

## The scale direct shear test effect on the shear strength characteristics of different sands in Lahore, Pakistan

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### Abstract

#### Article History

Received:  
26-Jun-2025

Revised:  
28-Aug-2025

Re-revised:  
01-Nov-2025

Accepted:  
03-Nov-2025

Published:  
10-Nov-2025

Updated:  
11-Dec-2025

The direct shear test is a widely used method for determining soil and material shear strength parameters. This study examines the impact of shear box size on the shear strength properties of poorly graded sands collected from Lahore, Pakistan. Sand samples were classified using the Unified Soil Classification System and tested at dry densities ranging from 1.601 to 1.825 g/cm<sup>3</sup> using shear boxes with 60 mm, 100 mm, and 160 mm diameters. Tests were performed at a constant rate of 1.25 mm/min under normal stresses of 23.42, 35.76, and 48.11 kPa. Results indicate that increasing box size leads to higher cohesion and lower friction angles, while increasing soil density enhances both parameters. Regression relationships were developed to relate small-scale and large-scale test results. These findings underscore the importance of accounting for scale effects in laboratory shear testing and offer guidance on extrapolating small-scale results to design applications. The study highlights the significance of considering container size effects in the interpretation of laboratory shear tests. Future research may explore varying soil types and moisture contents to generalise these findings further. Understanding these scale effects is crucial for improving the accuracy of geotechnical assessments and ensuring safe construction practices.

**Keywords:** Angle of internal friction, cohesion, direct shear test, sand, scale effects, soil mechanics, regression analysis, ASTM standards.

**How to Cite:** Ahmad, I., Rehman, Z. U., Iqbal, M. J. & Rahman, W. U. (2025). The scale direct shear test effect on the shear strength characteristics of different sands in Lahore, Pakistan. *Asian Journal of Science, Engineering and Technology (AJSET)*, 4(1), 140-152. <https://doi.org/10.47264/idea.ajset/4.1.9>

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## 1. Introduction

Over the past few decades, interest in shear stress testing of soils has grown significantly worldwide, reflecting its importance in geotechnical engineering practice. Understanding the engineering characteristics of soil layers at the required depths is crucial for designing structures safely and economically. These characteristics are typically determined through laboratory and field experiments (Bowles, 1997). Among various soil shear tests, the direct shear test is widely preferred due to its simplicity, repeatability, and cost-effectiveness (Zhou *et al.*, 2009). This test has been used for more than 50 years to evaluate soil shear strength (Cerato & Lutenegeger, 2006). Historically, Coulomb (1776) first expressed shear stress as a function of friction angle and normal stress using a simple shear apparatus on materials such as wood blocks. Later, slope stability and soil shear behavior were explored more systematically by Alexandre Collin in the early 1800s (Skempton & Collin, 1949). Matthews (1988) provided a detailed historical account of the applications of direct shear testing in engineering.

The influence of specimen size on shear test results was first reported by Parsons (1936), who observed that larger shear boxes produced lower friction angles when testing clean sands and crushed quartz. Subsequent studies confirmed that shear strength parameters are affected by shear box size and scale, though systematic investigations remained limited for many years (Cerato & Lutenegeger, 2006; Bareither *et al.*, 2008; Wang *et al.*, 2008; Zhou *et al.*, 2009). These studies highlighted that direct shear tests using different box sizes could yield varying values of friction angle and cohesion, emphasizing the need for scale-aware interpretation (Wu *et al.*, 2008).

Recent research has further advanced the understanding of scale effects in direct shear testing. Deiminiat and Li (2022) performed tests on waste-rock-derived materials. They found that a specimen width-to-maximum particle size ratio ( $W/d_{max}$ ) of at least 60 was required to minimize scale artifacts, thereby validating the scalping technique for extrapolating shear strength parameters to field conditions. Similarly, Li *et al.* (2021) investigated soil-rock mixtures using both laboratory tests and numerical modelling, demonstrating that particle breakage and composition significantly influence scale-dependent shear behaviour.

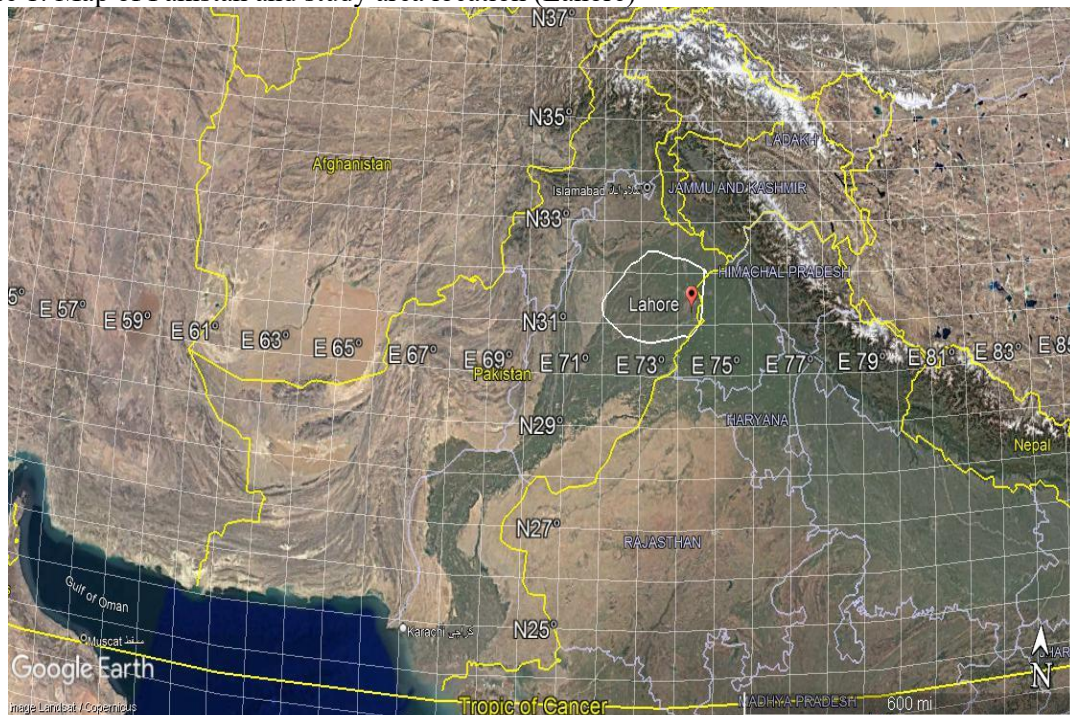
Zhao *et al.* (2024) developed a novel large-scale direct shear apparatus for frozen coarse-grained soils, showing the importance of testing at representative scales for challenging materials. Discrete Element Method (DEM) studies have also contributed valuable micromechanical insights; for example, Wu *et al.* (2023) used PFC2D simulations to reveal how specimen size affects deformation patterns and stress distributions during shear testing. Cantor and Ovalle (2023) examined the granular materials with varying gradations. They found that a stable critical-state shear strength was only achieved when the specimen aspect ratio (height-to-width) exceeded approximately 15, highlighting the role of geometry in direct shear testing.

Since Lahore is one of Pakistan's largest and most rapidly urbanising cities, construction activities in this region are increasing, making it essential to understand the engineering behaviour of local soils. Figure 1 shows the sampling locations, where poorly Graded Sands (SP), classified according to the Unified Soil Classification System (USCS), were collected. While several international studies have examined the influence of shear box size and shape on the shear strength parameters of sands (e.g., Cerato & Lutenegeger, 2006; Bareither *et al.*, 2008;

Wu *et al.*, 2008), minimal research exists for Pakistani soils, particularly the sands found in and around Lahore.

Furthermore, most prior work has focused on either uniform or idealized laboratory sands, often neglecting region-specific variability in gradation and mineralogy. This study addresses this gap by performing systematic direct shear tests on locally sourced SP sands using shear boxes of three distinct geometries—square (60 mm × 60 mm), circular (diameter = 100 mm), and rectangular (160 mm × 130 mm). The goal is to quantify the effect of shear box size and shape on the measured friction angle and cohesion for these soils, thereby generating data directly relevant to foundation design and earthworks in Lahore, and providing comparative insights for global practice.

Figure 1: Map of Pakistan and study area location (Lahore)



## 2. Materials and methods

### 2.1. Sands

Three naturally existing sands with nearly identical geologic origins (originating from a river) were tested. The sands came from open pits in the riverbed. Grain size, density, specific gravity, and void ratio were employed to characterize the sands used in this study according to the ASTM standard test procedures (ASTM International, 2020).

The oven-dried sand samples were classified based on the USCS. In general, the grain size analysis of sands was carried out according to the standard test method ASTM D-422. The grain size distribution curves for sand samples are shown in Figure 2. According to USCS (ASTM D-2487), the sands could be classified as SP. The sands employed in the testing had a poor grading (poorly graded sand), and their maximum and minimum dry densities were determined as shown in the Table 1. Other physical properties of sands are also shown in the Table-1.

Figure 2: Grain size distribution curves of sands used in this study

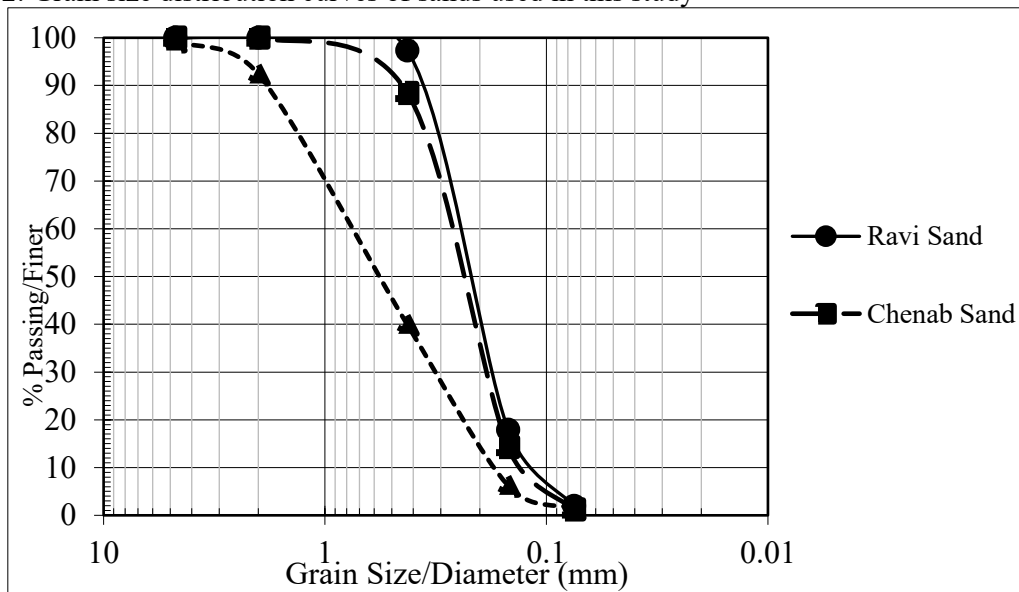


Table-1: Physical properties of sand used in this study

Sand Sample	Ravi Sand	Chenab Sand	Lawrencepur Sand
% Sand	% Coarse	0	6.87
	% Medium	2.68	52.44
	% Fine	95.4	38.54
% Silt and Clay	1.92	1.20	1.38
USCS Soil Classification	SP (Poorly Graded Sand)	SP (Poorly Graded Sand)	SP (Poorly Graded Sand)
Specific Gravity, $G_s$	2.622	2.672	2.693
Density, $\gamma_d$ (gm/cc)	1.601	1.608	1.825
Void ratio, $e$	0.638	0.630	0.476

## 2.2. Direct shear test

The direct shear test is the earliest technique for examining the shearing resistance of soils, including cohesion and the angle of internal friction (Terzaghi *et al.*, 1996). When breaking along a predetermined horizontal plane, the direct shear test is used to calculate the laterally constrained sample shear strength (Oyanguren *et al.*, 2008). When preparing test specimens for the direct shear box test, ASTM D-3080 requires several particle size to box size parameters. It recommends that the initial minimum specimen thickness be at least six times the diameter of the maximum particle, and the specimen's minimum width be at least ten times the diameter of the maximum particle size.

It should be noted that the direct shear tests of soils in accordance with ASTM D-3080 standard test method require that both the horizontal and vertical dimensions of the apparatus be at least twice as large as the greatest particle size. The size of particle to size of box requirement is a subject of increasing interest in research. For instance, Taylor and Leps (1938) conducted comparative tests of large (305 x 305 mm) and small (76 x 76 mm) shear boxes on Ottawa sand (oven-dried). They noticed that the angle of internal friction in the small shear box was  $0.5^\circ$

more than that of the large shear box. According to Ingold (1982), the angle of internal friction from a shear area of 60 mm x 60 mm obtained was 2 to 3° greater than that from a shear area of 300 mm x 300 mm obtained. According to Jewell and Wroth (1987), the length of the shear box to the average size particle ratio should be between 50 and 300. Shear boxes of different sizes were used. A series of gears that are mobilized by an electric motor regulate the movement of the lower shear box in the horizontal direction. The shear box's size may influence the results of the test.

According to the results of tests from the studies of Cerato and Lutenecker (2006), direct shear testing exhibits a scaling effect. They obtained that smaller friction angles were produced by small-size particle to box-size ratios. Additionally, they demonstrated how the relative density as well as the particle's relative size to the box had an impact on the friction angle. For sand backfill, Bareither *et al.* (2008) showed that the internal angle of friction difference to the corresponding peak strength observed in small-scale and large-scale direct shear boxes ranges between and 4 2°. Wu *et al.* (2008) presented the findings of the Toyoura sand test, revealing a reduced value of the angle of internal friction for large-scale shear boxes.

Most of the civil engineering structures, such as retaining walls, slope stability, foundations, and other structures in soil, are designed with consideration of the friction angle and cohesion. These parameters are determined using the direct shear test. The sand samples were obtained from open-pit/borrow pits in different places across Lahore city, Pakistan.

In this research, shear boxes of three different sizes were used. The dimensions of the first square shear box (small box) were 60 mm in width and 20 mm in depth, the second circular shear box (medium box) were 100 mm in diameter and 30 mm in depth, and third rectangular shear box (large box) were 160 mm in length, 130 mm in width, and 40 mm in depth. The aspect ratios (H/L) of square, circular, and rectangular shear boxes are 0.33, 0.3, and 0.25, respectively. 1.25 mm/min was used as the constant speed (strain rate) for shearing the samples. In all of the shear boxes, a dead-weight system was used to execute direct shear tests with three different normal stresses of 23.42, 35.76, and 48.11 kPa.

### 3. Results

The size of the shearing device may influence the direct shear test results. For a smaller shear box, the device friction and the effect of the boundary are typically more important. Direct shear tests were performed on all the sand samples. This section provides a summary and discussion of the findings of this research. It is generally known that the Mohr-Coulomb failure criterion typically provides an accurate description of how a granular material fails (Lambe & Whitman, 1979). The angles of internal friction and cohesion were calculated for each test series as the regression best fit over the typical stress range.

Three different-sized shear boxes were used for direct shear tests in this research. Figures 3 and 4 show the angle of internal friction and cohesion for each sand sample as a function of the size of the box. By enlarging the size of the box, as shown in Figures 3 and 4, the angle of internal friction is reduced, and cohesion is increased. Additionally, Figures 3 and 4 demonstrate that the range of angles of internal friction for small, medium, and large shear boxes are 34.88 to 42.05, 32.75 to 39.18, and 31.94 to 37.35, respectively, and the cohesion range for small, medium, and large shear boxes are 0.17 to 1.08, 0.54 to 2.15, and 0.76 to 2.35, respectively. It can be argued that the results of the large shear box show higher cohesion and

lower angles of internal friction, whereas the results of the small shear box show higher angles of internal friction and lower cohesion for the sands studied.

Figure 3: Variation of friction angle with shear box size for the tested sands

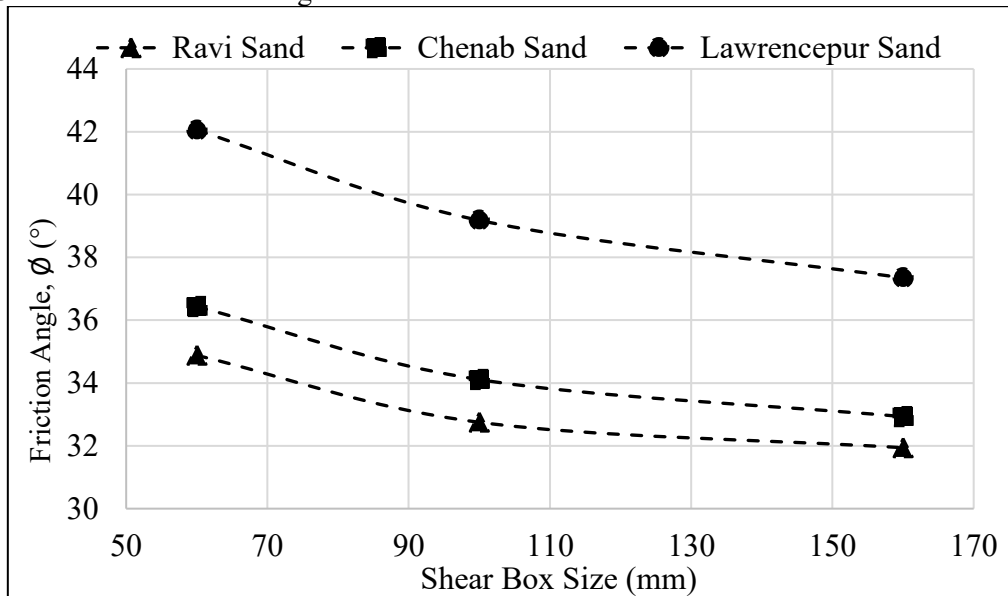
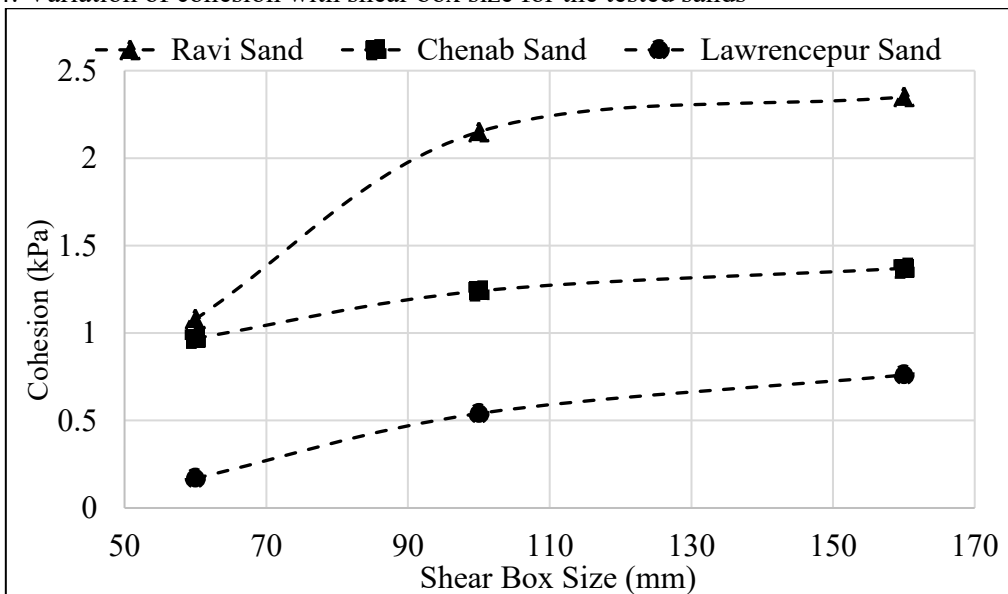


Figure 4: Variation of cohesion with shear box size for the tested sands



### 3.1. Strength parameter affected by density factor

This study assessed the impact of density, one of the physical properties, on the strength parameters of Punjab sands. For all the sand samples, density, angle of internal friction, and cohesion were calculated. The test findings also demonstrate that, in each of the three boxes, the angle of internal friction and cohesion increases with increasing density (Figures 5 and 6). The test findings in this study demonstrate that direct shear testing exhibits a scale effect. These findings aid in the explanation of the earlier discovery concerning the effects of scale in the direct shear boxes.

Figure 5: Influence of density on angle of internal friction of sands at different box sizes

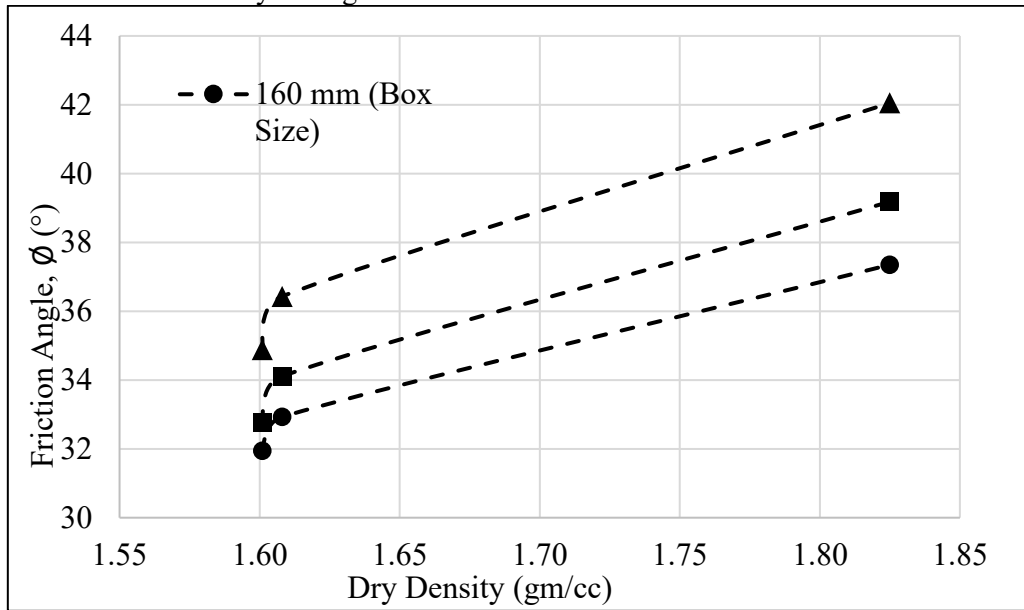
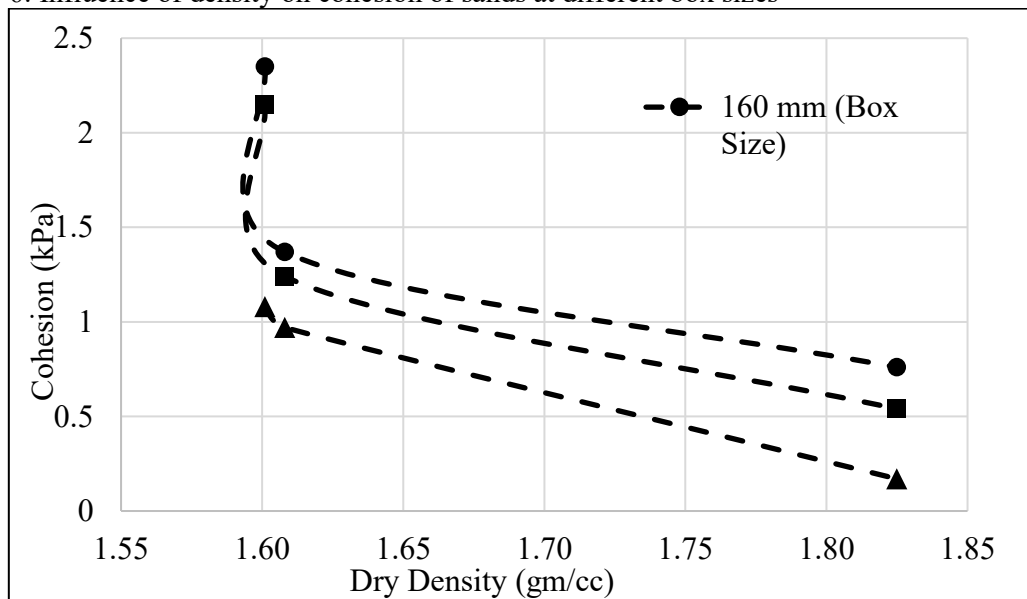


Figure 6: Influence of density on cohesion of sands at different box sizes



### 3.2. Comparison of different-scale direct shear test

Large-scale direct shear tests on sand (160 x 130 mm) are expensive, challenging, and time-consuming. Therefore, it is typically not possible to conduct these tests on small projects. Figures 7 and 8 compare the angles of internal friction and cohesion for small- and large-scale direct shear boxes. We examined the test results from small-, medium-, and large-scale direct shear boxes. Regression analysis was done to determine the link between the scale size, direct shear, and the shear strength characteristics of the sands. Both the cohesion determined from the results of small- and large-scale direct shear tests and the friction angle of the small and large shear boxes exhibit significant relationships. In order to get the shear strength characteristics for a large-scale direct shear box, we can use the results of a small-scale direct shear box.

$$\text{Friction Angle: } \phi_{(160 \times 130)} = 0.7631\phi_{(60 \times 60)} + 5.2387 \quad (R^2 = 0.9988)$$

$$\text{Cohesion: } C_{(160 \times 130)} = 1.38C_{(60 \times 60)} + 0.4721 \quad (R^2 = 0.7302)$$

Figure 7: Relationship between the friction angle of large and small-scale direct shear boxes

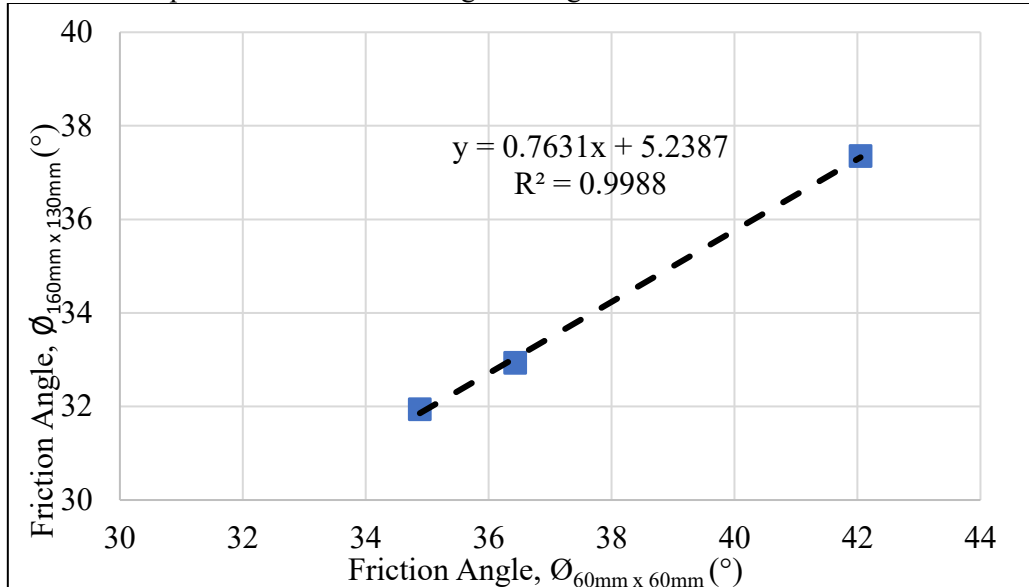
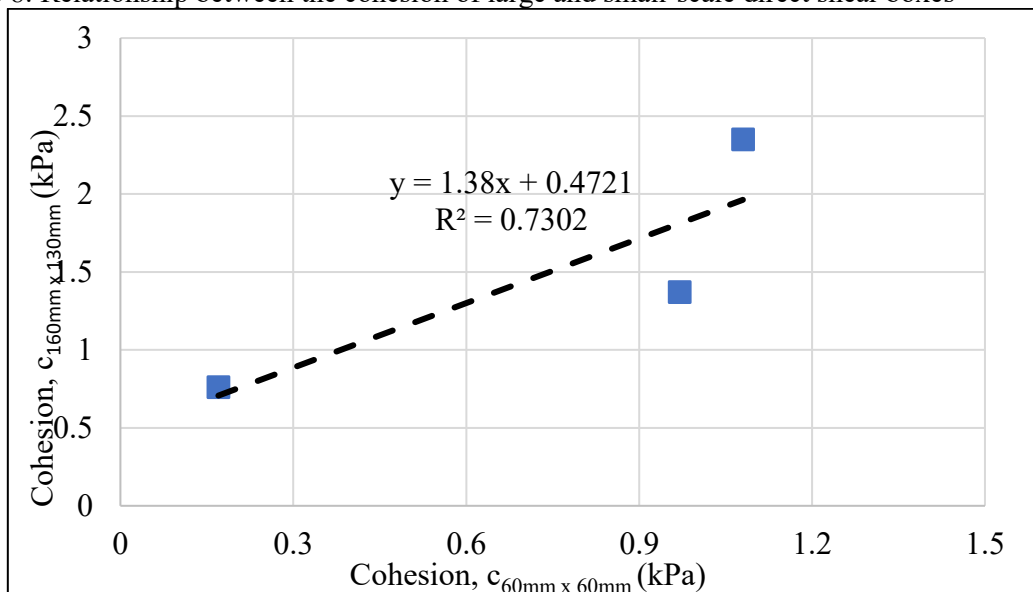


Figure 8: Relationship between the cohesion of large and small-scale direct shear boxes



#### 4. Discussion and analysis

The findings of this research confirm that both density and specimen scale significantly influence shear strength parameters in direct shear testing. A statistical comparison of results across small, medium, and large shear boxes reveals that cohesion values tend to increase with box size. In contrast, the friction angles tend to decrease with increasing box size. This trend is consistent with earlier observations by Parsons (1936) and Cerato and Lutenegeger (2006), who reported a reduction in the friction angle with the larger box sizes and slight increases in the apparent cohesion.

The decrease in friction angle with increasing shear box size may be attributed to several factors. Larger shear boxes allow for the mobilization of more heterogeneous particle interactions, including potential particle breakage and non-uniform stress distribution along the shear plane (Wu *et al.*, 2008; Li *et al.*, 2021). These effects tend to reduce interparticle locking and thus lower the measured friction angle. Additionally, the larger shear plane in larger boxes can accommodate greater particle rearrangement and dilation, which may dissipate shear strength and result in lower peak friction values (Cantor & Ovalle, 2025).

Conversely, the observed increase in cohesion in larger shear boxes is often attributed to scale effects rather than true soil cohesion (Cerato & Lutenecker, 2006; Bareither *et al.*, 2008). Larger specimens contain more particles spanning the shear plane, which can create localized bridging or interlocking effects, especially in poorly graded sands like those tested in this study. This interlocking can mimic apparent cohesion, even in granular materials with negligible true cohesion. Moreover, boundary effects, such as friction between the soil mass and the shear box walls, can become more significant in larger boxes, contributing to the measured increase in cohesion (Zhou *et al.*, 2009; Deiminit & Li, 2022).

It is also important to consider the influence of relative density. As reported by Cerato and Lutenecker (2006), increasing relative density generally increases the friction angle; however, when the same density is maintained, the scale effect tends to dominate, leading to a reduced friction angle with increased box size. The current study's findings align with this behavior, showing friction angle variations of generally less than  $3^\circ - 4^\circ$  across sizes, indicating that while density influences shear strength, scale effects remain significant.

These results underscore the importance of selecting a suitable shear box size in relation to particle size and gradation for accurate interpretation. For engineering practice, this suggests that results from small-scale tests may overestimate the friction angle and underestimate the cohesion for coarse or poorly graded sands, while large-scale tests may provide more conservative and representative values for field applications.

## 5. Conclusion and recommendations

In this study, sands with nearly identical properties were tested using three different shear box sizes to evaluate the influence of specimen scale on shear strength parameters. The results confirm that shear box size significantly affects both the angle of internal friction and apparent cohesion. Larger and medium-scale boxes consistently produced lower internal friction angles and higher apparent cohesion values compared to small-scale tests. Despite these differences, results across the scales were well correlated, and equations relating shear strength parameters for small and large-scale tests were developed. Additionally, all boxes showed an increase in friction angle and cohesion with increasing density.

From a practical standpoint, these findings suggest the following recommendations for engineering applications:

- Small-scale direct shear tests can provide valuable preliminary data when soil is relatively uniform, particle sizes are fine to medium, and the structure being designed imposes light to moderate loads (e.g., pavements, residential foundations). They are also appropriate for routine laboratory testing when resources or space are limited.

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- Large-scale testing should be preferred when working with coarse-grained soils, poorly graded sands, or materials containing larger particles, as well as for projects involving heavy loads, embankments, retaining walls, or critical infrastructure. Larger boxes better capture particle interlocking, dilation, and stress distribution, producing results more representative of field conditions.
  - Care should be taken to maintain an adequate width-to-particle size ratio (e.g.,  $W/d_{\max} \geq 60$ , as suggested by Deiminiat and Li (2022) to reduce scale-related artefacts.

These recommendations can help practitioners select appropriate testing scales and interpret results more accurately, ultimately leading to safer and more cost-effective geotechnical designs.

**Acknowledgements**

The authors would like to express their sincere thanks to the Geotechnical Laboratory, University of Engineering and Technology, Lahore, for their support.

**Declaration of conflict of interest**

The author(s) declared no potential conflicts of interest(s) with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship and/or publication of this article.

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