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COAST
JOURNAL OF THE SCHOOL OF SCIENCE
November, 2025 ISSN: 2714-3716
Coast, J. Sch. Sci. 7 (2): 1610 - 1621

DEVELOPMENT OF A LOW-COST DIRECT SHEAR BOX MACHINE FOR ASSESSMENT OF SHEAR STRENGTH OF SOILS

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https://dx.doi.org/10.4314/coast.v7i2.4

Abstract

The shear strength of soils is a critical parameter in geotechnical engineering, influencing the design and stability of structures such as foundations, retaining walls, and slopes. The traditional soil testing methods face challenges related to accuracy, repeatability, and ease of operation. It is against these drawbacks that this paper presents a novel design, development, and fabrication of a direct shear box machine leveraging locally sourced materials to improve precision, user-friendliness, and reliability. A three-stage approach was adopted, which includes the design stage, the fabrication stage, and the assembly, installation, and calibration stage. At the design stage, emphasis was placed on mechanical re-engineering, innovation, automation, and validation against standard testing methods. The development phase considered the choice of tooling, ease of processing, and product quality in carrying out soil tests both in the laboratory and field with minimal stress. The fabrication phase entails the fabrication of parts and components of the designed shear box machine, while the third stage entails the assemblage, installation, and calibration of the fabricated parts and components. The developed device, when deployed for soil testing results showed a linear relationship, such that as the load increases, the deflection increases in a similar manner, and was found to be consistent with the expected statutory range with superior performance in terms of precision, accuracy, and repeatability. The developed machine cost N1,700,000.00 as against the importation price, which stood at N2,500,000.00, leading to a saving of N800,000.00. This innovative device is therefore a good substitute for traditional approaches and also a source of internally generated revenue for Olusegun Agagu University of Science and Technology, Okitipupa, Ondo State, Nigeria.
Keywords: Shear Box Machine, Soil Shear Strength, Shear Strength, Force and Deflection

Introduction

The assessment of soil shear strength is fundamental for geotechnical engineering applications and in many engineering problems, such as the design of foundations, retaining walls, pipes, sheet piling, slab, and bridges, etc., the value of the angle of internal friction and cohesion of the soil involved are required for optimized design (Stefanow and Dudziński (2021), Opeyemi et al., (2011)). These parameters can be quickly predicted using the direct shear test (Giwangkara et al., (2020), Opeyemi et al., (2015)). The direct shear test is an experimental procedure conducted in geotechnical engineering practice and research that aims to determine the shear strength of soil materials (Stefanow and Dudziński (2021), Opeyemi et al., (2015)). Shear strength connotes the maximum resistance that a material can withstand when subjected to shearing, while shear, on the other hand, is regarded as the force that causes two touching parts of the same body to slide parallel to their plane of contact (Hamada et al., 2020), Afolayan and Opeyemi, 2010). Testing a material's shear strength is important, as it determines one's choice of tooling, ease of processing, and product quality.

The most common use of a shear test is to determine the shear strength, which denotes the maximum shear stress that the material can withstand before failure occurs (Opeyemi et al., (2015)). This shear test is considered as one of the most common and simple tests to derive the strength of a soil and can be performed on undisturbed or remoulded samples. Shear box assemblies are manufactured from brass and steel and designed to contain the water that surrounds the specimen. This consists of a square box with a rigid-walled round or square hole, complete with adapter loading pad, retaining plate, two (2) grids, two (2) perforated grids, and two (2) porous plates, etc. The direct shear tests are favored for their simplicity and ability to directly measure the shear resistance of soils under applied normal load conditions. The direct shear test methodology dates back to the early 20th century (Höffgen et al., (2023)) providing insights into the behavior of soils under shear loading.

Several advancements have been made so far, and some of them are reviewed in this section. For instance, Coulomb in 1976 used the direct shear test for the first time, and it is one of the oldest shear strength determination tests for cohesive consolidated soil (Stefanow and Dudziński, (2021)). Shear strength is a mixture of sand and gravel, which is one of the most important issues in geotechnical engineering, but because of the effects of the dimension of experimental specimens, most studies are performed by eliminating coarse grains (Babaei (1999), Davies and Le Masurier (1997)). Also, other studies have discussed the effects of coarse grains on density, shear strength, and soil shape deformation traits by presenting the concept of density (Fragaszy et al., (1990), Fragaszy et al., (1990)). Furthermore, researchers (Kokusho et al., (2004) and Vallejo (2001)) worked on increasing strength by increasing coarse grains.

Similarly, research on grain shape effects on the shear strength of soil was studied by Yagiz (2001), and the outcome of their research shows that sharp-corner grains of gravel cause an increase in shear strength of sandy soil against round-corner grains. On the other hand, the research of Barr et al., (1991) delved into errors of correcting grading on seven (7) different specimens gathered from coarse grains in Tehran under optimum proctor humid conditions, and equal dry weight, were studied, and their correlations have been presented. Furthermore, there are instances of the development of large shear box apparatus in the literature, which were used to investigate different aspects of material behaviour and geotechnical problems (Jain and Gupta 1971), Pedley (1990), and Krahn (2001). Similarly, ASTM International (2017) developed ASTM D3080 / D3080M-11 as the standard test method for the direct shear test of soils under consolidated drained conditions, but the cost of procurement is exorbitantly higher, which is one of the major shortcomings limiting its wide usage (ASTM International. (2017), ASTM D3080/D3080M (2011).

The review of the development and deployment of the shear box machine for assessing the shear strength of soils from the inception opens up some gaps that are pushing for its local development, and some of these challenges include non-readily availability of the device for use in the laboratory or field, both for the training of civil engineering students and for real field applications. Also, many of the existing shear box machines often suffer from limitations such as non-uniform stress distribution, difficulty in controlling strain rates, and manual measurement inaccuracies. The foreign-made shear box machines are relatively too expensive, making them out of reach for the common man and many growing universities. It is on this background that its local fabrication becomes a necessity. This locally made shearbox will help to achieve direct measurement of the shear strength of soil samples with a relatively easy testing procedure, in addition to simple and easy sample preparation, where almost all soil types can be tested, and both peak and residual shear strength can be determined with minimal stress but with high precision, accuracy, and repeatability.

Materials and Methods

Design and Development

At the design stage, the key innovations embedded within design device include integration of digital sensors for precision measurement of force and displacement, automated data logger with a software interface that helps in facilitating real-time monitoring of the device during shear strength assessment, and enhanced selection of materials for the fabrication of components and parts, which helps to reduce and minimize friction and wear during deployment. Also, the developed direct shear box machine consists of a vertically split shear box held in a rigid frame, with a servo-controlled motor to apply horizontal force. The normal load is maintained constant using a mechanical actuator.

The general procedural steps deployed to achieve the design and implementation of this direct shear box machine with these enhanced features include definition of machine requirements, design phase, material selection phase, fabrication phase, testing procedures phase, validation phase, and documentation phase.

i). Define Requirements:

This stage critically looked into specific requirements of the direct shear box machine for shear strengths, and the maximum loads it should withstand when deployed for all kinds of soils, such as loamy soil, sandy soil, and clay soil, among others.

ii). Design Phase:

This design phase involved frame design, shear box assembly, load application system, displacement measurement, and safety features. The frame design considers the selection of materials that are not only sturdy but also can handle all kinds of loads. The shear box assembly looked into designing of shear box assembly that will hold the soil sample to be tested for shear strength, and this typically includes upper and lower halves with a shear plane in between. The load application system was designed for applying normal and shear loads to the soil sample. The displacement measurement design for the developed machine measures the displacements during shearing. Also, safety features were incorporated to facilitate emergency stops and protective shields.

iii). Material Selection:

This stage entails the choice of appropriate materials for each component, considering factors like strength, durability, and compatibility with soil testing procedures.

iv). Fabrication:

This entails the fabrication of the machine frame according to the design specifications. Shear box assembly fabricates the upper and lower halves of the shear box, ensuring they fit together accurately and securely. The load application system sees to the fabrication of the mechanisms for applying normal and shear loads. The displacement measurement looked into the installation of digital sensors for accurate displacement measurement. The assembly sees to assemble all components according to the design, while the calibration ensures accurate measurements of the shear strength of the direct shear box machine.

v). The testing procedures phase

This stage develops the procedures for conducting shear strength tests on soils using the direct shear box machine, and this includes preparing soil samples, applying loads, and recording measurements.

vi). The validation phase:

This phase was designed to validate the performance of the direct shear box machine by testing it with known soil samples to compare results with established standards or theoretical calculations.

vii). The documentation phase:

This phase documented the procedures involved in design, fabrication, calibration, testing procedures, and validation results for future reference and to comply with any standards or regulations.

Throughout these steps, experts in soil mechanics and mechanical engineering were consulted to ensure that the direct shear box machine meets industrial standards and provides reliable results. Also, Table 1 shows different parts of the direct shear box fabricated in terms of quantity and specifications, which were strictly followed during hardware implementation. Also, their pictorial representation of some of these parts, such as Moulds, Base plate, Porous disc, Dial gauge indicator, Gear box assembly, Bolts and nuts, Slotted weight, and Frictionless balls, is shown in Appendix A

Table 1. Parts of the direct shear box apparatus and specifications

S/N	Name	Qty	Specifications
1	Detachable frame	3	150mm x 50mm x 1000mm L U channel MS steel section
2	Weight holder	1	150mm diameter x 10mm thick MS plate
3	Rail	2	20mm x 20mm 180mm MS square bar grooved
4	Set of Load hanger	1	250mm x 40mm 850mm long
5	Box	1	200mm x 120mm x 70mm thick bronze
6	Moulds	2	60mm x 60mm x 19mm thick bronze
7	Base plate	1	60mm x 60mm x 5mm thick bronze
8	Porous disc	2	60mm x 60mm x 3mm thick bronze
9	Loading yoke	1	60mm x 60mm x 10mm thick bronze
10	Proven ring holder	2	30mm x 40mm 120mm T bar
11	Proven ring	1	5 kN capacity
12	Dial gauge indicator	1	0-10mm (0.001) resolution
13	Push rod	1	10mm x 30mm SST
14	Gear box assembly	1	1: 10 reducer ratios
15	Alen bolts	4	M8 x20 (8.8)
16	Bolts and nuts	8	M10 x 50mm (8.8)
17	Bolts and nuts	1	M12 x 75mm (8.8)
18	Slotted weight	3	10kg capacity
19	Frictionless balls	12	10mm diameter SST ball
20	Ball guide	2	15mm x 180mm x 5mm thick flat bar

Operational Mechanism

The shear box comprises two halves containing the soil specimen. A normal load is applied, and the horizontal force is incremented until the soil fails in shear. The use of high-resolution sensors improves the accuracy of force and deformation measurements, with the system calibrated against known standards.

Design Computations

These stages consider the computation of tangential force and proving the Ring factor (S). The straight line between the shear resistance against normal vertical load was computed using equation Eqn(1);

$$s = C + n\tan \qquad (1)$$

Where: s = horizontal force divided by the area (A) of the cross section of the soil specimen, i.e., the unit shear resistance, C = cohesion per unit area, the horizontal shear force under no vertical load (The cohesion for a granular soil (dry sand) is zero), n = vertical normal load per unit area, and θ = angle of shearing resistance or the angle of internal friction. Also, the proving ring factor (S) was computed using Eqn(2), thus;

$$S = \frac{\Delta y}{\Delta x} \qquad (2)$$

$$S = \frac{0.0392 - 0.01962}{0.64 - 0.32}$$

$$= 0.0613 \text{kN/Div}$$

Results and Discussions

The developed direct shear box

Shown in plates 1 to 3 are the different sectional views of the developed and fabricated direct shear box machine enhanced with precise digital sensors for force and displacement measurement, automated data logging with a software interface for real-time monitoring, and enhanced material selection for reduced friction and wear.

Plate 1: Top view of the Shear Box Machine

Plate 2: Assemblage of the Shear Box Machine

Plate 3: Assemblage of the Shear Box Machine (side view)

Discussion of the operational performance of the developed direct shear box

In the shear box test, failure is caused in a pre-determined plane of the soil, and the shear strength or shearing resistance, and the normal stress are both being measured directly, as it is a direct shear machine. The essential feature of the apparatus is a rectangular box divided horizontally into two halves; the lower half box is fixed, and the upper half is movable. The soil to be tested is enclosed in the two half boxes, and porous stone plates or metal plates are placed above and below the specimen. While a constant vertical compressive force is applied, a gradually increasing horizontal force is applied to the upper half of the box, thus causing the soil prism to shear along the dividing plane of the box. This measures the horizontal load required to shear a soil corresponding to any vertical normal compressive load.

Performance testing of the developed direct shear box

Different soil specimens of capacities 1kg to 5kg were used to test shear strength capacity, The test is repeated on other identical specimens under different vertical loads, and the results are plotted as shearing resistance against normal vertical load (shear stress is plotted vertically and the normal stress horizontally), and a line of best fit is drawn through the points using Equation (2) above.

Table 2 presents the results of the initial tests conducted with the developed and fabricated machine under different loading conditions, which range from 1kg to 5kg, the corresponding deflection and the force developed are also shown in Table 2.

Table 2: Initial tests for machine's performance

Load (kg)	Deflection DF (Div)	Force (KN)
1	0.16	0.00981
2	0.32	0.01962
3	0.48	0.02943
4	0.64	0.03924
5	0.80	0.04905

Also, the relationship between the force and the deflection was as shown in Figure 1, which shows a linear relationship as the force increases, the deflection also increases accordingly.

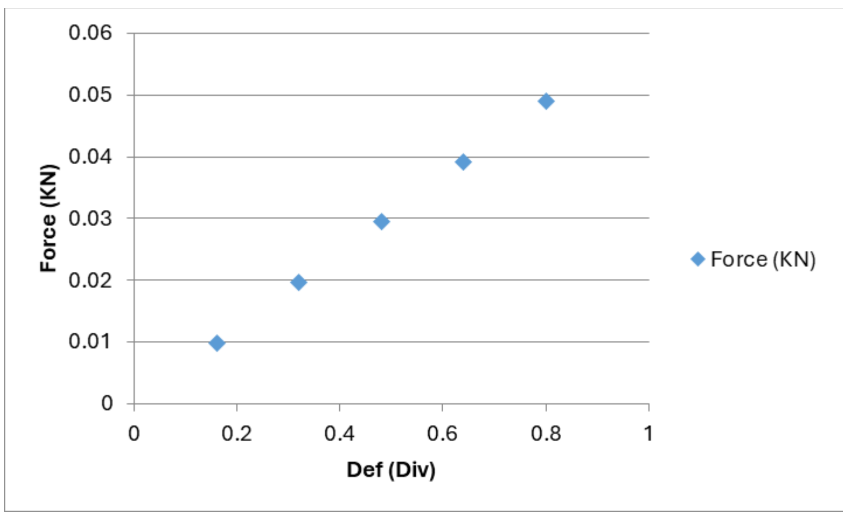


Figure 1. The plot of Force vs Deflection

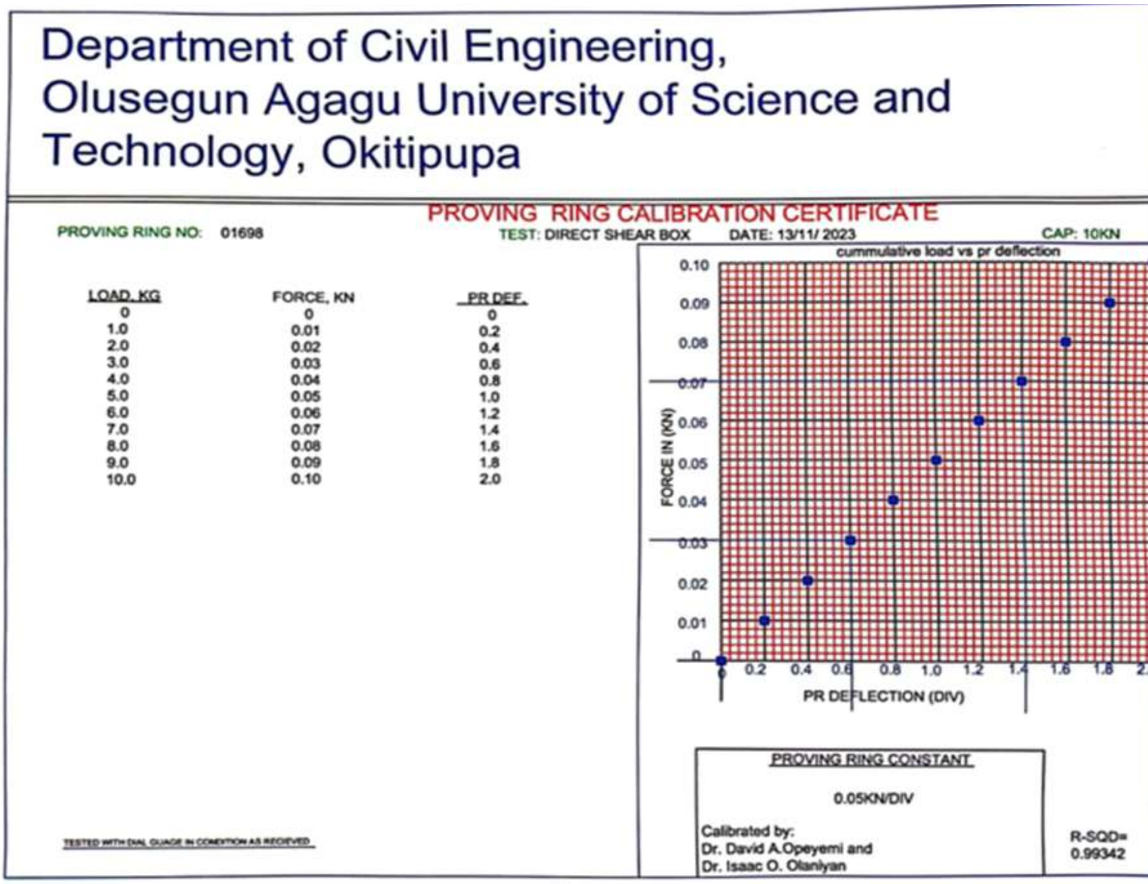
Table 3 presents the results of the deployment of the developed and fabricated device for conducting three different test scenarios. The loading varies from 10kg to 30 kg in steps of 10kg; the corresponding force and the deflection produced are also shown.

Table 3 Test Result and Calculation

Test	Load (kg)	Deflection (Div)	Force (KN)
1	10	2.0	0.123
2	20	2.7	0.166
3	30	3.6	0.221

Calibration and Validation: Case Study

The initial tests were conducted using standard sand and clay samples to verify the machine's performance. Calibration involved comparing measured results with those from established direct shear devices. The machine demonstrated consistent results with minimal variance, validating its accuracy. Also, three case studies involving different soil types under varying conditions are presented, demonstrating the machine's efficacy in diverse scenarios. The results obtained using the developed and fabricated machines show reliable and repeatable measurements across multiple test runs.



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PROVING RING CALIBRATION CERTIFICATE

PROVING RING NO: 01698 TEST: DIRECT SHEAR BOX DATE: 13/11/ 2023 CAP: 10KN

LOAD, KG	FORCE, KN	PR DEF.
0	0	0
1.0	0.01	0.2
2.0	0.02	0.4
3.0	0.03	0.6
4.0	0.04	0.8
5.0	0.05	1.0
6.0	0.06	1.2
7.0	0.07	1.4
8.0	0.08	1.6
9.0	0.09	1.8
10.0	0.10	2.0

PROVING RING CONSTANT

0.05KN/DIV

Calibrated by:
Dr. David A.Opeyemi and
Dr. Isaac O. Olaniyan

R-SQD= 0.99342

TESTED WITH DIAL GUAGE IN CONDITION AS RECEIVED

Plates 4: Proving ring calibration certificate.

It was observed that the developed and fabricated shear box machine addresses many limitations of traditional designs, offering improved accuracy, automation, and user interface. Interpretations of test results suggest enhanced reliability and potential for broader applications in geotechnical investigations.

Conclusions

This paper developed a low-cost direct shear box machine for the assessment of the shear strength of all kinds of soils. The developed machine was enhanced with the integration of digital sensors for precision measurement of force and displacement, an automated data logger with a software interface that helps in facilitating real-time monitoring of the device during shear strength assessment, and selection of materials for the fabrication of components and parts, which helps to reduce and minimize friction and wear during deployment. The developed machine resulted in saving a substantial amount of money relative to buying a foreign-made direct shear box machine, solving the problem of non-readily availability to low-income artisans and many growing universities. Also, the developed machine addresses the problems of non-uniform stress distribution associated with the traditional shear box machines, producing a linear relationship between the loading and deflection. Also, it equally showed superior performance in terms of precision, user-friendliness, and reliability when deployed for shear strength assessment of different kinds of soils.

Acknowledgements

The authors would like to appreciate the Tertiary Education Trust Fund (TETFund), Nigeria for the Institutional Based Research (IBR) grant and the Management of the Olusegun Agagu University of Science and Technology, Okitipupa, Nigeria.

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Appendix A

Component & Description	Pictorial Representation
Moulds (60mm x 60mm x 19mm thick bronze	
Porous disc (60mm x 60mm x 3mm thick bronze)	
Dial gauge indicator (0-10mm (0.001) resolution)	

Gear box assembly (1: 10 reducer ratios)	
Bolts and nuts (M10 x 50mm (8.8))	
Bolts and nuts (M12 x 75mm (8.8))	
Slotted weight (10kg capacity)	
Frictionless balls (10mm diameter SST ball)