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Numerical investigation of box shape effects on soil direct shear test

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Summary The direct shear test is a fundamental method in geotechnical engineering, that provides crucial soil shear strength parameters, including cohesion (c) and the internal friction angle (φ). These parameters play a pivotal role in structural design, slope stability assessment, and soil stability evaluation. However, achieving a uniform normal stress distribution within the shear box remains a challenging task, which can result in inaccuracies in test results. This study investigates the impact of shear box shape, specifically comparing circular and square configurations, on the outcomes of the direct shear test. The findings reveal that the choice of lower or upper box movement has a minimal effect on test results. Moreover, circular boxes demonstrate superior normal stress distribution, leading to reduced variations in comparison to square boxes. Wall friction effects lead to lower shear capacity measurements, with circular boxes yielding higher shear levels when contrasted with square boxes. Additionally, the soil along the sides and corners of the specimen experiences diminished shear stress due to reduced normal stress. This research contributes significantly to our comprehension of how shear box shape influences the determination of shear strength parameters in direct shear tests, ultimately enhancing the reliability of geotechnical engineering assessments.

Keywords: direct shear test, shear strength parameters, box shape, normal stress distribution, finite element modeling

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Introduction

The direct hear test holds significant importance in the field of geotechnical engineering as it provides essential shear strength parameters such as cohesion (c) and the internal friction angle (φ) for various soil types. This data plays a critical role in the design of structures, foundations, slope stability assessments, and overall evaluations of soil stability in diverse engineering projects. For instance, the direct shear test and the shear strength reduction (SSR) method in geotechnical engineering are closely related through the internal friction angle. The SSR method assesses soil slope stability, relying on

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accurate φ determination. Engineers use internal friction angle in SSR simulations to make informed decisions about slope stability and design, effectively mitigating soil slope failure risks [1–5]. In the direct shear test procedure, a soil specimen is typically positioned within a shear box apparatus. Subsequently, the sample is subjected to a constant vertical load while undergoing controlled horizontal displacement or shear deformation. As the horizontal shear force is gradually applied, the specimen experiences shearing along a predetermined plane within the soil sample. Throughout the testing process, the horizontal displacement is increased steadily at a fixed rate until the specimen either fails or reaches a predefined deformation limit. Continuous measurements of shear stress and shear displacement are recorded during the test. Geotechnical experts utilize these data to create shear stress versus shear displacement plots, enabling a thorough analysis of the soil's shear strength characteristics. Nevertheless, one of the primary challenges encountered in this testing procedure pertains to achieving a uniform distribution of normal stress across the soil samples inside the shear box. The presence of non-uniform normal stress distribution can result in inaccurate and unreliable shear strength measurements [6]. Numerous researchers have undertaken both experimental and numerical studies concerning soil direct shear apparatus. Furthermore, certain researchers have put forward adjustments and enhancements to the experimental equipment.

Tsubakihara et al. (1993) [8] conducted laboratory tests to understand how different soils interact with mild steel under specific conditions. The findings showed that the type of soil and its composition influenced the friction behavior. They observed various modes of friction, including sliding at the interface, shear failure within the soil, and a combination of both. Steel surface roughness also played a crucial role in determining whether sliding occurred. Shibuya et al. (1997) [9] designed a novel direct shear box apparatus to analyze sand deformation and examined boundary effects like wall friction and loading platen constraints. Their findings revealed significant errors in estimating average normal stress on the shear plane due to interface friction along the vertical faces of the sample. Liu et al. (2005) [10] investigated the influence of shear box friction on direct shear tests using distinct element method simulations. They found that the internal frictional forces skewed shear strength measurements in both dense and loose samples. The study introduced two modifications to the conventional test setup to mitigate this error, including freeing the upper shear box vertically and pulling it with a flexible rope. Kostkanova et al. (2012) [11] experimentally explored the influence of wall friction on shear strength measurements. They introduced a method to directly measure this friction, offering a solution to enhance the accuracy of shear strength tests, particularly for soft soils. In 2019, Medzvieckas et al. [12] numerically studied the impact of direct shear box device design on soil strength parameter determination. They focused on the distribution of vertical stresses within the soil during testing and the role of friction between the soil and device walls. Initial stress on the shear plane was lower than at the top of the soil sample, but it increased during testing, eventually exceeding the top stress.

The objective of this paper is to demonstrate the direct shear test mechanism for cohesive soil and its shortcomings in normal stress distribution across the shear plane with enhanced detail and deeper insight provided by a 3D finite element model. Our study highlights the significance of wall friction and the impact of box shape on the obtained results.

Numerical modeling

Validation

To create a 3D model for the direct shear test, we employed the finite element method using PLAXIS 3D software [13]. For the development and validation of our numerical model, we drew inspiration from a renowned case study found in "Applied Soil Mechanics with ABAQUS Applications" by Sam Helwani (2007) [7]. This study examines a clayey soil characterized by an internal friction angle of 26.5° and a cohesion value of 9 kPa. Additionally, through the calibration process, Young's modulus and Poisson's ratio were found to be 10 MPa and 0.3, respectively, with the dilation angle assumed to be zero. The direct shear test was modeled as a square box measuring 0.3m x 0.3m x 0.15m and a circular box by 0.15 m in radius and 0.15 m depth, which includes a movable bottom box designed to capture the shear displacement behavior of the soil sample. The modeling process is delineated in several phases:

1. Assembly Phase: In this initial phase, the entire model is set up within PLAXIS. All geometrical and boundary conditions are activated except for the application of the normal stress and moving the bottom box.

2. Normal Stress Phase: Here, the normal stress is activated and applied to the soil sample.

3. Shear Displacement Phase: During this phase, shear displacement is applied horizontally to the lower box.

In terms of boundary conditions, the upper box is fully constrained throughout the simulation, ensuring no movement. Conversely, the lower box remains fully fixed until the shear displacement phase, where it is allowed to move in the x-direction. The complete model setup is presented in figure 1.

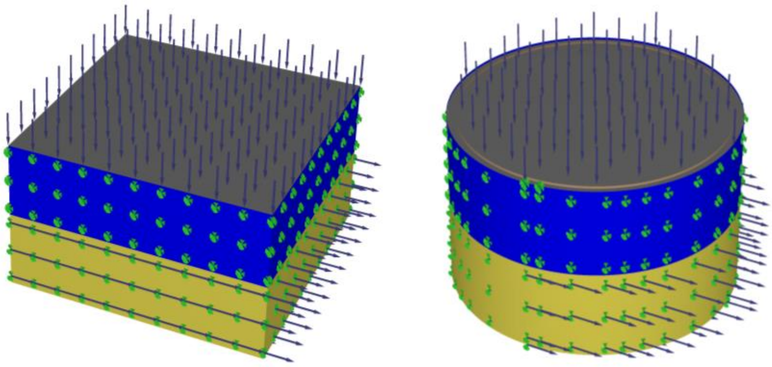

Figure 1: Created model with condition in phase 3 for square and circular shape box

To capture soil behavior during the simulation, we adopted the Mohr–Coulomb failure criterion, a common approach used by other researchers in finite element method modeling of direct shear tests [12, 13]. For the meshing process, a ten-noded triangular mesh was utilized. To evaluate the influence of box shapes on geotechnical properties, both standard rectangular and circular box models were examined. The square box model was comprised of 19,572 elements, with the element size becoming finer, down to a minimum of 2 mm, as it approached the shear plane. The circular box model incorporated 14,800 ten-noded triangular elements, with a minimum element size of 1.5 mm proximate to the shear plane. Figure 2 illustrates the mesh density for both models. Also, mesh sensitivity analysis was conducted, and it was found that using a finer mesh size did not alter the results. It's worth noting that in this study, we solely considered a surcharge load of 50 kPa. An interface element was incorporated into the model to account for the soil-steel box interaction effects. The interface coefficient for the interaction between clay and steel was set at 0.5 [14].

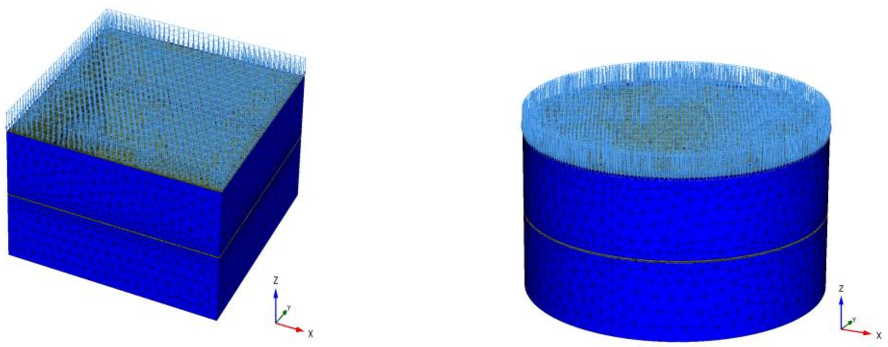

Figure 2: Mesh density and applied normal stress during the second phase for both square and circular box

In the figure 3, the relationship between shear stress and shear displacement for both box configurations and the reference case is depicted. The finite element method (FEM) outcomes demonstrate a notable congruence with the reference data. Notably, the shear response of the circular box exhibits some deviation from the reference, attributable to its lack of corner-induced stress concentrations found in the square box. A more in-depth analysis of this variation will be explored in subsequent sections.

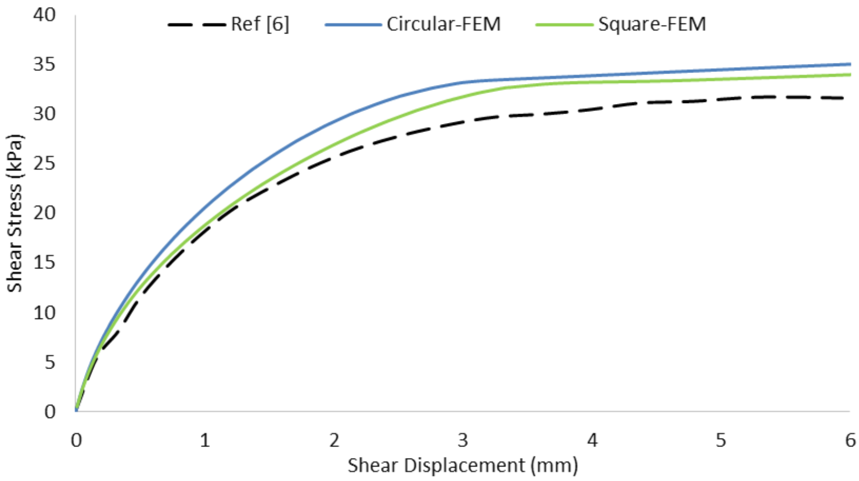

Figure 3: Comparison of shear stress–displacement responses: FEM models vs. reference under 50 kPa normal stress

Parametric study

Effect of Upper or lower Box Movement

In this section we investigated the effect of upper or lower box movements on the results, to aim this in the phase three one time we give the displacement to the lower box and in another model upper box moved to capture the shear stress versus shear displacement behavior. In figure 4 the results are shown for 50 kPa normal stress. As illustrated there is no difference between a model with lower box and upper box movements, as both states can be used without effecting the results.

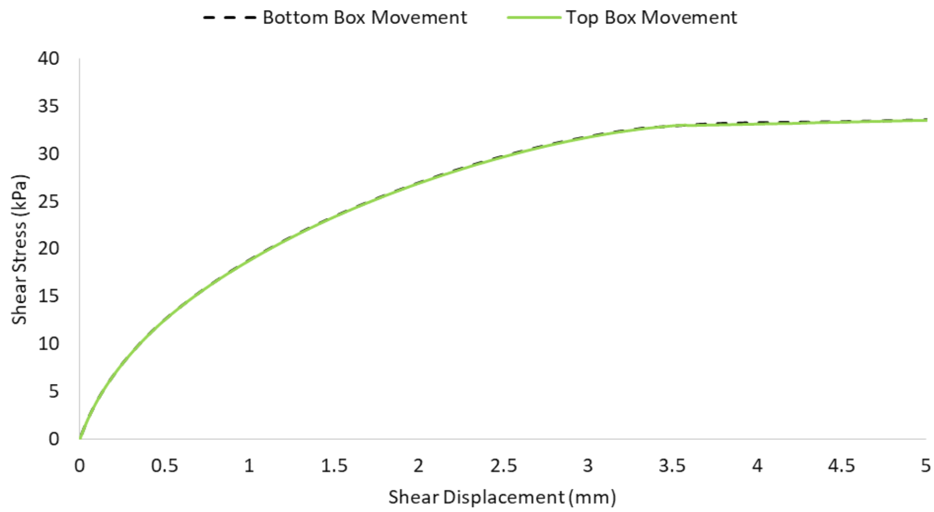

Figure 4: The upper and lower box movement effect on the shear stress result

Effect of friction on the normal stress distribution

Here we investigated the friction coefficient effects on the distribution of induced normal stress on failure plane for the two box shapes. In figure 5 the normal stress on shear planes for both the circular and square box are presented. It can be seen that close to the wall and corners the normal stresses reduced significantly due to the friction.

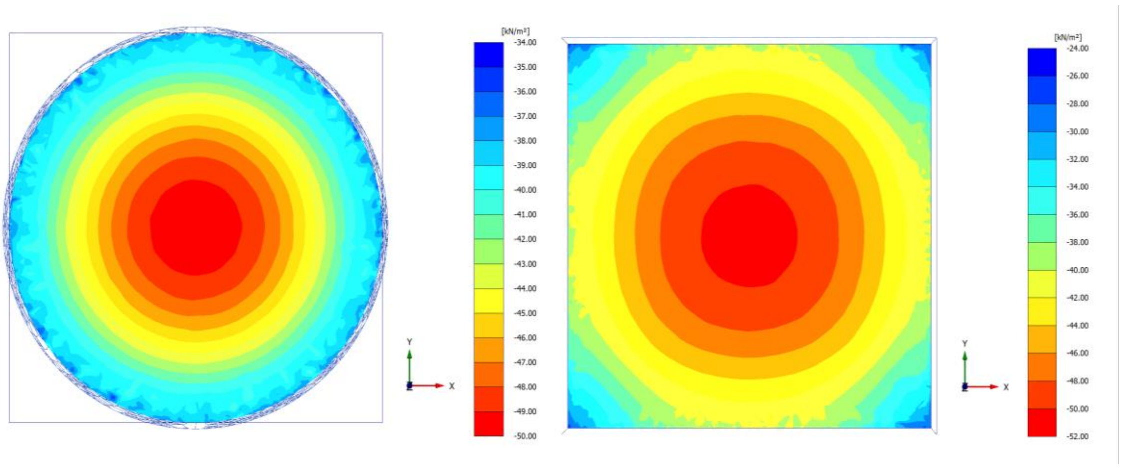

Figure 5: Normal stress distribution with 50 kPa surcharge load and 0.5 as the friction coefficient in both circular and square box

In the bar charts below, the normal stress on the different locations of the soil sample in the box is presented under different friction coefficients. Results presented in figures 6 and 7 are extracted for the clayey soil under 50 kPa surcharge load.

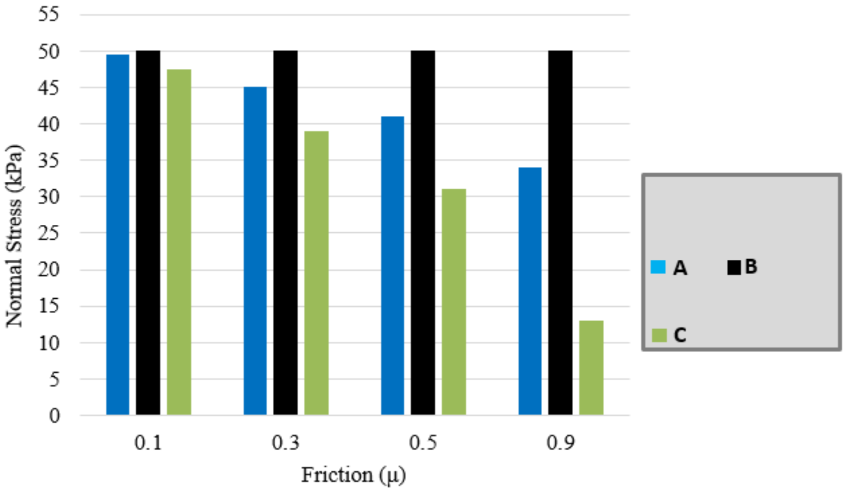

Figure 6: Normal stress on soil sample in square box under 50 kPa surcharge load for different friction coefficients

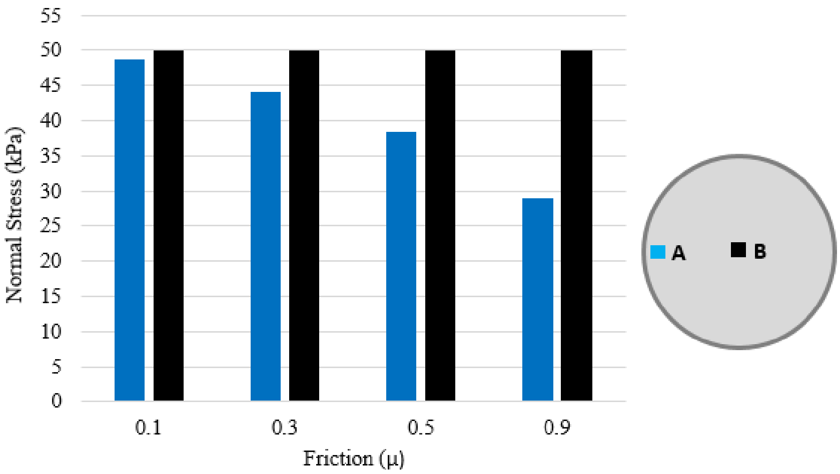

Figure 7: Normal stress on soil sample in circular box under 50 kPa surcharge load for different friction coefficients

As can be seen from the bar charts, the reduction of normal stress on the sides of both boxes is very similar in both circular and square shapes. However, the corners of the square box reduce the normal stresses significantly due to the interaction of the soil with the box walls on both sides. This indicates that the circular shape, by eliminating corner effects, provides a more uniform applied normal stress on the shear plane compared to the square shape, resulting in more realistic results. As presented, the center was not affected by the wall friction in both box shapes.

Shear stress inside samples

In figures 8 and 9, the shear stress behavior of the two boxes are presented. It can be seen that soil on corners and side wall meets its maximum shear capacity in a lower stress level owing to less normal stress affected on their parts.

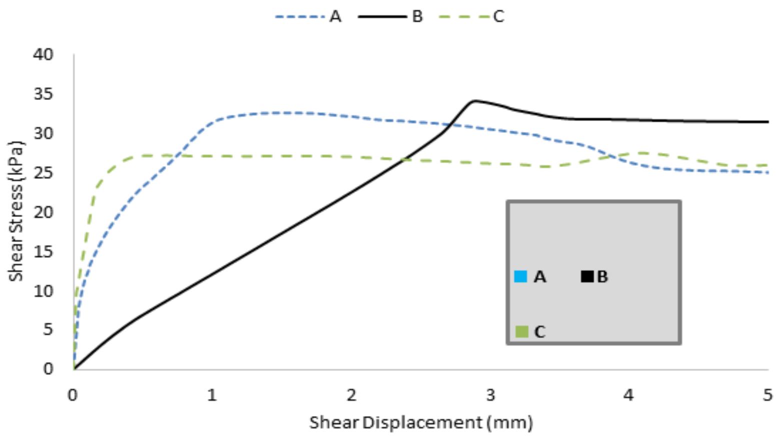

Figure 8: Shear stress versus displacement inside square box under 50 kPa surcharge load and friction coefficient of 0.5

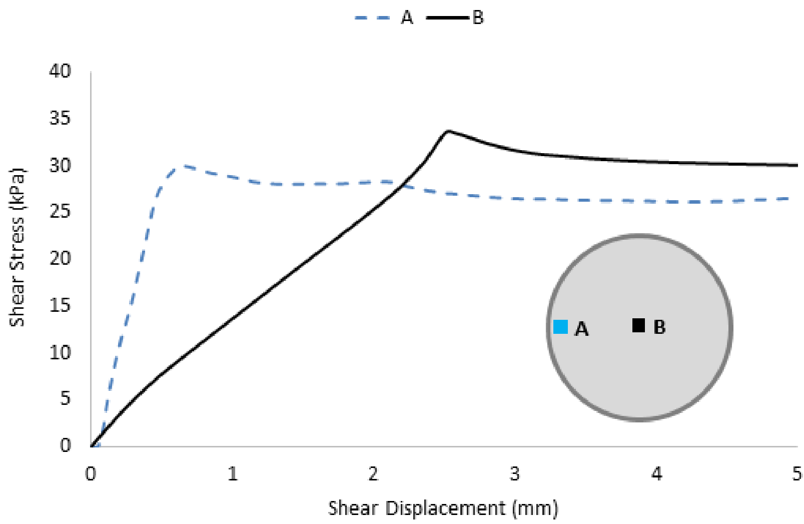

Figure 9: Shear stress versus displacement inside circular box under 50 kPa surcharge load and friction coefficient of 0.5

The distribution of shear stress across the shear surface is non-uniform. Consequently, shear failure initiates earlier at the sides and corners than it does at the center of the soil. This phenomenon aligns with Terzaghi's analogy of the process being akin to tearing a piece of paper, where the entire shear surface does not experience shear failure simultaneously. In the area near the box wall, where normal stress is not uniform, the affected zone is smaller compared to the region with more constant normal stress. As a result, we can conclude that the shear capacity of the soil in the direct shear apparatus is slightly underestimated.

Effect of different surcharge loads on normal stress

In this section, we examined the induced normal stress on both the sides and the center of a circular soil sample under various surcharge loads. Figure 10 illustrates that the differences between the normal stresses at the center and the sides are 55%, 30%, and 24% for surcharge loads of 10 kPa, 30 kPa, and 50 kPa, respectively. This suggests that wall friction has a more pronounced effect on tests with lower normal loads. It can be concluded that the direct shear test tends to provide more accurate and realistic results for soil in deeper or heavily loaded positions, as these tests are conducted under higher normal loads.

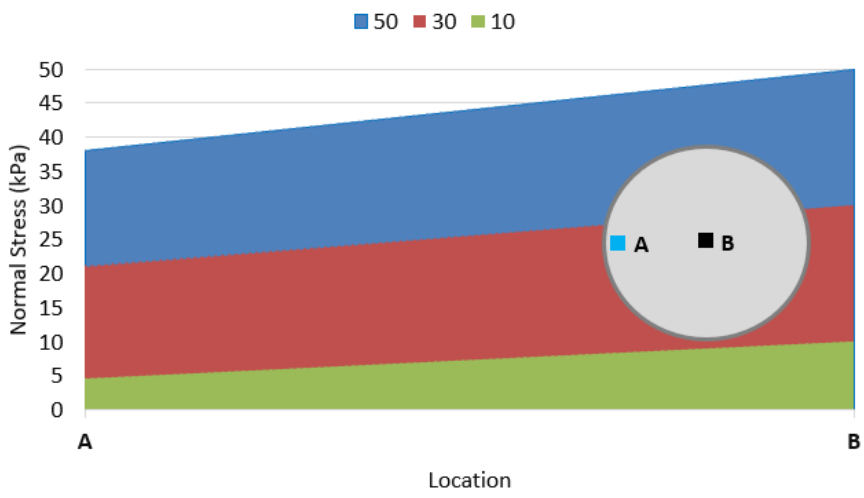

Figure 10: Normal stress distribution within a circular sample at the center and corner, under varying normal loads

Conclusion

In this research we numerically investigated two common box shapes, circular and square, to evaluate their merits and disadvantages countering wall friction effects. The outputs are as follows:

- There is no difference between an apparatus with lower box movement and upper box movement.
- Circular box has better normal stress distribution over shear surface and less normal stress difference than square box. In our study, for a circular box under a 50 kPa surcharge load with a friction coefficient of 0.9, the minimum normal stress induced on the shear surface was 29 kPa, and at the center, it was 50 kPa. In the case of a square box, the corresponding values were 13 kPa and 50 kPa, respectively.

- Friction effects make the test to give less shear capacity than reality, and this is the reason circular box gives higher shear level through a test compared to a square box test.
- Soil on the sides and corners yield with a lower shear stress owing to smaller normal stress compared to the center of the sample.
- Direct shear tests yield more accurate shear parameters for soil samples with higher normal stress, while tests with lower normal stress are affected by wall friction and produce less accurate results.

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