Determination of the Effect of Soil Particle Size Distribution on the Shear Behavior of Sand

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Abstract. *Many geotechnical problems require the determination of soil engineering properties such as shear strength. Therefore, the determination of the reliable values for this parameter is essential. For this purpose, the direct shear test, as one of the oldest tests to examine the shear strength of soils, is the most common way in laboratories to determine the shear parameters of soil. There are far too many variables that influence the results of a direct shear test. In this paper, a series of 10×10 cm direct shear tests were carried out on four different poorly graded sands with different particle size distributions to determine their shear behaviors. Four different poorly graded sands with a different median diameter or medium value of particle size distribution (D_{50}) (0.2, 0.53, 1.3, and 2.3 mm) has been selected, and about 40 direct shear tests were conducted. It was concluded that a soil's friction angle is affected by coarse-grained material. Accordingly, sandy soils with bigger particle sizes record a higher friction angle than soils containing small particles. The investigations also showed that sand with bigger particle sizes has a higher dilation angle. In addition, a non-linear regression analysis was performed to establish the exact relationship between the friction angle of the soil and the characteristics of the soil particles.*

1. Introduction

Shear strength of soils is one of the most critical parameters in the geotechnical designs used in analyzing problems such as lateral soil pressure, bearing capacity of foundations, slope stability, earth dams, and other geotechnical problems [1, 2]. Standard tests for measuring soil shear strength include triaxial, direct shear, and simple shear tests. The non-uniformity of stress and strain in direct shear test, predefined failure plane, and having rigid boundary condition are three major disadvantages of direct shear tests. However, among those, the direct shear test is still the most common test due to its wide application in understanding the mechanical behavior of soils [3-5] since the direct shear test takes less time to fail and complete than the triaxial test and simple shear test [1, 6, 7]. Recently, considerable literature has grown around the shear strength characteristics of sands and sand-gravel mixtures [8-16]. The academic literature on their shear strength has revealed the emergence of several contrasting themes. The shear strength of sand is primarily controlled by its gradation curve, according to these studies.

A few of these researches have shown the reduction of shear strength with increasing the median diameter or medium value of particle size distribution (D_{50}) [8-10]. On the other hand, others have reported an increase in shear strength as the D_{50} of sands increases [11-14]. There are also a number of other observations on the shear strength characteristics of sandy gravels or gravely sands that indicate the significant impact of soil gradation on mechanical behavior [17-24].

A large number of cross-sectional studies have found a relation between D_{50} as well as sand shear strength. According to Fragaszy et al. (1990) [8], increasing D_{50} increases the void ratio of the soil matrix, decreasing the fiction angle and dilation angle of soils. Unlike Fragaszy et al. (1990), Yagiz (2001) [11] argues that the shape and content of gravel particles have a major impact on the friction angle of the mixture, and increasing D_{50} increases the shear strength of soils. Similarly, Simoni and Houlsby (2006) [25] have observed the same findings. Simoni and Houlsby (2006) conducted 87 large direct shear tests on sand-gravel mixtures of different D_{50}s and came to the conclusion that increasing D_{50} would increase the dilatancy rate and the critical state friction angle.

Salimi et al. (2008) [26] investigated the effect of particles' sizes and shapes of two different gravel on the shear strength of sand-gravel mixtures in low gravel contents of loose mixtures and reached the conclusion that the form and size of the particles have only a minor impact on the shear strength and friction angle of soils. When the D_{50} increases, though, it becomes more apparent. Hamidi et al. (2009) [14] used a large-scale direct shear apparatus with a 30 cm $\times$ 30 cm $\times$ 17 cm shear box to study the shear strength of sandy soils with different D_{50}s. To do so, they performed a series of direct shear tests on sand-gravel soils comprising 20, 40, and 60 percent gravel. All of the experiments were carried out on dry samples in drained conditions. Three different densities of 35, 60, and 85 percent were included in the experiments, as well as three different normal stresses of 150, 300, and 450 $\frac{kN}{m^2}$. They discovered that increasing the D_{50} and relative density causes the shear strength and dilation of the mixture to increase.

The D_{50}, on the other hand, has a more noticeable impact on shear strength than on relative density. In another investigation, Hamidi et al. (2012) [27] studied the shear strength and dilatancy of well-graded sand-gravel mixtures by conducting 27 large-scale direct shear tests and reported that the particle size distribution and D_{50} of the tested soils significantly affect their shear strength. In a comprehensive study of the impact of D_{50} on the shear behavior of soils, Rasti et al. (2021) [28] performed a series of direct shear tests on four different sands and found that the D_{50} of soils affects their critical friction angle.

The studies presented thus far provide evidence that particle size distribution of sands has an essential effect on their shear behaviors [29, 30]. Considering all of this evidence, however, the impact of D_{50} on the shear behavior of poorly graded sands received little attention. The purpose of this investigation is to explore the relationship between the shear behavior of poorly graded sand (Based on the ASTM D2487-17) and D_{50}. To do so, 40 direct shear tests were performed on the four different poorly graded sand with different D_{50}s. This paper has been divided into three parts. The first part deals with materials and testing programs, the second part discusses the impact of D_{50} on the shear strength behavior of sands, while the last part discusses the deformation behavior of soils.

2. Materials and testing program

2.1. Sand

Four different sands with different particle size distributions (Based on ASTM D6913-04) were collected from Tehran and were used in this study. The sand particles were sieved, and their particle size distribution is shown in Fig. 1. As can be seen from Fig. 1, the D_{50} of materials are estimated and ranged between 0.2 mm and 2.3 mm. The index properties of sands are presented in Tab. 1.

Tab. 1: Typical engineering properties of soil samples. $^{*}C_U = \frac{D_{60}}{D_{10}}$, $^{**}C_C = \frac{D_{30}^2}{D_{60}D_{10}}$.

Sample ID	Soil name	Soil symbol	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	$^{*}C_U$	$^{**}C_C$	Max. Particle size (mm)
Soil #1	Poorly graded sand	SP	0.14	0.19	0.25	0.28	2.00	0.92	> 5
Soil #2	Poorly graded sand	SP	0.26	0.38	0.53	0.60	2.30	0.92	> 2
Soil #3	Poorly graded sand	SP	0.91	1.08	1.30	1.41	1.55	0.90	> 2
Soil #4	Poorly graded sand	SP	1.01	1.57	2.30	2.67	2.64	0.91	> 0.9
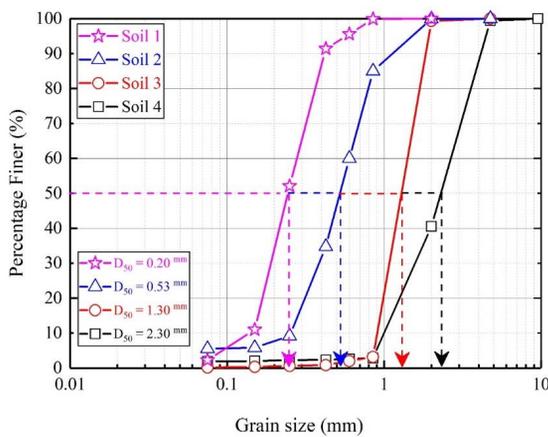
Fig. 1: Particle size distributions of used materials.

Fig. 2: (a) A sketch of the shear box used for the experimental tests; (b) Direct shear box container.

2.2. Sample preparation and testing program

Direct shear tests were conducted using the Azmoon Company apparatus. The size of the shear box is 100 mm by 100 mm, and its height is 35 mm as shown in Fig. 2. All of the samples were made in three successive layers in dry conditions. Each layer was compacted to achieve the required density of 1.6 gr/cm³. All of direct shear tests were conducted based on the American Society for Testing and Materials (ASTM) standard (ASTM D3080) at a constant and low displacement speed of 0.5 mm/min under three different normal stresses of 60, 120, and 180 kPa to estimate the shearing response of materials.

3. Results and discussion

3.1. Repeatability

Three tests were performed under the same conditions on each sample to assure repeatability of the results. Considering this fact, together with application of four different sand and three different normal stresses of 60 kPa, 120 kPa, and 180 kPa, more than 36 direct shear tests were conducted. Figure 3 shows the shear and deformation behavior of sand 3 under 120 kPa normal stress. As shown in the below figure, the results

can be reasonably well reproduced. Therefore, the averaged data are used to report the results in the following sections of the paper.
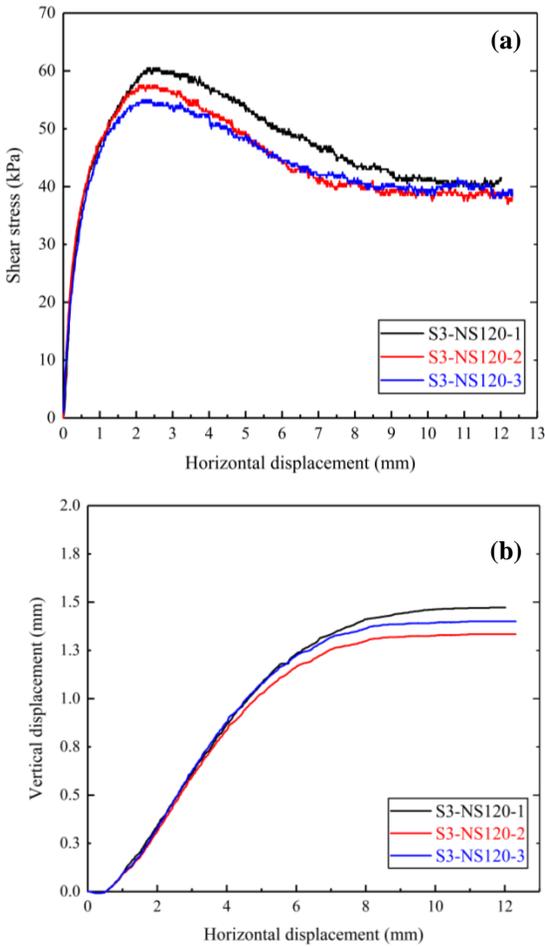
Fig. 3: (a) Shear stress-Shear displacement; (b) Vertical displacement-Shear displacement of sand 3 under 120 kPa normal stress. S and NS stand for the Sand and Normal Stress, respectively.

3.2. Shear strength

Shear strength behavior of sands with different D_{50} of 0.20, 0.53, 1.30, and 2.30 mm are presented in the following figures. Figure 4 illustrates the shear strength behavior of sands under three different normal stresses. The results show the well-predicted behavior of samples which consist of strain hardening of sand samples followed by strain-softening toward the critical state under the applied normal stresses.
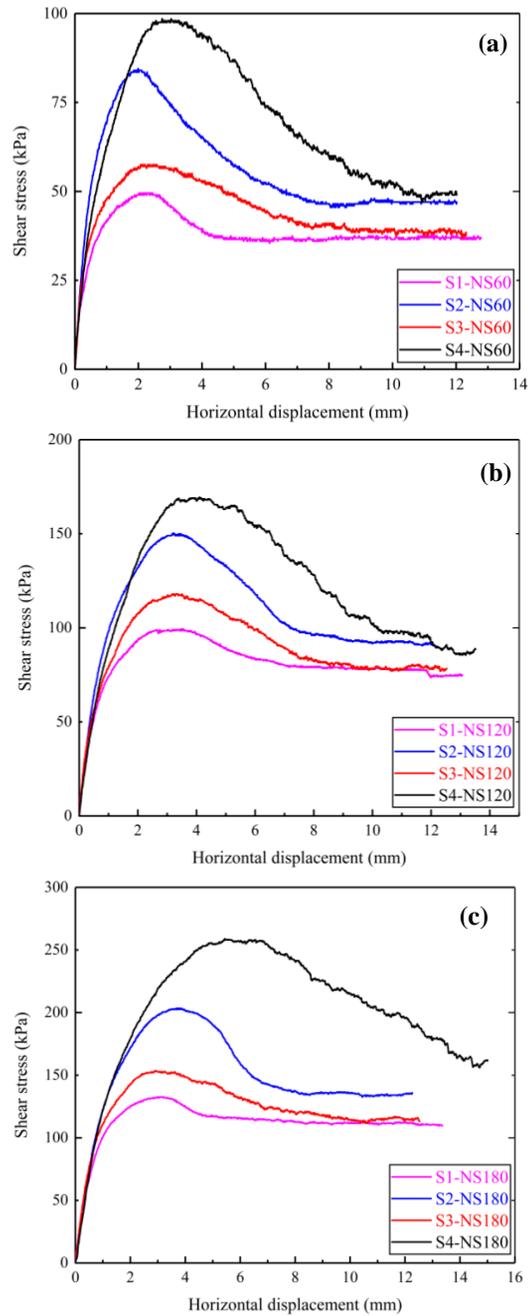
Fig. 4: Shear stress-Shear displacement of sands under normal stresses of (a) 60 kPa; (b) 120 kPa; (c) 180 kPa. S and NS stand for the Sand and Normal Stress, respectively.

From Fig. 4(a, b, c) we can also see that the initial stiffness of sands is consistent with increasing D_{50}, while peak shear stresses and that the

shear displacement corresponding to the shear strength of samples increase. Notice that the effect of D_{50}s on stress-displacement behavior of the samples is more significant under normal stresses of 120 kPa and 180 kPa compared to those under 60 kPa normal stress. This finding was also reported by Yagiz (2001) [11]. The impact of normal stress on the peak shear strengths and friction angles of the samples is shown in Fig. 5(a, b).
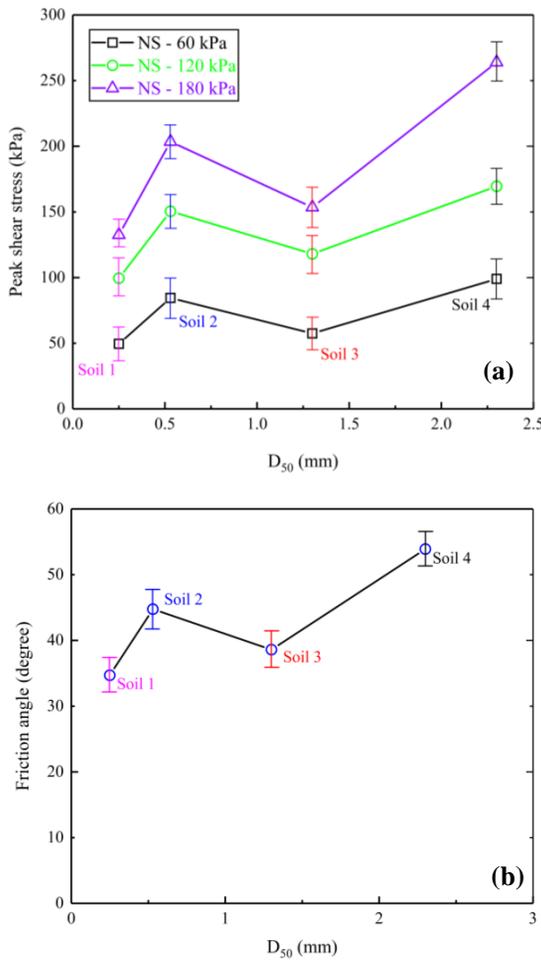
Fig. 5: Effect of D_{50} on: (a) Peak shear stress; (b) Friction angle of sands. NS stands for Normal Stress.

Fig. 6: Vertical displacement-Shear displacement of sands under normal stresses of: (a) 60 kPa; (b) 120 kPa; (c) 180 kPa. S and NS stand for the Sand and Normal Stress, respectively.

Figure 5(a, b) presents the peak shear strength and friction angle of all samples. It confirms clearly that shear strengths of samples with bigger D_{50} are higher than mixtures with smaller ones; therefore, particle size distributions of sands play a significant role in the shear strength of samples [31]. It is encouraging to compare this figure with that found by
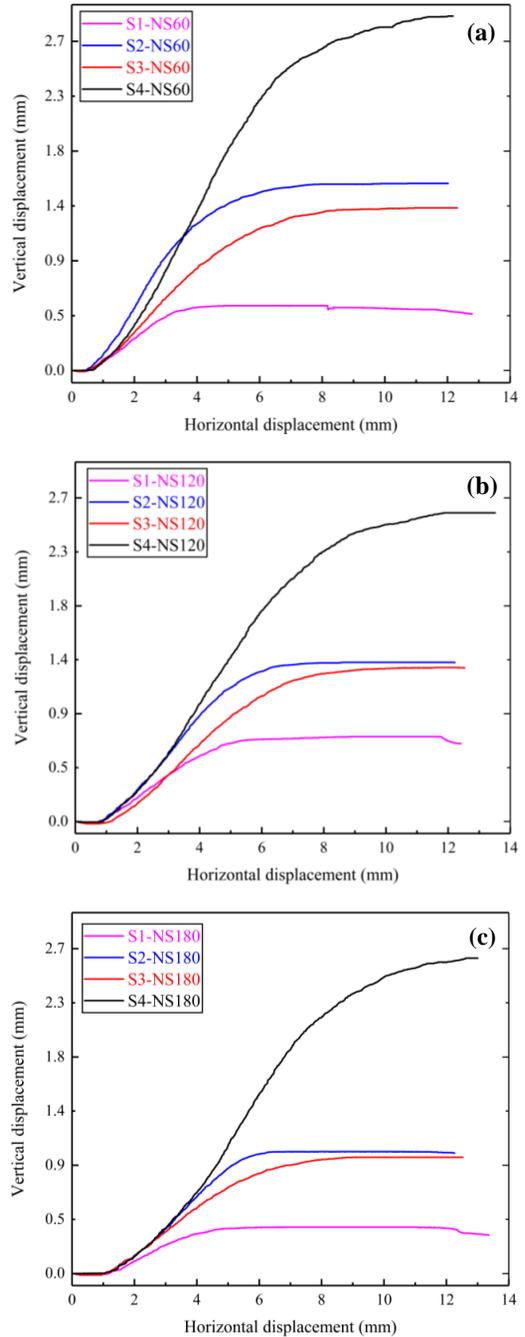
Rasti et al. (2021) [28], who also found that with increasing D_{50}, the peak shear strength of samples increases. One unanticipated finding in Fig. 5(b) is that sand 4 has friction angle of about 50°, however this magnitude is also reported in Bareither et al. (2008) [32], Sladen et al. (1986) [31]. The results in this section indicate that particle size distribution and D_{50} have an important impact on the shear strength of sands. The next section, therefore, moves on to discuss the dilatancy behavior of sands with different particle size distributions.

3.3. Dilation behavior

The vertical displacement of samples with different D_{50}s are shown in Fig. 6(a, b, c). Results show the compressive behavior of sands followed by dilative behavior at higher shear displacement. The deformation behavior of sands also shows that the tendency of the samples to dilate increases by increasing the D_{50}s of the samples. These results provide further support for the hypothesis that the overall dilation and deformation behavior of the sands are controlled by their particle size distributions and D_{50}s.

The schematic behavior of sand particles is illustrated in Fig. 7. In fact, when sands have bigger particles and they roll on each other in a direct shear test, they will have bigger vertical displacement and dilation. These results are in agreement with Hamidi et al. (2009) [14] findings that showed increasing D_{50} will increase the dilative behavior of sands.
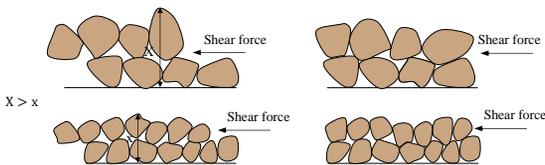
Fig. 7: Schematic view of displacement response, due to the shear loading.

To measure the dilation angle at the peak shear stress, at first, the maximum shear stress was found as in Fig. 8(a), then the displacement corresponding to that point was determined in its vertical displacement diagram (Fig. 8(b)). In the next step, the slope of this point was calcu-

lated from Fig. 8(b) and is considered as the dilation angle. The results of the dilation angle are shown in Fig. 9.
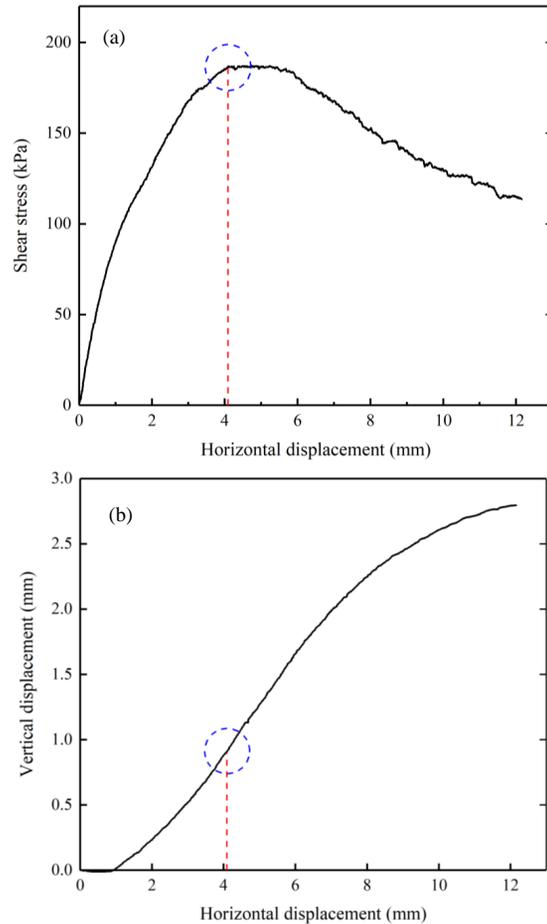
Fig. 8: (a) Shear stress-Shear displacement; (b) Vertical displacement-Horizontal displacement behavior of sand.

The variation of the dilation angle at the peak shear stress in terms of D_{50}s under different normal stresses is shown in Fig. 9. In general, the angle of dilatancy increases by increasing the D_{50}s of sands. This is consistent with Fig. 5(b); a material with a higher friction angle shows higher dilatancy under shear [33]. Note that based on Fig. 9, at higher normal stresses, less material dilation is observed, which should be expected.

In Fig. 10, the friction angle of sands versus the dilation angle (for three normal stresses of 60, 120, and 180 kPa) is shown. Notice the
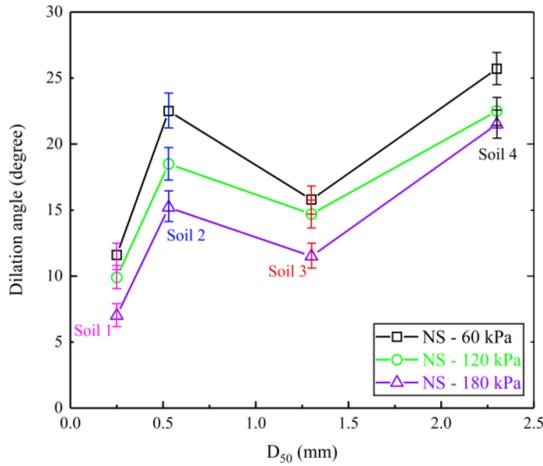
Fig. 9: Effect of D_{50} on dilatancy of sands at different normal stresses.

friction angle increases as the dilation angle and D_{50} increase, which is consistent with the observations of soil behavior reported in the literature [31-35].
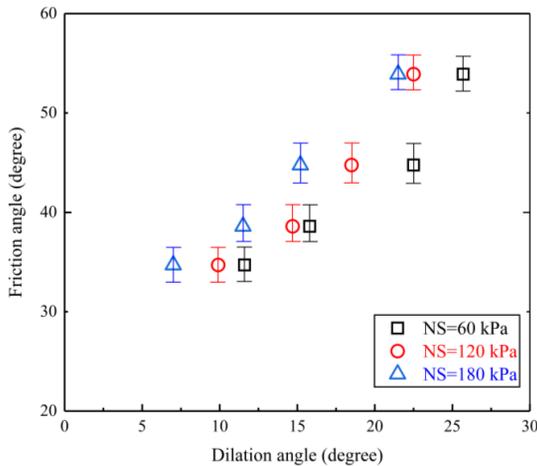
Fig. 10: Friction angle versus dilation angle of sands.

The effect of various soil particle variables on their friction angles was evaluated using non-linear regression analysis. Table 2 presents the relationship between the sands' friction angle and their particle characteristics. Between the soil uniformity coefficient, D_{50}, and their friction angle, it found a power function with a decent coefficient of determination. As presented in the table, the relationship between friction angle and CU has the highest coefficient of de-

termination. As a result, D_{50} and CU of soil can be used to estimate the soil's friction angle.
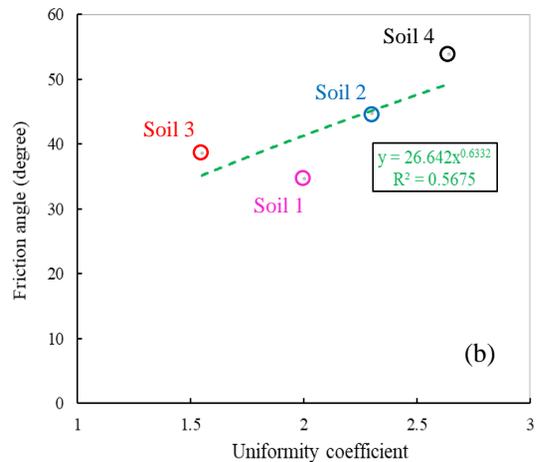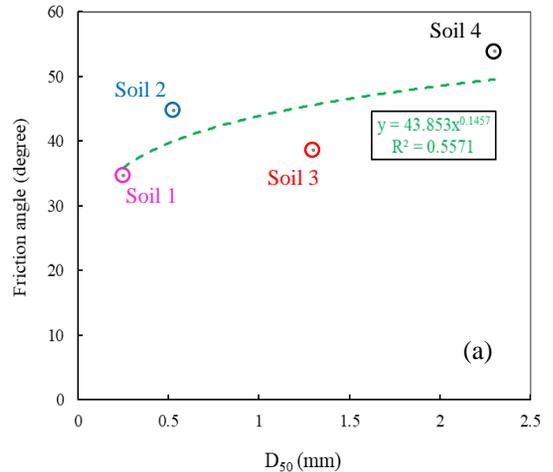
Fig. 11: (a) Friction angle – D_{50} for sands; (b) Friction angle – Uniformity coefficient (CU) for sands.

From Fig. 11, we can see that friction angle increases with increasing the D_{50} and uniformity coefficient. These results seem to be consistent with other research (e.g. Rasti et al. (2021)) which found that soils with bigger D_{50} and uniformity coefficients have higher friction angles. However, soil 3 gives a lower friction angle than soil 2; a possible explanation for this might be that the average data used in this study. Another possible explanation for this is the shape of grains which can influence the friction angle, and didn't consider in this study.

Tab. 2: Proposed relation between the friction angle and soil particle characteristics.

Dependent variable	Independent variable	Proposed equation	R^2
Friction angle	Median diameter or medium value of particle size distribution (D_{50})	$43.85*(D_{50})^{0.145}$	0.56
	Uniformity coefficient (CU)	$26.64*(CU)^{0.633}$	0.57

4. Conclusion

The present study was designed to determine the effect of D_{50}s and particle size distributions on the deformation and shear strength characteristics of four sandy soils. This research has found that generally friction angle of soil is affected by the presence of coarse-grained materials and their particle size distributions. The results of this investigation show that friction and dilation angles of soils will increase with increasing D_{50}s. It also was concluded that there is a relationship between friction angle and a soil's uniformity coefficient. One of the more significant findings to emerge from this study is that the friction angle increases by increasing the uniformity coefficient. Since the study was limited to poorly graded sands, it is impossible to extend all of the results to all soils. Further research needs to examine more closely the links between particle size distribution of soils and their shear behaviors, especially on the clayey soils.

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