Development and Calibration of Large Scale Direct Shear Test Apparatus for Testing Geomaterial

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***Abstract* - Over the last 50 years, the direct shear test has survived in geotechnical applications due to its simplicity and repeatability. Due to the limitations of small devices for direct testing of shear forces that lead to variation in the classification and nature of the soil samples, a large-scale direct shear apparatus needs to be utilized. This paper presents the design, fabrication, and then calibration of the apparatus. For calibration, a total of 54 tests were carried out on a large scale and small scale direct shear apparatus at different loading conditions. Materials used for the test were sand in six forms including fine sand with loose and dense form, medium sand with loose and dense form, and coarse sand with the loose and dense state. From the results, it was concluded that the direct shear apparatus performs well and gives comparative results with small-scale direct shear machines. The small scale shows about 7.16% larger angle of friction angle as compared to large scale direct shear apparatus.**

Index Terms **- S**hear strength parameters; Laboratory testing; Geomaterials

1. INTRODUCTION

Shear strength of the soil plays a vital role in the civil engineering field because the shear failure of the soil is encountered in most geotechnical projects (Molina, Bradfield, Fityus, Simmons, & Lizcano, 2020a, 2020b). It is the key parameter and most critical property of the soil which is used in the design of foundations, stability of slopes, embankment related problems, mechanically stabilized earth walls, earthen dam, and other geotechnical simulated factors (Amšiejus, Dirgėlienė, Norkus, & Skuodis, 2014; Stark, Choi, & McCone, 2005). The shear strength of the soil specimen is evaluated in terms of cohesive strength and angle of internal friction. The friction angle depends on soil particle size (Lepakshi & Reddy, 2020; Ravindran & Gratchev, 2020). Small scale direct shear test apparatus has experimental capacity for small size particles while coarse grain soil particles are eliminated that is counteracted with real field conditions, resulting in different shear strength properties and values (Sharma, Samanta, & Sarkar, 2020). Various test methods were used to find out the shear properties of the soil like vane shear test, unconfined compression test, triaxial compression test. But the direct shear test is the primordial and the simplest test method mostly used to determine the shear properties of the soil (Taylor, 1948; Zhang, Soltani, Deng, & Jaksa, 2019). Although the direct shear test has some limitations still it is very effective in maintaining plain strain due to low-budgeted tests (Tabari, TaghaviGhalesari, Choobbasti, & Afzalirad, 2019). Large scale direct shear test is the utmost favorable and consistent one with the field conditions as it also tests coarse-grained materials that have compatible results with actual field conditions (Suddeepong, Sari, Horpibulsuk, Chinkulkijniwat, & Arulrajah, 2020; Yu, Ji, & Janoyan, 2006).

Often, the materials used for the backfill of earth retaining walls are consist of larger particles as the construction of retaining walls often takes place at already constructed places (Bathurst, 2019; Stark, Handy, & Lustig, 2019). So the particle size becomes more issue for testing in small-scale direct shear boxes. So the ASTM 3080 standard for the direct shear test has also extension and scope to use large-scale direct shear boxes to comply with field requirements (Suddeepong et al., 2020). To investigate the effect of particles having a large size, there is a requirement to fabricate and design a large-scale direct shear test (LSDS) apparatus. This research paper includes design, fabrication, and then calibration of an LSDS box.

The Mohr Columb model is purely based on cohesion and friction angle which is used in instability of slopes, foundation bearing capacity determination, and retaining walls design and to evaluate the effects of effective earth pressures on them (Co, 2020) (Nakao & Fityus, 2008). Various researchers used the LSDS apparatus for shear strength properties determination. (Liu, Wang, Geng, Wang, & Lin, 2016) determined the interface interaction between geogrids and soil that is a significant factor in the design of foundation using pullout resistance tests in combination with LSDS apparatus. For the economical and safe design of earth retaining walls, one has to learn the interface interaction relationship of soil and reinforcement (Hegde & Roy, 2018b). The type of test has a great impact on the results. (Han, Ling, Shu, Gong, & Huang, 2018) Han et al 2018, determined the interface interaction between soil and the geogrid reinforcement that is a highly complex phenomenon, depends upon the type of test rather than load-deformation rate and conditions at which the load is applied. It was determined from the results obtained from both tests vary considerably. Also, the direct shear test apparatus gives the suitability of materials that are to be used as a backfill giving and friction angle. LSDS test enables one to test larger particles for shear strength properties determination that can be comparable to actual field conditions. In all over the world, construction of retaining walls increases day to day specifically in the transportation sector for the construction of highways and motorways (Li et al., 2020). Thus the basic parameter used when designing retaining structures is the angle of internal friction and their correlation with field condition is very necessary that can only be obtained by using LSDS apparatus (Jia, He, Li, Wang, & Yao, 2019; Wang, Yang, Wang, & Liu, 2019). In some cases, before backfill material is known, walls are designed based on an assumed friction angle but in later stages, this angle is to be considered as a minimum requirement for backfills (Nakao & Fityus, 2008).

Overburden pressure, density, Shape of soil particles, and gravel size affect the basic soil parameters (He, Mo, Siga, & Zou, 2019). In this research, the impacts of overburden pressure and material density on the behavior of sand, shear resistance parameters were calculated for fabrication purposes.

According to standard methods of shear test practice, there is a limit of size for particles to be tested in SSDS, and that is the fine materials. But in the case of coarser materials, an LSDS test is recommended. Otherwise, the particles should be readjusted in terms of grains size distribution to accommodate for SSDS (Mojtahedi, Rezvani, & Nazari, 2019). The output of the SSDS test is always larger than the LSDS test apparatus in terms of friction angle. But these can also be affected up to a larger extent by different factors including vertical loads, area of the shear box, moisture content, and strain rate (Mojtahedi et al., 2019).

There is also a limitation on the size of the specimen as well as of box dimensions. The diameter or the width of the box must be 50mm at least and the thickness of the sample should be 13mm. In terms of particle diameter that are to be tested, the minimum width of the box must be at least ten times the diameter of particles and the width of the sample must be 6 times the particle size (Mojtahedi et al., 2019; Sakleshpur, Prezzi, Salgado, Siddiki, & Choi, 2019). So for the small scale direct shear test, the particles with a diameter or size greater than 4.75mm must be removed before testing (Sakleshpur et al., 2019).

The basic concept behind the rupture or failure of soil is the Columb concept which is based on the theory of shear that it occurs when the normal and shear forces combine and not due to only shear or normal stress. A curved line was developed to define the failure envelop. It is also possible to approximate the shear stresses at the failure plane based on normal stresses. The mathematical correlation between shear and normal stresses is expressed by the following relationship (Lupinl, Skinner, & Vaughan, 2009).

$$\tau = c + \sigma \tan\varphi \tag{1}$$

Where

S= Shear strength of soil sample, σ = Normal stress and ϕ = Friction angle

The shear test may be either stress-controlled or strain-controlled. In the case of controlled stress, the incremental stress is transferred to the sample with increasing load until it fails. But in strain-controlled, a rate of displacement is kept constant while applying to the soil sample and the resistance corresponding to this displacement is measured by proving ring or load cell (Ghazizadeh & Bareither, 2018; Sweta & Hussaini, 2018).

Various researchers carried out work on a direct shear test including a large scale and small scale. They have used various types of materials for testing including, tire-shred sand mixture, sand mediums, and sand gravel mix. (Palmeira & Milligan, 1989) carried out shear tests for the determination of the effect on shear strains of the sample due to an inclined bar to the plane. (Xiao, Ledezma, & Hartman, 2014)tested tires shreds in LSDS test ranging from 25 mm in size to 75mm. (Balunaini, Yoon, Prezzi, & Salgado, 2009) Yoon et al. 2009 has performed laboratory tests on tires chips-sand mixture and evaluated the effect on the interaction between geogrids and mixtures. They have used various proportions of tire chips have been used in proportions with sand.(Arulrajah, Rahman, Piratheepan, Bo, & Imteaz, 2014) Rahman et al. 2014 has performed LSDS tests on recycled foam glass having reinforced geogrids and concluded that it increases the confinement of foamed glass particles in direct shear tests. The materials that are considered lightweight is used to reduce settlement as well as to minimize bearing pressure. (Tabari et al., 2019)Taghavi Ghalesari et al. 2019 used LSDS tests for composite clays consisting of clays and coarse-grained materials that can be used for building and roadways platforms. From this research, it was concluded that increasing gravel particles in addition to soil mix increases the angle of internal friction as well as reduces optimum moisture content. To ensure the density of the medium, a modified proctor test has been performed. The shear strength behavior of geogrids and soil interface has been examined by using large-scale direct shear tests and also interfacial shear strength affected by particle size has been taken into account (Han et al., 2018). Later on, the researchers concluded that there are specific size materials that have more interlocking with geogrids enhancing properties of shear strength of a medium. To improve the performance of flexible pavements, it is highly recommended to use geogrids. (Simoni & Houlsby, 2006) Simoni and Houlsby carried out a direct shear test to investigate the impact of particle size distribution on the shear strength soil properties and carried out about 87 direct shear tests. The effect of dilatancy and friction on the shear strength of soil as a function of specific gravity and particle size distribution was determined.

(Xiao, Ledezma, & Hartman, 2015) Xio used LSDS test on tire-derived aggregates, tire-derived aggregates, and sand mixture to determine shear resistance. (Hegde & Roy, 2018a)Hegde and Roy carried out a numerical simulation of the LSDS test and pullout resistance test for the comparison of interface resistance. For sub-ballast-geogrid interfacial properties of shear strength determination, LSDS test has been used to carry out an experimental study (Biabani, Indraratna, & Nimbalkar, 2016). The effect of different factors including normal stress, shearing rate, and relative density on granular particles in reinforced and unreinforced conditions was determined.

(Arulrajah et al., 2014)researched the shear strength parameters of construction demolition materials reinforced with geogrids to use them as an alternative material of construction and to check their viability. The demolished materials were consisting of crushed bricks and recycled aggregate from concrete. The interface and residual shear strength of a mixture of recycled concrete aggregate and geogrid reinforced and non-reinforced materials were found to be higher than crushed bricks. However, from the LSDS test, it was evaluated that the interfacial properties of shear resistance of unreinforced crushed bricks were found to be higher than that of reinforced due to interlocking at the interface of materials. Few researchers have also carried out the

LSDS test on tire shred aggregate of size 25mm-75mm (Xiao et al., 2015). In this research, the effect of shear resistance of tire-derived aggregates in contact with sand, concrete and geosynthetic products. From the studies, it was revealed that there is no peak shear resistance obtained during direct shear testing for tire-derived aggregates.(Riahi, Chenari, & Karimpour-Fard, 2015) Chenari et al. performed LSDS test on sand-tire powder mixture for shear strength properties determination. They have mixed various powders of rubber mix with loose sand to assess the shear strength parameters of the mix. (Rao, Sood, Subrahmanyam, & Govindaraj, 2009) Sood et al. conventional direct shear test apparatus to carry out laboratory test on planer rock joints keeping the normal load constant using a servo-controlled system, However by using surrounding rock mass, dilation was restricted and under constant normal load, shearing does not take place. (Fragaszy, Su, Siddiqi, & Ho, 1992) Su et al. used the triaxial test method to determine the near field density and the far-field density of coarse soil. It was investigated that the density of sand is affected by large-scale particles. (Amini & Hamidi, 2014)Amini and Hamidi carried out laboratory experiments to analyze the influence of gravel content mixed with sand. The test was performed under dry conditions using the LSDS apparatus. It was concluded that by increase gravel content in soil samples increases shear strength. (Seminsky, 2013) Conducted research on oversized particles to observe their effect on the soil mixture. The relationship used by Goth was verified experimentally as well as numerically. The LSDS apparatus was used for testing of large size particles in the sand with gravel mixture while the Discrete Element Method (DEM) is used for numerical modeling. From test results, it was evaluated that as the concentration of large-sized particle increases in the mixture, the shear strength parameters also increases. For the determination of interface shear strength properties, (Shallenberger & Filz, 1996) Shallenberger and Filz developed a large-scale direct shear apparatus. The device can handle interfaces as large as 28 by 16 inches, the lower box should be fixed and have no movement concerning the upper half shear box. It was notified that the large-scale direct shear apparatus has very negligible effects in relation to standard direct shear apparatus. It was further stated as long as the displacement increases in large-scale direct shear test apparatus, interface residual shear strength can be determined effectively.

(Shou & Lin, 2012) Shou and Lin designed, compared, and constructed LSDS test apparatus to eliminate the chances of error in SSDS apparatus. The researcher focused on the main parts of the apparatus including hydraulic system, control system, mechanical operations, and frame structure to support desired compressive and shear loads in his studies.

2. Methods

2.1 Material

In this research, three ranges of sand samples were used which were obtained by sieve analysis (C. ASTM, 2006). The sand passes through sieve no. 60 and retains on sieve no. 200 for fine sample. The sample was passed through sieve no.20 for a medium sample and kept on sieve no. 60 and for coarse sand, sample passing through sieve no. 10 and retained on sieve no. 20. A total of six samples was collected. As for as to test soil samples in dry condition, the collected samples were kept dry in plastic bags. For labeling samples, fine sand was designated as F-L indicating fine loose sand and F-D was fine dense sand. Similarly, medium sand was labeled as M-L and M-D whereas, coarse sand as C-L and C-D as shown in Table 1. The specific gravity of all three samples was calculated by pycnometer (Soil & Rock, 2006). The specific gravity values evaluated are; for fine-grained soil, Gs =2.62, medium sand, Gs =2.63, and coarse-grained sand, Gs =2.64.

TABLE 1

DESCRIPTION OF SOIL SAMPLES

Sample	Soil Condition	Material	Particle size (mm)
F-L	Loose	FINE	0.06 - 0.2
F-D	Dense		
M-L	Loose	MEDIUM	0.2- 0.6
M-D	Dense		
C-L	Loose	COARSE	0.6 – 2
C-D	Dense		

2.2 Small Scale Direct Shear Test (SSDS)

According to the procedure described in ASTM D3080 / D3080M – 11(D. ASTM, 2011). Tests were carried out for SSDS test using a square shear box having a dimension of 64 mm wide and 32 mm thick specimen as shown in Figure 1. Sand samples, in this case, were tested under normal loads of 1.27 kg, 2.54 kg, and 3.81 kg at a constant strain rate of 0.5 mm/min, for each size and condition. The sand used was air-dried. The sand was compacted in the shear box by tamping the top of each lift with a steel tamper in three lifts of equal thickness. The number of tamps per layer has been adapted to achieve the target density for each specimen which is 95% of the maximum dry density set by the modified Proctor compaction (Connelly, Jensen, & Harmon, 2008), which was the United States Federal Highway Administration's recommended backfill compaction criterion (Salgado, Yoon, & Siddiki, 2003). Drainage on the top and bottom of the specimen was permitted via perforated 9 mm thick PVC sheets. Measurements were recorded for shear force, horizontal shear displacement, and vertical displacement. The normal and shear stresses were computed using a displacement-corrected area of the shear plane from the loads.

FIGURE 1

SMALL SCALE DIRECT SHEAR TEST APPARATUS

2.3 *Large scale direct shear test (LSDS)*

The testing on large scale was also performed on a large scale according to the standard- ASTM D3080 / D3080M – 11. The schematic view of the large-scale direct shear test apparatus is exhibited in Figure 2. The box size was dependent upon the size of the particles that need to be evaluated. So it is very important and crucial to fabricate a box of the size that fulfills the requirements of ASTM. According to ASTM D 3080-90, the following is the minimum size requirement for a shear box for LSDS apparatus. The thickness of the box should be at least = 6D, Width of the shear box should be at least = 10D. The 'D' defines the maximum diameter of the particle size intended for use during testing. The device is designed with a capacity to test soil specimens with gravel having a maximum diameter of 60 mm. However, sand with a max. size of 2 mm was used in this study.

The shear box consists of two steel boxes, one was the upper box, a horizontal arm was attached to the frame of the machine to prevents the movement of the upper shear, having a maximum size of 600 mm x 550 mm x 300 mm and the lower box is moveable with maximum dimensions of 600 mm x 550 mm x 300 mm as indicated in Fig 3a. The lower shear box size was kept extended beyond 150 mm in length so that the shear plane area remains constant during shearing. For frictionless movement, guide rails were placed at the base plate on which the lower shear box was mounted upon. A horizontal hydraulic jack was used to push the lower box to shear the sample. The base plate having a system for load cell was kept at the center of the upper shear box and a hydraulic jack was used to continuously apply load which was attached to the data logger for data acquisition as shown in Fig 3b. To reduce friction at the sidewalls, the interior walls of the box were coated with a teflon cover. Before each test, the Teflon lining was inspected and periodically replaced, as needed. The above-tabulated densities and weights for each sand is used to equate effects of LSDS tests with small scale for calibration of LSDS equipment.

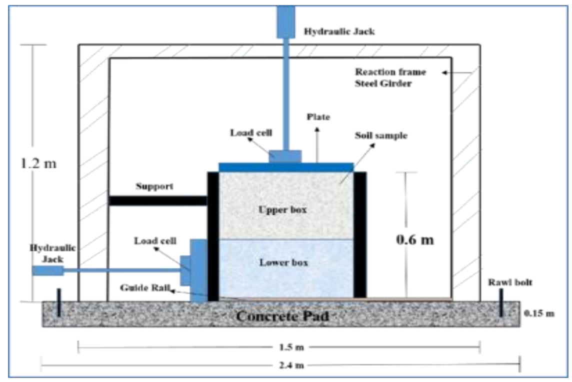


FIGURE 2.

SCHEMATIC VIEW OF LARGE SCALE DIRECT SHEAR TEST APPARATUS

FIGURE 3

A) PICTORIAL VIEW OF LARGE SCALE DIRECT SHEAR TEST APPARATUS B) LOADING PLATE WITH LOAD CELL

2.4 Design of large scale direct shear test machine

The probability of an error in the shear strength properties of soil samples in small-scale direct shear devices, the large-scale direct shear test apparatus needs to be designed. To design the direct shear apparatus, four main parts including frame, hydraulic system, mechanical and control system, and software program for data acquisition has man importance to be taken into consideration.

2.5 Design of the supporting frame

The supporting frame was designed according to American Steel Construction Institute (AISC)[47]. Steel girder of 1.8 x 1.2 m with a yield strength of 344 kN/mm^2 and W 6 x 12 was chosen from Table1-1 of the AISC manual, as the nearest section. The support frame was checked both for bending as well as shearing, details as under the depth of the girder is 153 mm and width of flange is 100 mm, Section properties for AISC's W 6 x 12 can be found from the American steel construction manual.

2.6 Checking shear and bending for horizontal and vertical girder

To determine section classification as shown in Fig 4, $\in=\sqrt{35/fy}=0.85$, the limit for outstand flange to be in class one is $c/t=9\times\in$. As c/t=7.57 is greater than 5.04 consequently it is in class-1, for internal compression member subjected to tension,$c/t=72\ \times\in$ as 60.47 is larger than 41.3 so it is in class one. Evaluating the shear stress of the cross-section.$V = AV(f_Y \div \sqrt{3})$ Shear area $AV = A - 2xbxt_f + (t_w + 2\gamma)t_f > h_w t_w \eta$ Therefore, shear area governs $V = AV(f_y \div \sqrt{3})$, As shear resistance exceeds maximum shear resistance (48.73 > 11.03), Thus the section is safe in shear.

Now to verify the bending resistance of the section $\frac{M}{I} = (f_y \div y)$, for maximum y=c, $\frac{I}{C} = 7.31$ from Table 1-1 of AISC Manual, the third edition as M > Mmax.. Moreover, the shear section and bending section is satisfactory. Based on the above design of the supporting frame, the load cells, pressure gauges, base plate, shear boxes, and hydraulic system were selected and arranged.

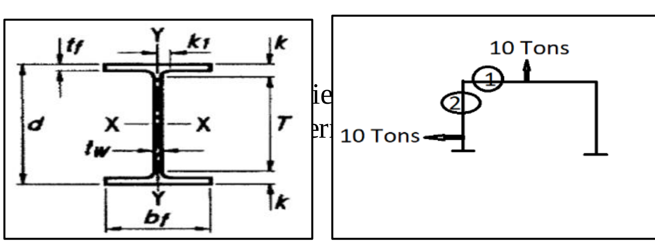


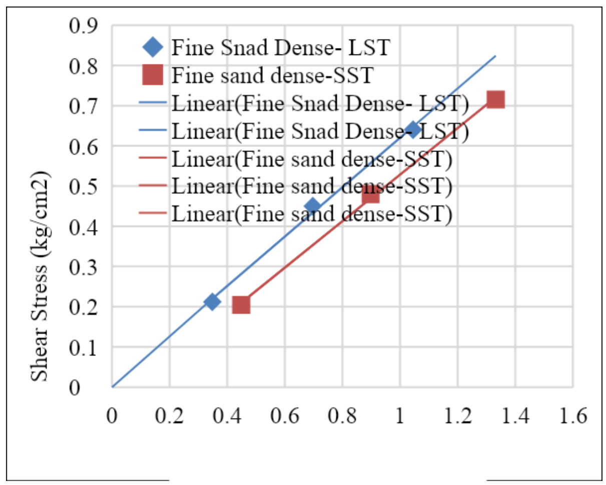
FIGURE 4

A) GIRDER SECTION B) APPLIED LOADS

3 Results and Discussion

3.1 Calibration of LSDS

The SSDS and LSDS tests were performed on three types of sand that are fine medıum and coarse sand under two condıtıons loose and dense. For each test, a Mohr-Coulomb failure envelope was specified with a non-negative intercept by linear least-square regression. The shear strength parameters for the Mohr-coulomb failure envelopes are listed in Table 1. For all practical purposes, the envelopes were linear, with regression ranging from 0.9953 to 1.000 for small-scale direct shear, and from 0.9915 to 0.9985 for LSDS. The intercepts depict friction in the shear box that was not accounted for by box friction correction, and possibly nonlinearity of the near-origin envelopes for failure.



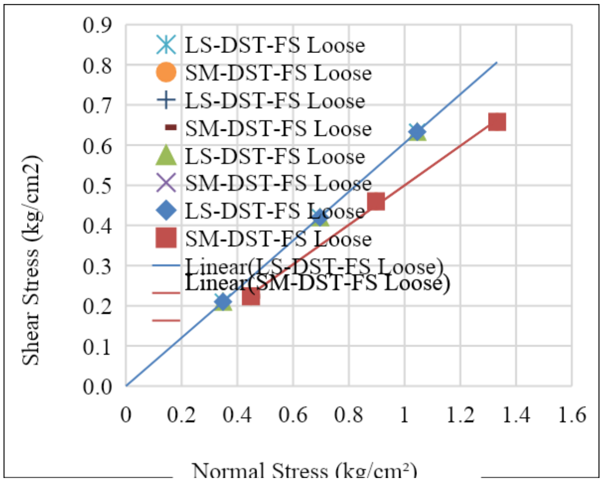


Figure 5. Failure envelops obtained from LSDS and SSDS for fine sand in a) loose state b) dense state

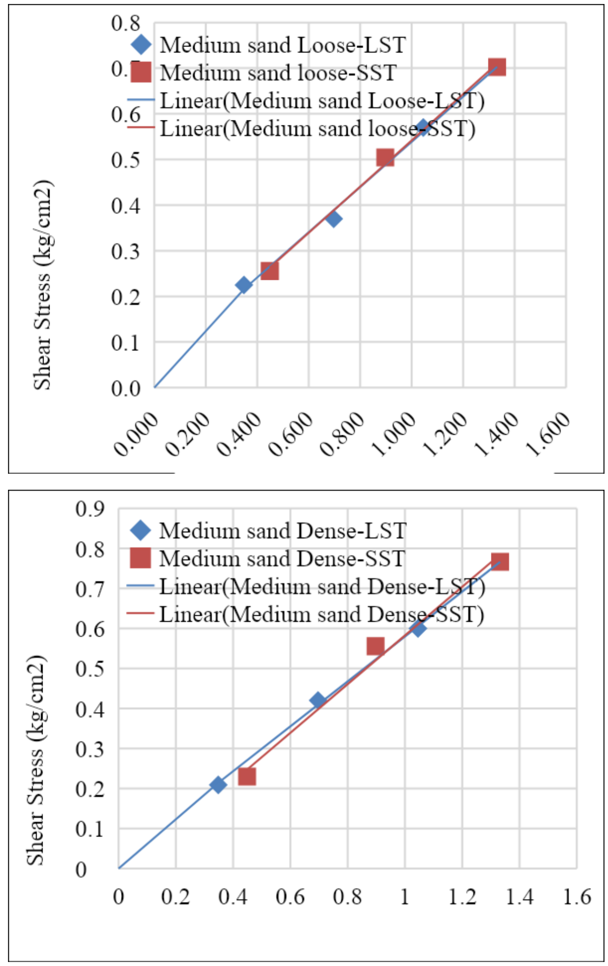


Figure 6. Failure envelops obtained from LSDS and SSDS for medium sand in a) loose state b) dense

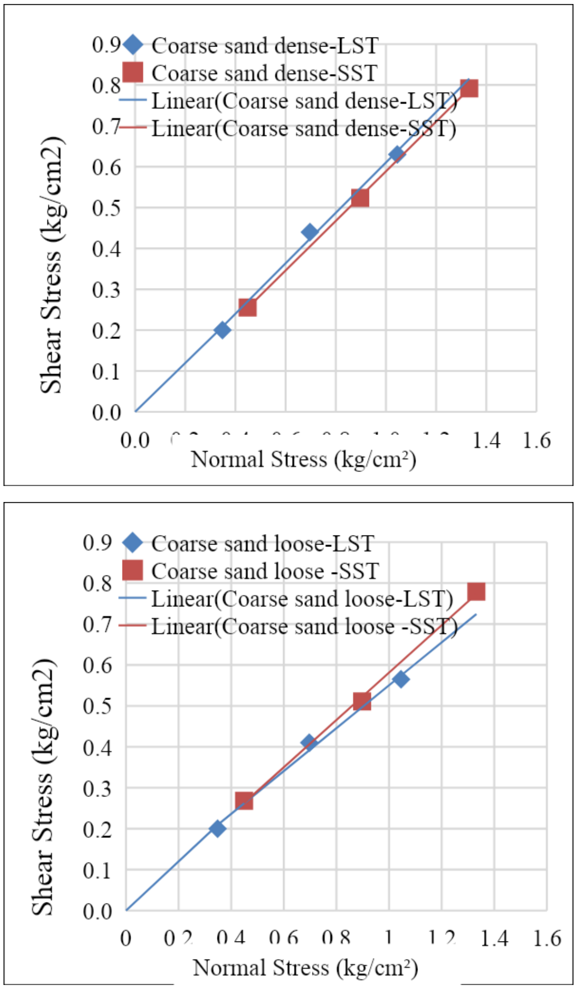


Figure 7. Failure envelops obtained from LSDS and SSDS for Coarse Sand in a) Loose State b) dense

The comparison of the friction angle calculated from the LSDS tests and those obtained from the SSDS tests is shown in Fig. 5, 6, and 7. The cohesion value obtained from both small scale and large scale is approximately zero that is why the angle of internal friction governs shear strength. Table 2 indicates the comparable and marginally lower value given by large-scale shear tests for the internal friction angle. From the results, it's inferred, that that the results obtained from the LSDS apparatus and SSDS test show a small difference. Thus it was concluded that the LSDS test apparatus designed and fabricated in this research is properly calibrated.

TABLE 2

RESULTS OF LSDS AND SSDS

Sample	State	large scale		Small Scale	
		φ	R^2	φ	R2
Fine	Loose	26.6	0.9979	27.1	1
Fine	Loose	30.2	0.9987	31.0	0.9958
Medium	Medium	26.1	0.9915	27.1	0.9916
Medium	Medium	29.3	0.9871	31.4	0.9979
Coarse	Dense	28.0	0.9985	30.1	0.9879
Coarse	Dense	31.3	0.9989	32.5	0.9953

4 Summary and conclusion

The main purpose of this research was to design and fabricated LSDS to determine the shear strength parameters of larger particles to replicate the field samples. The field sample also consists of large particles along with fine particles, which should be removed while performing SSDS test which contradicts the actual conditions. In the light of the above, it was essential to design a large-sized direct shear testing apparatus for testing soil samples with large particle sizes in order, to obtain results that are most similar to the actual soil conditions at the site. LSDS tests were conducted under varying normal loads, and the same sand samples were also tested in small-scale testing apparatus to verify that apparatus is properly calibrated.

This study also assessed the effect of density on the shear strength parameters and shows a significant improvement in the shear strength of the soil is noted in dense conditions due to an increase in frictional resistance within the soil particles. The angle of internal friction for dense sand is about 11.7 % than loose sand.

Tests conducted on LSDS apparatus under varying normal loading conditions concluded that the equipment assembly can carry the design load.

Comparison of test outcomes exhibits that there is a minimal difference in the results obtained from both small-scale and large-scale tests, so the apparatus is well calibrated.

The friction angle in small scale direct shear apparatus was slightly larger than large scale direct shear because the packing of the particles did not allow the free movement of particles during shearing and confining effect of the shear box was observed. The small scale shows about 7.16% larger angle of friction angle as compared to large scale direct shear apparatus.

• In both small and large scale direct shear apparatus, relative displacements corresponding to peak displacements are equivalent for sands displaying peak stress behaviour.

Data availability

The data used to support the findings of this study are included in the article.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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