

Stress fluctuations in granular material response during cyclic direct shear test

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Abstract This paper presents the results of an intensive series of experiments on various types of sands using cyclic direct shear testing apparatus. Two different grain shapes (rounded and angular) of sands having distinct sizes (0.25–0.5 and 1.0–2.0 mm) were tested in an automated constant normal load cyclic direct shear testing apparatus at an 100 kPa vertical effective stress, and two rates of shearing (2.0 and 0.025 mm/min). Experiments on the specimens resulted in sharp decreases followed by gradual increases in shear stress values. The results suggest that these successive drops and formations give a stick–slip nature to the fluctuations, which might be attributed mainly to the rate of loading, shape of grains, size of grains, and fines contents.

Keywords Granular materials · Cyclic direct shear · Fluctuation

1 Introduction

Granular materials, which are composed of many solid particles that interact through contact forces, are often encountered in geotechnical engineering practice. The shearing mechanism in these materials is a complex issue, which has been the subject of extensive experimental and numerical studies [2, 38, 41, 44, 48]. The stick–slip nature in shear stress fluctuation is one of the phenomena observed during the laboratory tests and the numerical simulations [3, 4, 7, 9–12, 14, 25, 27, 38, 47, 50]. The stick–slip phenomenon occurs in granular materials, when particles slide and slip with

respect to each other. The stick–slip motion in granular media is one of the problems in physics with a huge practical significance. In recent years, there has been a heightened interest in the stick–slip response of assemblies of particles [5, 6, 18, 19, 26]. A commonly accepted view is that shear induced ‘fluidization’ and pressure induced ‘solidification’ accompany the stick–slip mechanism in a discrete particles system. During sticking, the bulk of material behaves like a solid, and the particles at the interface are closely packed and have high shear strength. Later however, the material dilates and behaves like a fluid, allowing the slider to slip [18]. The main reason of this phenomenon might lie in the fact that the internal forces do not uniformly propagate through the specimen but are localized through force chains of strained grains. An applied external load results in the development of an internal structure resisting the stress. Above a certain threshold of stress, this system may jam depending on the magnitude and direction of the load [19]. Such as, a solid object being pulled slowly through a granular medium is resisted by local jamming, but if the applied force exceeds a certain threshold corresponding to the strength of jammed state, the solid object moves [13]. These successive breakdowns result in fluctuations [18].

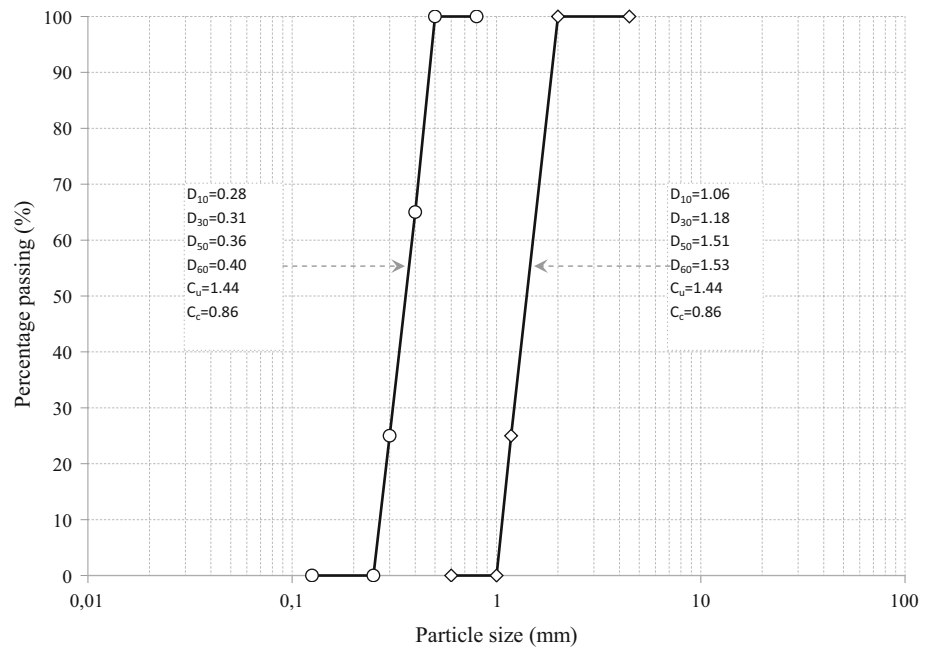
The behavior of soils in laboratory and field cannot be completely understood unless the effect of grain characteristics (i.e., shape, size) is taken into account. The fact is that it has been long understood that grain shape characteristics have a significant effect on the engineering properties of soil matrix [1, 22, 29, 36, 37, 43, 45, 46, 49]. Terzaghi [49] is one of the first engineers to make an investigation to understand the shape characteristics using flat-grained constituents. Terzaghi [49] postulated that the compressibility of cohesionless material is governed by the grain size, uniformity, volume of voids and mica content. The observations made by Gilboy [29] that any system of analysis or classification of soil

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which neglects the presence and effect of the shape will be incomplete and erroneous. Numerous researches have been carried out because of the importance of grain shape and its role in the behavior of sands for practicing engineers and researchers in helping to estimate soil behaviour. Holubec and D'Appolinia [33] showed that the results of dynamic penetration tests in sands depend on grain shape. Cornfort [23], and Holtz and Kovacs [32] demonstrated how grain shape impacts the internal friction angle (φ). Cedergren [20] pointed out that grain shape affects the permeability. Grains shape also has a significant role in liquefaction potential [35]. Wadell [52], Krumbain [36], Powers [45], Holubec and D'Appolinia [33], Mandelbroth [40], and Cho et al. [21], Hyslip and Vallejo [34], and Arasan et al. [8] have introduced detailed explanations of grain shape. In general, two independent properties are typically employed to describe the shape of a soil grain, which are roundness (a measure of the extent to which the edges and corners of a particle has been rounded), and sphericity (form) described the overall shape of a particle (a measure of the extent to which a particle approaches a sphere in shape). Wadell [52] proposed a simplified sphericity (S) parameter, ($D_{\max-\text{insc}}/D_{\min-\text{circ}}$), where $D_{\max-\text{min}}$ is the diameter of a maximum inscribed circle and $D_{\min-\text{circ}}$ is the diameter of a minimum sphere circumscribing a gravel particle. Wadell [52] defined roundness (R) as $D_{i-\text{ave}}/D_{\max-\text{insc}}$, where $D_{i-\text{ave}}$ is the average diameter of the inscribed circle for each corner of the grain. Besides, in recent years, fractal geometry techniques have few applications on engineering properties of soils [30, 51, 53]. The concept of fractals developed by Mandelbroth [40] is a relatively new mathematical approach for describing the geometry of irregular shape objects in terms of frictional numbers [8].

Fig. 1 Particle size distributions for the sands used during the experimental study



The present study aims to investigate the stick–slip behavior in cyclic direct shear testing apparatus, with emphasis on the role of grain characteristics (i.e., shape, size), rate of shearing, and the fines content. The paper presents new experimental findings of a comprehensive experimental programme by observing the response of two different particle sizes (0.25–0.5 and 1.0–2.0 mm) of sands having distinct shapes (rounded and angular) in an automated constant normal load (CNL) cyclic direct shear test apparatus at a 100 kPa vertical stress level, and two rates of shearing (2.0 and 0.025 mm/min).

2 Experimental study

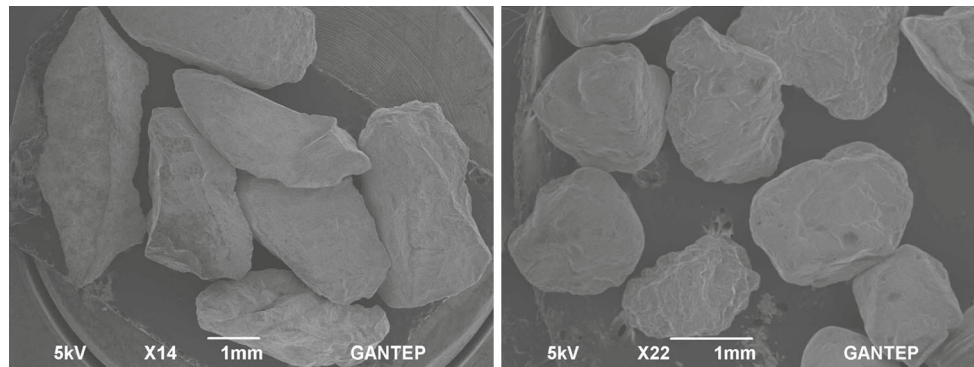
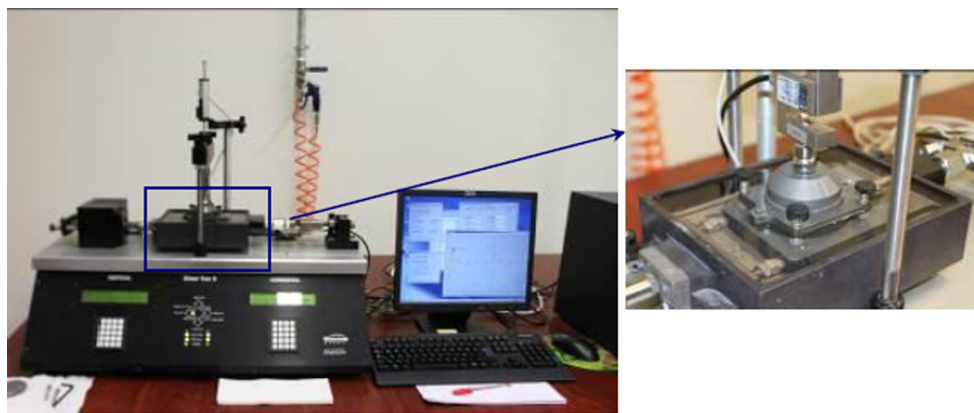
2.1 Materials

The materials used in the experimental studies described in this paper are ‘Trakya’ sand, and ‘Crushed Stone’ sand. Trakya Sand (TS), obtained from the Thrace Region in North-west of Turkey, was supplied by Set/Italcementi Group, Turkey, confirming to TS EN 196-1. A commercially available Crushed Stone Sand (CSS) was supplied from the southern-central Turkey, which is widely consumed in earthworks, in Gaziantep City and its vicinity. The specific gravity values of the grains were found to be 2.65 for Trakya Sand, and 2.68 for Crushed Stone Sand. Two different gradations of the sands falling between 0.25 and 0.5, and 1.0 and 2.0 mm were selected to provide uniform specimens for visual classification purposes. The D_{10} , D_{30} , D_{50} , and D_{60} sizes are around 0.28, 0.31, 0.36, and 0.45 for finer sands, 1.06, 1.18, 1.51, and 1.53 for coarser sands (Fig. 1). Thus, the coeffi-

Table 1 Some properties of the sands used during the experimental study

Sand	Size (mm)	e_{\max}	e_{\min}	G_s	C_u	C_c	$\phi(^{\circ})$	R	S
TS	0.25–0.5	0.97	0.69	2.65	1.44	0.86	36°	0.43	0.67
	2.0–1.0	0.99	0.59	2.65	1.44	0.86	40°	0.43	0.67
CSS	0.25–0.5	1.0	0.661	2.68	1.44	0.86	36°	0.16	0.55
	2.0–1.0	1.1	0.57	2.68	1.44	0.86	48°	0.16	0.55

TS Trakya sand, CSS crushed stone sand, R roundness, S sphericity

**Fig. 2** SEM pictures of the CSS (left), and TS (right) used during the experimental study**Fig. 3** Testing set-up employed during the experimental study

cient of uniformity (c_u) and the coefficient of curvature (c_c) have been calculated as 1.44 and 0.86, respectively. Some properties of the sands including roundness (R) and sphericity (S) estimations based on the study by Muszynski et al. a42 are listed in Table 1. Figure 2 shows the Scanning electron micrograph (SEM) pictures of the sands used during the experimental investigations presented in this study.

2.2 Test set-up

Cyclic direct shear tests were carried out in a fully automated direct shear apparatus, which is a product of Geocomp, and confirming to ASTM D3080. Direct shear testing apparatus is capable of performing the consolidation and shearing steps of a standard direct shear and residual shear test with fully automated (Fig. 3).

2.3 Specimen preparation and test procedure

The specimens in ‘cyclic direct shear test’ apparatus equipped with an external linear displacement sensor were approximately 63.5 mm in diameter by 25.4 mm height. To study the mechanical properties of specimens tested, it is crucial to maintain consistency between the specimens prepared for testing. Therefore, great care was taken to have reasonable repeatability during the preparing of the specimens to be tested. For the initial sand/water specimen, the required amount of sand was weighed, mixed with de-aired water and then spooned, without vibration, into the mould with thin layers. When the mould was completely filled, the top platen was placed on, and then the desired amount of water was added to the cell to make the specimen fully saturated. After a period of 24 h at room temperature (about 22 °C), the spec-

imens were loaded to a vertical stress of 100 kPa, and then shearing was commenced. The behavior of the sand mixtures was investigated through constant normal load (CNL) tests. The cyclic tests were strain controlled tests with the displacement of ± 3 mm, and with the loading rates of 2 and 0.025 mm/min.

3 Results and discussion

The behaviors of various sands were investigated by employing three different parameters, which are grain size, grain shape, and the rate of shearing. The study describes the stress–strain behavior of two different grain sizes (between the sizes of 0.25 and 0.5 mm, and between the sizes of 1.0 and 2.0 mm) of sands with distinct shapes (rounded and angular) in an automated constant normal load (CNL) cyclic direct shear testing apparatus. The tests were carried out at a 100 kPa vertical stress, and at two rates of shearing (2.0 and 0.025 mm/min). The results are presented by displaying the shear stress (kPa) versus shear displacement (mm). Figure 4 shows the shear stress versus shear displacement for the 1–2 mm Trakya Sand tested under two different rates of shearing (0.025, 2.0 mm/min). A stress fluctuation was observed in the shear stress responses for the specimen tested at 0.025 mm/min rate of shearing. Whereas, any fluctuation in the specimen tested under 2.0 mm/min rate of shearing was not observed. In order to obtain a better understanding of a soil behavior investigated in a shear testing, it is important to estimate the internal friction angle (φ), and cohesion (c) between the soil grains [32]. However, it would not be possible to make an accurate estimate for φ , and c values because of the successive drops and formations observed in the specimen tested at 0.025 mm/min rate of shearing. Experiments on the 1–2 mm TS specimens indicate that the shear stress in earlier cycles were at less values. The stress values exhibit a

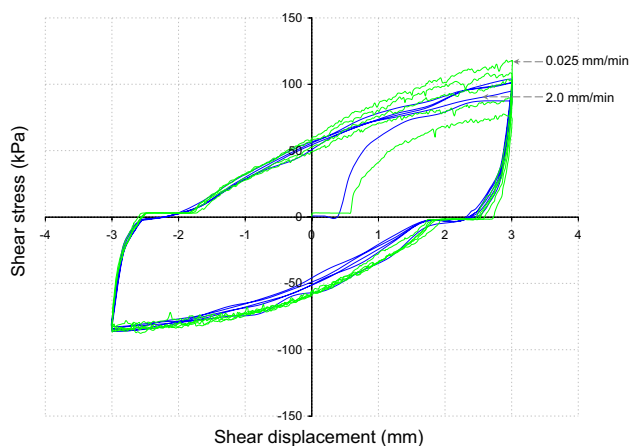


Fig. 4 1–2 mm TS specimens tested at different rates of shearing

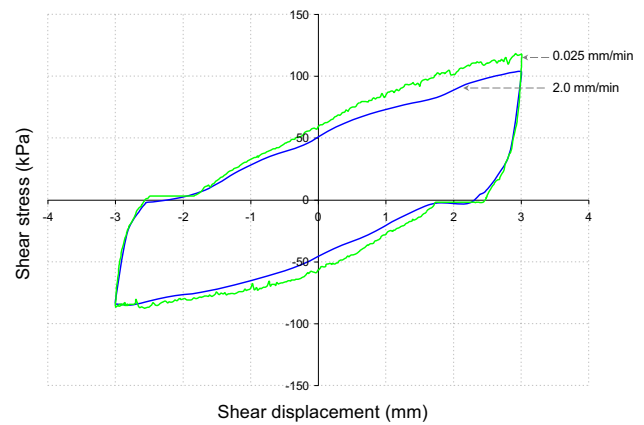


Fig. 5 5th loop for the TS specimens tested at different rates of shearing

continuous increase with the progress of cycles, then reach to a maximum value at the 5th cycle (the last one). It was also seen that the shear stress values for the TS specimens tested at 0.025 mm/min rate of shearing are scattered in a relatively wider band because of a more substantial reorientation in the contacts with cycling. Figure 5 presents the specimen's response during the last loop. It is postulated that the mechanism observed in the specimens tested at a lower rate of shearing was because of two main reasons; (1) the specimen's own material properties (2) any compliance in the apparatus. In the light of the study by Gajo [28], it was seen that the influence of system compliance on collapse of sand samples needs to be taken into account. However, it is beyond the scope of this study to provide a detailed discussion on the apparatus compliance, since the apparatus used during the testing of all specimens was the same apparatus. Here in this paper therefore, it will be more specifically focus on the material properties of the specimens tested.

Considering the material properties of the specimens tested, it is thought that such mechanism observed in a specimen could be because of (1) higher number of contact points, (2) a number of open fabric structure in the specimens, and (3) stick–slip behaviour between soil grains. The higher number of contact points is due to the higher relative density values in the specimens. The sand grains in the specimens are held in by interlocking in a denser packing leading to a higher internal friction. Therefore, The rotational and axial movement of each grain in the specimens tested at a higher shearing rate develops gradually and in a shorter time. However, movement of the grains in the specimens tested at a lower shearing rate develops discontinuously, and it takes more time to overcome interlocking among the grains. Similar to the observations by Luding [39], the grains in the shear band of the specimens tested at a lower rate do not move as easy as those of the specimens tested at a higher shearing rate.

Figure 6 shows the changes in relative density during the shearing process. Initial relative density values of the speci-

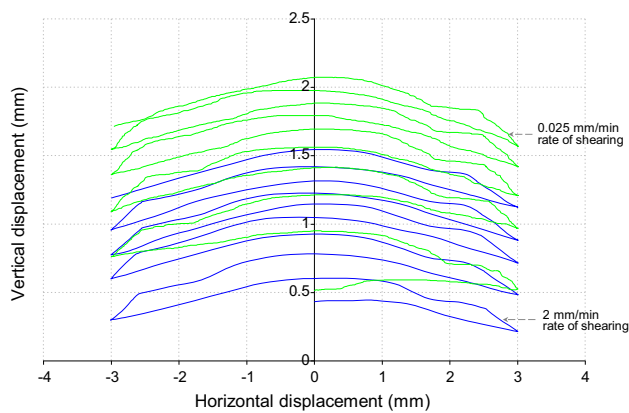


Fig. 6 Horizontal versus vertical displacement of TS (2–1 mm) tested at different shearing rates

mens tested in this investigation fell around 35%. From the Figure 6, it was observed that fluctuation mechanism appears to be independent from the density of the specimens.

One of the reasons that leads to the fluctuations observed in the specimens tested at a lower shearing rate is the fabric structure. Although a series of open fabric structure (i.e., honeycomb) seems to be able to give a fluctuation mechanism in a shear stress vs. shear displacement plots, it is expected that the fluctuations would be in a descending trend in shear stress amplitude and a decrease in frequency. However, this is not the case observed here, as the amplitude of shear stress values increased.

The fluctuation mechanism observed in the specimen tested at a lower shearing rate of is attributed to the stick–slip. This is a complicated phenomenon that can be identified mainly by the stress drop amplitude ($\Delta \tau$) and the displacement ($\Delta \epsilon$) (or time, Δt) between two successive stress drops. The shear stress fluctuations is attributed to the stick–slip mechanism between the sand grains as they form force chains to support the applied load. A jamming occurs because the sand particles form the chains (primarily) along the compressional direction. During the sticking, the sand grains are more closely packed and exhibit a gradual increase in shear stress. However, when the force chain becomes relatively unstable, some grains slide out of the column resulting in the shear stress to sharply drop. The shear stress subsequently builds up again to form a new chain of columns so as to support an applied stress. Stick–slip behavior in granular materials has been already investigated by numerous researchers in different disciplines [5, 18, 24, 26, 31]. These investigations, however, were limited to spherical grains. Whereas the research presented here has investigated the response of non-spherical grains with different sizes. The reason of the jamming noted in the specimens tested at a lower rate of shearing (0.025 mm/min) might lie in the fact that the forces do not propagate uniformly through the specimen

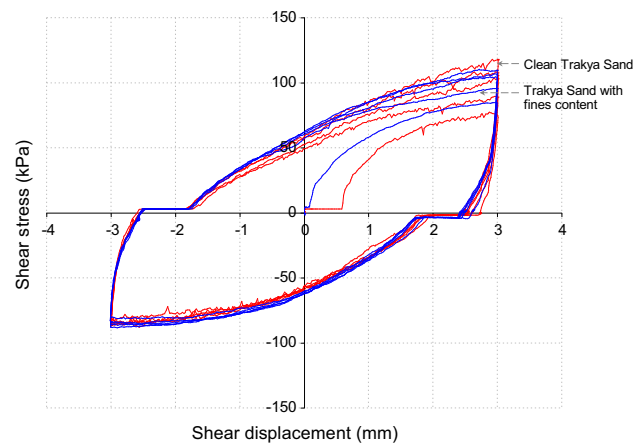


Fig. 7 Response of clean TS, and TS with 0.25 and 0.5 mm 50% CSS, tested at 0.025 mm/min rate of shearing

but are localized along the force chains. The jammed state is dependent on the properties of the network of these force chains. A similar behavior was also noticed by Cates et al. [19], Alshibli and Roussel [7], and Cabalar and Clayton [14]. The author considers that the potential energy of the grains tested at lower shearing rate (0.025 mm/min) indicates a relatively higher inhomogeneity of the forces and stresses. The stress value during the shearing process can change significantly from one grain in a chain to the next one outside of the chain in a specimen. An increase in shear stress for the specimens tested at lower shearing rate (0.025 mm/min) causes a relatively unstable stress distribution in the matrix. However, stress distribution in the specimen tested at a higher rate of shearing (2.0 mm/min) occurs substantially. Furthermore, during the shearing process, force chains distribution in the specimens tested at lower shearing rate (0.025 mm/min) are formed slower than those in the specimens tested at 2 mm/min shearing rate.

The interaction between the coarse and fine grain matrices affects the stress fluctuations in mixture of these soils response during cyclic direct shear test. Researches related to the influence of fines on overall stress–strain behavior, liquefaction potential, and compressional characteristics of composite soil matrices have been recently accelerated [17]. Figure 7 presents the response of 1–2 mm clean TS, and the response of 1–2 mm TS with 50% 0.25–0.5 mm Crushed Stone Sand (CSS) at 0.025 mm/min rate of shearing. As can be seen from the Fig. 7, shear stress values for the clean TS specimen are scattered in a relatively wider band. The most striking point in these plots is that the clean TS exhibits a stick–slip behavior, whereas the TS with fines shows relatively smooth changes in shear stress values within the measured strain level. It was also observed that the clean 1–2 mm TS specimen has a higher shear strength values than the TS specimen with fines. The shape of TS grains has different

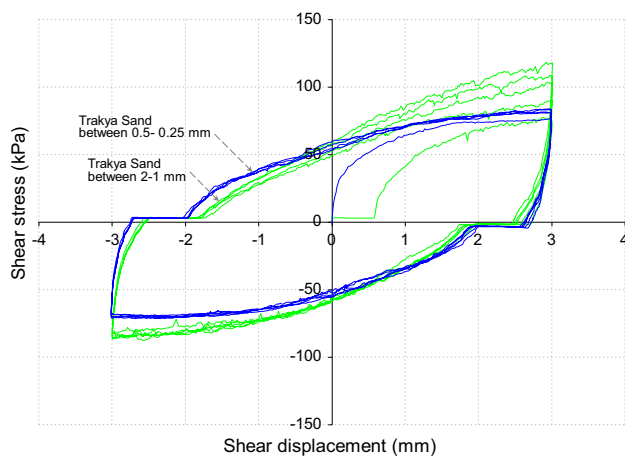


Fig. 8 TS with various size distributions tested at the 0.025 mm/min rate of shearing

characteristics than that of the CSS grains (Fig. 2). The shape of soil grains is already known to influence some engineering properties, such as shear strength parameters, permeability, compressibility, etc [15–17, 20, 28, 33, 49]. Figure 8 indicates that response of the 0.25–0.5 mm TS specimen is significantly different than the response of 1–2 mm TS specimen. It was observed that different size of the sands gives different responses in stress–displacement curves, although grain shapes of the TS tested were same. As can be seen from the Fig. 8, maximum shear stress values in 0.25–0.5 mm TS specimen (80 kPa) is much lower than those in 1–2 mm TS specimen (120 kPa). The shear stress values for the 1–2 mm TS specimen are scattered in a much wider band. It is also observed that the 0.25–0.5 mm TS specimen does not exhibit any fluctuation in shear stress values, whereas the 1–2 mm TS specimens exhibit a strong stick–slip behaviour. Similarly, observations made on the response of 1–2 mm TS specimen and the 2–0.5 mm TS specimen reveal that the finer grain specimens exhibit less fluctuations (Fig. 9). Accordingly, the author concludes that the finer grain specimens and the composite soil matrices with a certain amount of fines suppress the fluctuations in shear stress changes. Furthermore, the study also investigates the cyclic direct shear behavior of CSS with 30% TS between 0.25 and 0.5 mm (Fig. 10). Although a very similar behaviour pattern was observed for the tests conducted using two different type of specimens (1–2 mm CSS, 1–2 mm CSS with 30% 0.25–0.5 mm TS), an overall decrease in stress values was realized in the response of 1–2 mm CSS specimen with 30% 0.25–0.5 mm TS. The author considers that fine grains occupy the voids between coarse sand. Based on the amount of finer materials present in the mixture, the coarser grains are in contact with each other and the behavior of the composite specimens is controlled by either coarser or finer particles. When the contacts between coarser grains reduce, the behavior of the samples becomes softer, regardless of the shape of coarser/finer grains.

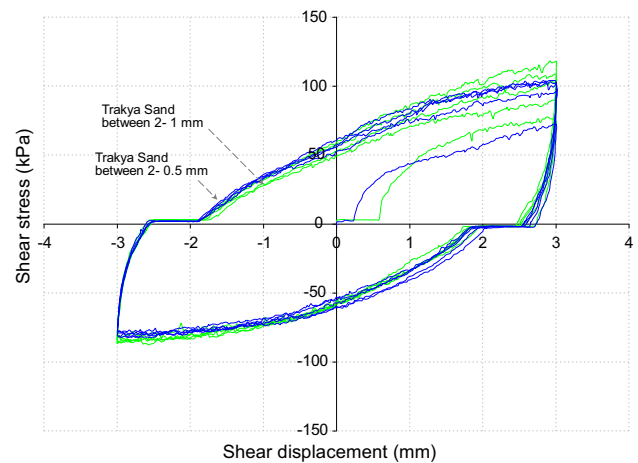


Fig. 9 TS with various size distributions tested at the 0.025 mm/min rate of shearing

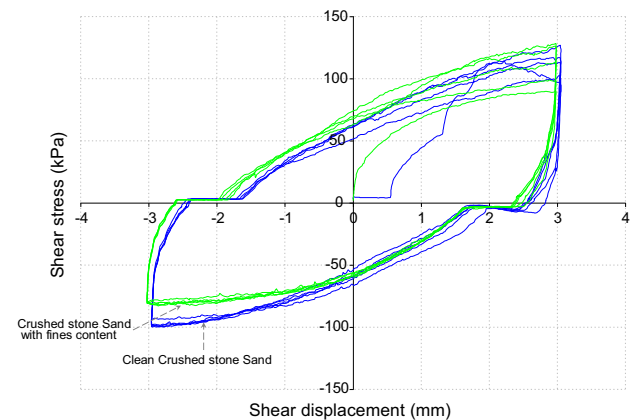


Fig. 10 Response of clean CSS, and CSS with 30% 0.5–0.25 mm TS

The fact is that it has been long understood that particle shape characteristics have a significant effect on the engineering properties of soil matrix [1, 16, 17, 22, 29, 37, 43, 49]. Today, the significance of particle shape has been well documented, as particle shape estimates are valuable for researchers and practicing engineers to interpret soil behaviour. Whereas, there are limitations of image based analysis systems for characterizing some types of sand size grains. Because of such limitations, it would be useful for the practice of soil mechanics to employ existing visual approach. Muszynski and Stanley [42] have indicated that an engineer or technician can accurately characterize very angular sands, moderately rounded sands, and perfectly rounded sands using visual means. It is realized that this indication is also consistent with the observations made by Cho et al. [21]. From the binary images generated by an SEM and scanner, the R estimates for the sands used during the experimental study were obtained as 0.16 for CSS, 0.43 for TS; the S estimates were found to be 0.55 for CSS, 0.67 for TS (Table 1). Observ-

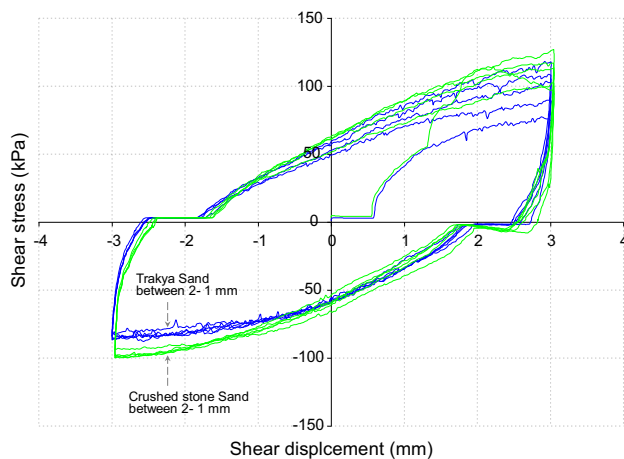


Fig. 11 Response of clean TS, and CSS with the same size distribution

ing the response of same particle sizes (1.0–2.0 mm) of TS and CSS having distinct shapes (rounded and angular) in the testing apparatus reveals that the CSS specimen has a higher shear stress horizontally applied than the TS specimen does (Fig. 11). Also, it is seen that the amplitude of shear stress values observed in TS specimen is more than those in CSS specimen.

4 Conclusions

The objective of the study was to develop a more understanding of the shear stress fluctuations in a granular material response during cyclic direct shear test. A series of experiments have been performed on Trakya Sand (TS), and Crushed Stone Sand (CSS) under a 100 kPa vertical stress level, and at two rates of shearing (2.0 and 0.025 mm/min). Experimental findings have been presented by observing the response of different grain distributions of the TS and CSS with distinct shapes (rounded and angular) in an automated constant normal load (CNL) cyclic direct shear testing apparatus. Experiments on the specimens resulted in sudden decreases followed by gradual increases in shear stress values. The main reason of these successive drops and formations, which give a stick–slip nature to the fluctuations, is the fact that the internal forces do not uniformly propagate through the specimen but are localized through force chains of strained grains. Interpretation on the literature reviewed, reveals that the mechanism raised above is attributed in mainly to the (1) rate of shearing, (2) higher number of contact point, (3) pore fluid characteristics, (4) crystal growth/bonding, (5) surface friction of the grains, (6) open fabric structure in the specimens, (7) compliance in the apparatus used in the experimental study, (8) the stick–slip behavior between soil grains. The laboratory tests presented in this paper indicate that

1. A less rate of shear applied to a specimen has resulted in a higher amplitude of fluctuations.
2. Tests on smaller size of sand grains have resulted in a lower amplitude of fluctuations, and smaller shear stress values.
3. Fines content in a soil mixture decrease the amplitude of fluctuations. Shape of the fine grains and host sands in the mixtures have not significant effect on the overall behaviour.
4. Although the shear stress–shear displacement curves for both sands (TS, CSS) demonstrated similar pattern of fluctuations, the higher roundness (R) and sphericity (S) values can cause to a lower shear stress values.

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