of the angular-shaped grains.

The void ratio ( $e$ ) of a soil matrix is commonly defined to be the ratio of voids to the volume of solid grains. It was noted that the ordered packing of identical grains leads to void ratio that is grain size independent (Figs. 6 and 7). The resulting void ratios by the clean, angular sand grains are larger than those for clean, rounded grains. However, the testing results described here have not been carried out on the clean sands, rather the results have been obtained on the sand–clay mixtures which are thought as a composite matrix of finer and coarser soil grains. Therefore, in light of the numerous investigations (Ni et al. 2004; Monkul and Ozden 2007; Thevanayagam 1998; Rahman and Lo 2008; Cabalar and Mustafa 2015), separating the effects of sand and clay grains has significant benefits and makes it more versatile to analyze the test results. This is especially true in the case when describing the use of intergranular void ratio ( $e_s$ ) as an alternative parameter to define the undrained shear strength behavior of sand–clay mixtures rather than using traditional void ratio ( $e$ ) values (Yamamuro et al. 1996; Thevanayagam and Mohan 2000; Yamamuro and Wood 2004; Cabalar and Hasan 2013).

The intergranular void ratio concept was first proposed by Mitchell (1976), and followed by Kenny (1977), Lupini et al. (1981), and Thevanayagam (1998), which is an assumption that the sand particles act as the skeleton of the soil matrix while the particles of clay occupy the space in between, which is defined as the intergranular void ratio ( $e_s$ ). The researchers showed that the overall behavior of the sand mixture is controlled by the sand grains depending on the amount of clay grains present. On the other hand, the amount of clay grains

can be increased to the point where the mixture is controlled by clay grains. When  $e_s = e_{max}$ , that is when intergranular void ratio equals the maximum void ratio of the sand grains, the sand grains are in directly contact with each other (Monkul and Ozden 2007). The clay content in the case of  $e_s = e_{max}$  is referred to as “transition fines content.” The fact is that the value of  $e_s$  is always higher than the value of  $e$  employed in both tests performed in the present study due to the characteristics of undrained shear strength tests, although the interactions between  $e_s$  and  $e$  were found to be changed in certain testing equipment including oedometer, triaxial compression, cyclic triaxial, and resonant column (Troncoso and Verdugo 1985; Tan et al. 1994; Monkul and Ozden 2007; Cabalar 2010). Hence, the present study assumes that sand grains (rounded and angular) are floating in the clay matrix. Then, it was seen that the clay with angular sand grains resulted in lower  $s_u$  values in vane shear tests, since random packings of angular grains resulting void ratios are larger than those of rounded grains. Thus, it was concluded that the less angularity in sand grains, the more  $s_u$  values obtained in the sand–clay mixtures. This conclusion might also be attributed to the difference in the  $G_s$  values, although it is considered to be less effective on the results. As indicated in the preceding section, the  $G_s$  of the angular sand grains were found to be slightly higher (2.68) than that of the rounded sand grains (2.65). Therefore, it is postulated that the segregation of rounded sand grains is less likely than that of the angular sand grains in the mixtures. Liquid limit ( $w_L$ ) and corresponding  $s_u$  values in fall cone test are estimated based on the penetration of cone by 20 mm in a cup of that has a height of 40 mm. Considering segregation of sand grains in the mixtures to be tested in the fall cone cup, the  $s_u$  values of the clay with sand grains at various contents would necessarily be different based on the  $G_s$  values measured (Fig. 8). A similar series of results

**Fig. 8** Clay with (left) angular sand grains, and (right) rounded sand grains resulting from segregation

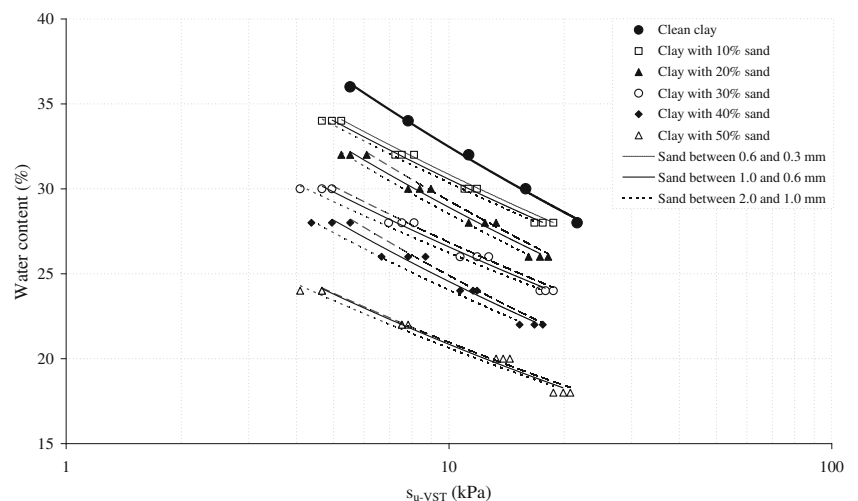


illustrated in Fig. 6 was observed in the tests conducted in vane shear testing apparatus, with certain differences in the range of  $s_u$  values estimated. For example, Fig. 7 presents the relationship between  $s_{u-VST}$  and water content for the clay with 0.6–0.3 mm in size of sand grains. As can be seen from Fig. 7, the clay with angular-shaped CSS grains has higher  $s_{u-VST}$  values than the round-shaped NS grains for all sand and water contents in the mixtures.

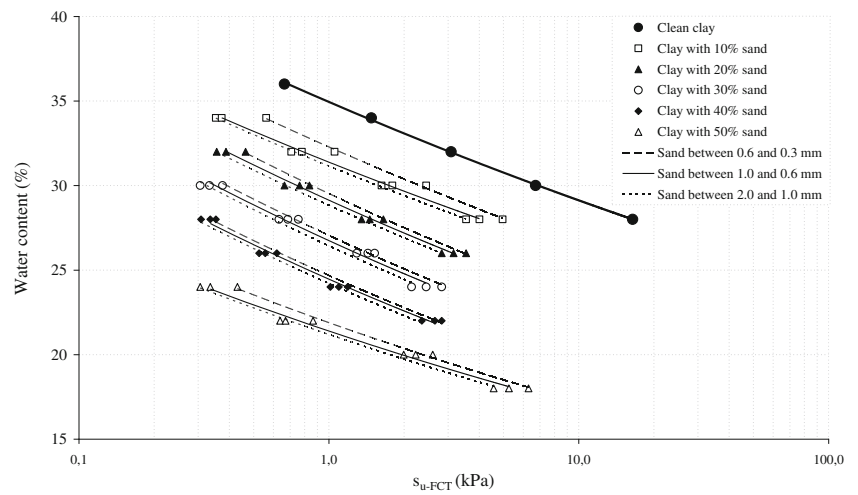
Figure 9 presents the changes in  $s_u$  estimated by vane shear testing equipment for clay with rounded sands (NS) at various gradations. It is seen that the clay with sand grains between 0.6 mm and 0.3 mm has the highest  $s_u$  values, and followed by the specimens with sand grains between 1.0 mm and 0.6 mm, and then the specimens with sand grains between 2.0 mm and 1.0 mm. Obviously, the sand grains with relatively smaller gradations have higher  $e_s$  values than those with larger gradations, and the voids are occupied by much more clay grains,

which leads to higher  $s_u$  values in such sand–clay mixtures. The packing of sand grains is likely the cause that this phenomenon occurs. The fact is that void ratio of a sand matrix composed of a random packing of grains is dependent upon the stability given to the matrix by frictional and cohesive forces between grains. There exists a relationship between these forces and the exposed surface area of individual grains, which is inversely proportional to grain size characteristics. This proves that a certain weight of coarse grains would be stabilized at a lower void ratio than the same weight of fine grains, when all the other parameters are the same with each other. McGeary (1961), who carried out a series of experiments to understand the influence of size grain packing, stated that the small particles can find a place inside the spaces of larger particles if their size ratio is a certain value, otherwise they will fall between the contacts. Several researchers have studied the effect of clays to the basic packing behavior of

**Fig. 9** Changes in  $s_u$  defined by vane shear tests for clay with rounded sands (NS) at various gradations



**Fig. 10** Changes in  $s_u$  defined by fall cone tests for clay with angular sands (CSS) at various gradations

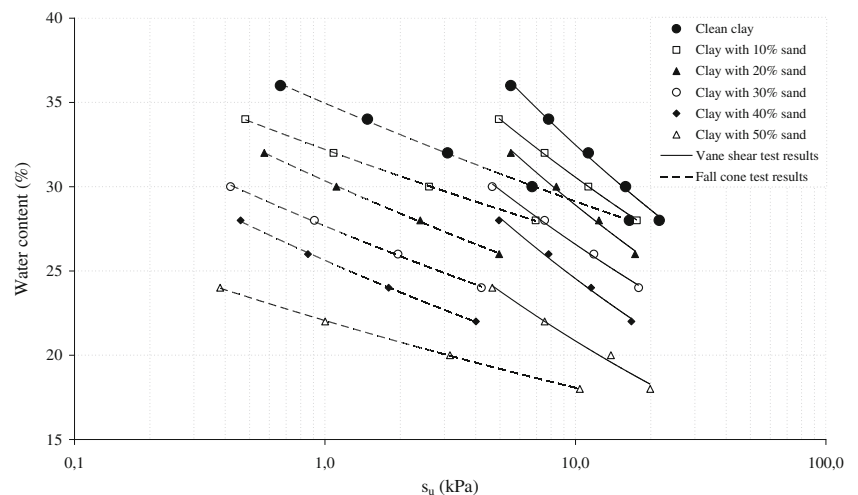


mixed soils using the binary packing concept (Thevanayagam et al. 2001; Ni et al. 2004; Rahman and Lo 2008; Cabalar and Mustafa 2015). However, soil shape and size experiments performed by McGeary (1961) were only with rounded balls having different sizes and shapes. The present study introduces sand, which has irregular shape characteristics compared with rounded balls, and is expected to contribute differently to the intergranular void ratio ( $e_s$ ) and the corresponding  $s_u$  characteristics of mixed soils. Thereof, the  $s_u$  estimates by fall cone testing equipment for clay with angular sands (CSS) at various gradations were presented in Fig. 10, in which a very similar behavior for the mixtures was observed.

The fall cone tests and vane shear tests were performed to compare and investigate the relationship of  $s_u$  values by using two testing equipment for various sand–clay mixtures. The estimated parameters given in Table 2 were employed to make a comparison of  $s_u$  determined with two tests. The  $s_u$  values estimated by the fall cone test is plotted against that estimated by the vane shear tests in Figs. 11 and 12 for different mixtures. It can be seen in Figs. 11 and 12 that the vane shear tests estimated higher  $s_u$  values in comparison with the fall cone

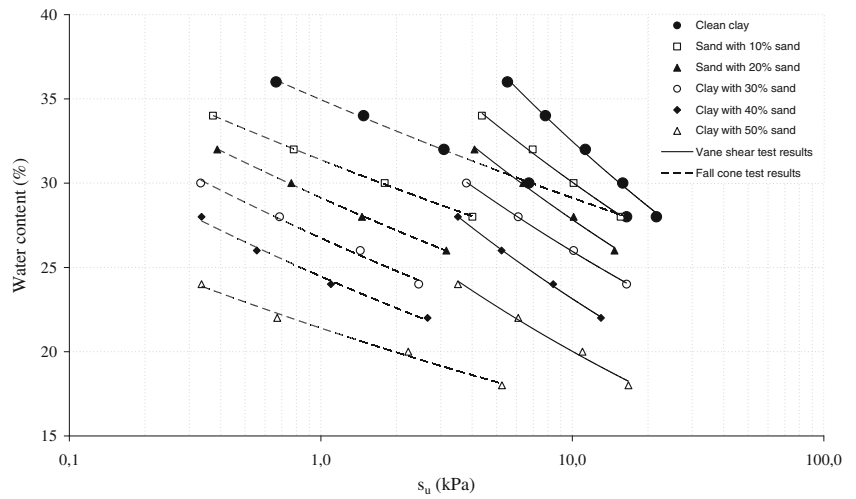
tests. In the vane shear tests, the clean clay had a value of  $s_u$  ranging between 5.52 and 21.6 kPa, while the values for the fall cone tests were only between 0.66 and 16.44 kPa for the water contents from 36 to 28%. The fall cone tests estimated the  $s_u$  values of rounded (NS) grains (between the sizes of 0.6 and 1.0 mm) to be between 0.42 and 10.42 kPa, while the vane shear tests gave the  $s_u$  values of the same specimens to be between 4.66 and 19.89 kPa for the water contents from 36 to 28% (Fig. 11). Likewise, the  $s_u$  parameters obtained from fall cone tests on angular (CSS) grains between 1.0 and 0.6 mm ranged from 0.34 to 5.25 kPa, while the same parameter obtained from vane shear tests ranged from 3.80 to 16.73 kPa for the water contents from 36 to 18% (Fig. 12). The results from both vane shear and fall cone tests were plotted together in order to observe the change of  $s_u$  with water content. For example, Fig. 13 presents a comparison of  $s_u$  values defined by fall cone and vane shear tests for clean clay and clay with 40% angular sand between 1.0 and 0.6 mm. A trendline is plotted for each of the tests in order to understand the correlation between the  $s_u$ , and the tests and equations were given for the correlation between the two tests. In

**Fig. 11** Comparison of the  $s_u$  defined by fall cone tests and vane shear tests for rounded sands (NS) between 1.0 and 0.6 mm





**Fig. 12** Comparison of the  $s_u$  defined by fall cone tests and vane shear tests for angular sands (CSS) between 1.0 and 0.6 mm



**Fig. 13** Comparison of  $s_u$  defined by fall cone tests and vane shear tests for clean clay and clay with 40% angular sand between 1.0 and 0.6 mm

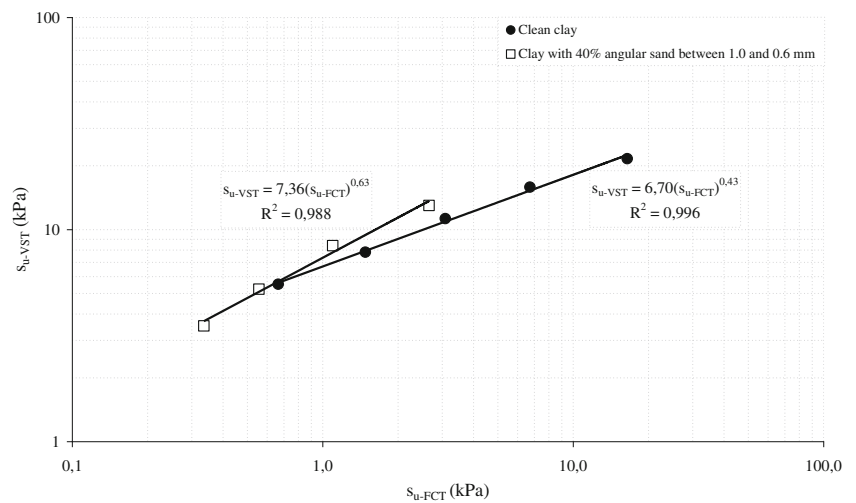


Table 3, correlations for all the experimental are presented. Actually, numerous researches on the shear strength estimates by means of fall cone testing equipment had previously correlated  $s_u$  values with cone penetration through cone weight and apex angle (Hansbo 1957; Kravitz 1970; Houlsby 1982;

Lee 1985; Wood 1985; Stone and Phan 1995; Stone and Kyambadde 2007). The fact is that apex angle parameter ( $k$ ) was initially developed for the Swedish fall cone by calibrating field vane shear testing equipment rather than laboratory vane shear testing equipment. Following an intensive series of

**Table 3** Correlations of the experimental results

Sand content (%)	Angular sand						Rounded sand					
	0.6–0.3 mm		1.0–0.6 mm		2.0–1.0 mm		0.6–0.3 mm		1.0–0.6 mm		2.0–1.0 mm	
	$s_{u-VST}$ (kPa)	$R^2$	$s_{u-VST}$ (kPa)	$R^2$	$s_{u-VST}$ (kPa)	$R^2$	$s_{u-VST}$ (kPa)	$R^2$	$s_{u-VST}$ (kPa)	$R^2$	$s_{u-VST}$ (kPa)	$R^2$
0	$6.70(s_{u-FCT})^{0.43}$	0.99	$6.70(s_{u-FCT})^{0.43}$	0.99	$6.70(s_{u-FCT})^{0.43}$	0.99	$6.70(s_{u-FCT})^{0.43}$	0.99	$6.70(s_{u-FCT})^{0.43}$	0.99	$6.70(s_{u-FCT})^{0.43}$	0.99
10	$6.78(s_{u-FCT})^{0.52}$	0.99	$7.55(s_{u-FCT})^{0.53}$	0.99	$7.31(s_{u-FCT})^{0.59}$	0.99	$7.09(s_{u-FCT})^{0.49}$	0.99	$7.11(s_{u-FCT})^{0.47}$	0.99	$7.17(s_{u-FCT})^{0.49}$	0.99
20	$7.25(s_{u-FCT})^{0.61}$	0.99	$7.53(s_{u-FCT})^{0.62}$	0.99	$7.65(s_{u-FCT})^{0.63}$	0.99	$7.97(s_{u-FCT})^{0.48}$	0.99	$7.65(s_{u-FCT})^{0.52}$	0.99	$7.70(s_{u-FCT})^{0.52}$	0.99
30	$7.97(s_{u-FCT})^{0.70}$	0.99	$8.19(s_{u-FCT})^{0.72}$	0.99	$8.37(s_{u-FCT})^{0.76}$	0.99	$7.98(s_{u-FCT})^{0.57}$	0.99	$7.85(s_{u-FCT})^{0.58}$	0.99	$7.66(s_{u-FCT})^{0.68}$	0.99
40	$7.60(s_{u-FCT})^{0.61}$	0.98	$7.36(s_{u-FCT})^{0.63}$	0.98	$7.47(s_{u-FCT})^{0.67}$	0.99	$8.09(s_{u-FCT})^{0.51}$	0.98	$8.04(s_{u-FCT})^{0.55}$	0.98	$7.99(s_{u-FCT})^{0.59}$	0.98
50	$6.48(s_{u-FCT})^{0.56}$	0.99	$6.92(s_{u-FCT})^{0.55}$	0.98	$6.93(s_{u-FCT})^{0.58}$	0.99	$7.12(s_{u-FCT})^{0.46}$	0.98	$7.47(s_{u-FCT})^{0.44}$	0.98	$7.71(s_{u-FCT})^{0.49}$	0.97

tests (more than 1000 measures) on soft marine clay soils by using both fall cone and laboratory vane shear testing equipment, Tiesong and William (1997) proposed a new  $k$  value in order to minimize the large differences observed between the laboratory vane shear testing results and the fall cone testing results. Accordingly, this parameter should be expected to be a reason of the discrepancies in testing results obtained by two different techniques here in the present study as well. Hence, it is concluded that alternative  $k$  values to be produced by a sufficient number of tests could minimize the differences between testing results obtained by these two approaches employed in order to estimate the  $s_u$  of various soils.

## Conclusions

Fall cone and vane shear tests have been performed on various sand–clay mixtures to investigate the relation between gradation/shape of sand grains in clay and undrained shear strength values of the mixtures. Three different gradations of both angular and rounded sands were mixed with CL-type clay samples at five different ratios. The experimental results have indicated that the undrained shear strengths were higher in samples with the mixture of clay and angular-shaped sand grains than the specimens with round-shaped sand grains. It is attributed to the open fabric structure in samples with the mixture of clay and angular sand grains, and higher  $G_s$  values of the angular-shaped grains, which results in a segregation in the mixture. It was also observed that the sand grains with smaller gradations have higher void ratio values than those with larger gradations, and the voids are occupied by much more clay grains, which leads to higher  $s_u$  values in such sand–clay mixtures. It is because of the packing of sand grains in the mixtures. The vane shear tests produce higher  $s_u$  values in samples in comparison with the fall cone tests. Evidently, in order to have a greater understanding of how the characteristics of sand grains influence sand–clay mixtures, further research in fall cone and vane shear testing is required.

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