

Development and Evaluation of a Portable *In Situ* Direct Shear Testing Device for Field Applications

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Abstract Soil sample disturbances leading to a decline in sample quality have long been a concern in geotechnical investigations. This research addresses these issues by developing and evaluating a portable *in situ* direct shear testing apparatus for field assessments of soil shear strength. The study was conducted in a landslide-prone area in Margawati village, Garut district, West Java, Indonesia, and was motivated by the limitations of conventional laboratory methods, particularly their susceptibility to sample disturbance. Multiple *in situ* tests were carried out to assess the reproducibility of shear strength measurements under varying normal stress conditions. The apparatus was tested with both *in situ* and reconstituted samples, allowing for a comparative analysis with conventional laboratory direct shear tests. The results indicated that *in situ* tests consistently yielded slightly higher peak shear strength values than laboratory tests, likely due to the minimal disturbance of natural soil samples. This research highlights the importance of considering sample disturbances in geotechnical testing and suggests that *in situ* testing offers a valuable complement to laboratory methods, providing more reliable data for geotechnical analysis and design. The findings have significant practical implications for field engineers, particularly in slope stability analysis, foundation design, and landslide risk assessment. The portable nature of this device makes it especially valuable for challenging terrain where conventional testing

equipment cannot be deployed, and it can be adapted for various soil conditions, including sandy soils, clayey soils, and areas with fluctuating water tables. The findings emphasize the potential of the *in situ* direct shear apparatus to significantly enhance the accuracy of soil shear strength evaluations, particularly in field settings where sample integrity is critical.

Keywords *In Situ* Direct Shear Test, Soil Shear Strength, Sample Disturbances, Portable Testing Device, Field Geotechnical Investigation

1. Introduction

A detailed and adequate investigation of soil conditions in the field can help identify soil characteristics and environmental conditions. This information can then be used in the development of disaster risk mitigation strategies, such as appropriate land use planning, the selection of suitable mitigation technologies, and pre- and post-disaster mitigation actions. One of these investigations involves geotechnical conditions, such as the physical properties of soil, slope measurements, groundwater levels, pore water pressure, and soil shear strength. Soil shear strength is the ability of soil to resist shear forces or forces applied parallel to the soil surface.

Soil shear strength is crucial in geotechnical studies as it determines the soil's ability to withstand loads and pressures applied to it. Challenges encountered in soil shear strength testing include obtaining non-representative test results that can affect the accuracy of geotechnical analysis and structural planning.

The impact of sample disturbance on geotechnical test results is substantial and well-documented. Recent studies have shown that sample disturbance can reduce undrained shear strength by 15-40% in soft clays and alter consolidation characteristics significantly [1][2]. In a comprehensive review of 150 geotechnical projects, it was demonstrated that sample disturbance was responsible for foundation design errors in approximately 23% of cases, leading to cost overruns averaging 18% of project budgets [3]. Furthermore, it reported that even "high-quality" tube samples exhibited a 12-25% reduction in cyclic resistance compared to frozen samples, highlighting the pervasive nature of this problem even with best practices [4]. Disturbances in soil samples can result from careless soil sampling and transportation, weather or environmental influences, and other factors.

One frequent challenge faced is the difficulty in obtaining representative soil samples. This can be attributed to various factors, such as differences in soil conditions at each sampling location and disturbances occurring during the sampling and handling process. Another issue in geotechnical field investigations is the difficulty in mobilizing large and heavy testing equipment, posing constraints on sample collection or testing at certain locations due to inaccessibility.

1.1. Sample Disturbance Mechanisms and Impacts

The impact of disturbances on the measured properties of soil has long been recognized. These disturbances arise from five mechanisms: changes in stress conditions, alterations in soil structure, shifts in water distribution and void ratio, chemical changes, and the mixing and segregation of soil components [5]. The consolidation process for clayey soil samples during handling should be considered in terms of the measured relative volume reduction, which indicates the quality of the tested soil. The greater the change in relative volume, the poorer the quality of the sample [6]. The mechanisms causing disturbances in a sample can be ordered chronologically based on the sequence from sampling to the actual testing of the sample [7]: (a) Changes in soil conditions at the front of the borehole during the drilling operation; (b) Penetration of the sampling tube and retrieval of the sample from the soil surface; (c) Redistribution of water content within the tube; (d) Extrusion of the sample from the tube; (e) Drying and/or changes in water pressure; and (f) Trimming and other activities necessary to prepare the specimen for laboratory testing. Disturbances in the sample will impact both the strength and compressibility [1][8][9][10], as well as the dynamic properties of the

tested soil [2][11][12].

1.2. *In Situ* Testing as a Solution and Research Gap

Given the substantial evidence of sample disturbance impacts, there is a clear need for testing methods that minimize or eliminate sample handling. While *in situ* testing methods exist, they are typically large, expensive, and require specialized transportation and setup. This creates a critical gap: field engineers working in challenging terrain—such as landslide-prone slopes, remote areas, or sites with limited access—lack portable, cost-effective tools for direct measurement of shear strength parameters.

As one alternative to reduce disturbances in soil samples, researchers opt to conduct direct field testing. With this approach, it is expected that the obtained data will be more representative and reflect the actual characteristics of the soil in the field. This step is taken to ensure that the test results have stronger relevance to the real conditions at the research site, which, in turn, enables more effective utilization of the data in a design context. In many practical situations, even for large projects where comprehensive sampling and affordable laboratory testing are feasible, *in situ* testing can provide valuable validation data.

Previous research has explored *in situ* direct shear testing for specific applications. An *in situ* direct shear device for rockfill materials has been developed, demonstrating the feasibility of field testing but with equipment too large for routine geotechnical investigations [13][14]. Field direct shear tests on backfill slopes were conducted [15]; however, the apparatus required substantial site preparation and could not be easily relocated. These studies validated the concept of *in situ* shear testing but also highlighted the need for more portable and versatile equipment.

1.3. Novel Contribution of This Research

The present study addresses this research gap by developing a portable, compact *in situ* direct shear testing device that differs from existing equipment in three key aspects:

First, the device weighs only 45 kg and can be disassembled into components transportable by a two-person team, enabling access to steep slopes and remote locations. Second, it incorporates a simplified setup procedure requiring only 30-45 minutes, compared to 3-4 hours for conventional *in situ* equipment. Third, it achieves comparable accuracy to laboratory tests ($\pm 5\%$ variation in repeated measurements) while eliminating sample disturbance entirely. Table 1 is a comparison of the proposed device with existing *in situ* testing equipment.

The primary objective of this research is to develop, validate, and demonstrate the field application of this portable *in situ* direct shear testing device, with specific focus on landslide-prone slopes where sample quality is critical, and equipment access is limited.

Table 1. Comparison of Proposed Device with Existing *In Situ* Testing Equipment

Feature	Conventional Lab Direct Shear	Large <i>In Situ</i> Devices (Liu, 2009)	Proposed Portable Device
Weight	15-25 kg (excluding sample)	150-300 kg	45 kg
Setup Time	N/A (requires sampling)	3-4 hours	30-45 minutes
Portability	High (but requires sampling)	Requires vehicle access	Man-portable to remote sites
Sample Disturbance	High (sampling + transport)	Low	Minimal
Normal Stress Range	50-500 kPa	50-1000 kPa	50-600 kPa
Cost (approximate)	\$5,000-8,000	\$25,000-40,000	\$8,000-12,000
Accessibility	Any location with lab	Vehicle-accessible sites only	Includes steep slopes, remote areas

2. Materials and Methods

2.1. Study Site Description and Selection Rationale

The study was conducted in Margawati village, Garut district, West Java, Indonesia (7°14'23"S, 107°53'41"E, elevation 680-720 m above sea level). This site was selected based on four critical criteria:

Geological Context: The area is situated within the Cikapundung Formation, characterized by Quaternary volcanic deposits including tuff, volcanic breccia, and weathered andesite. The region has experienced active volcanism and tectonic activity, resulting in highly weathered soils with complex engineering properties. Geological mapping indicates the presence of residual soils derived from andesitic parent material, with weathering profiles extending 5-15 meters in depth.

Geotechnical Characteristics: Preliminary investigations revealed predominantly silty clay soils (CL classification per USCS) with liquid limits ranging from 42-58%, plastic limits of 22-31%, and natural moisture contents of 35-48%. The soil exhibits moderate to high plasticity with clay fraction (< 2 μ m) comprising 25-35% by weight. *In situ* density measurements indicated unit weights of 16.8-18.2 kN/m³ with void ratios of 0.85-1.12.

Landslide History: The site has documented landslide activity with three significant events recorded in the past 15 years (2008, 2015, and 2019). The 2019 landslide affected approximately 2.3 hectares, displaced 47 families, and caused infrastructure damage estimated at \$1.2 million USD. Failure surfaces from previous landslides were identified at depths of 2.5-4.5 meters, corresponding to the weathered soil-bedrock interface. This history makes accurate shear strength determination critical for slope stabilization design.

Accessibility Challenges: The landslide-prone slopes have gradients of 28-35°, with limited vehicle access. Conventional *in situ* testing equipment cannot be deployed without significant site modification, making this an ideal

location to demonstrate the advantages of portable testing equipment.

Hydrogeological Conditions: Groundwater monitoring indicated seasonal fluctuations with water table depths varying from 1.5 m (wet season) to 4.5 m (dry season) below ground surface. Permeability tests suggested low hydraulic conductivity (1.2×10^{-7} to 4.8×10^{-7} m/s), characteristic of silty clay materials. These conditions contribute to elevated pore pressures during rainfall, a primary landslide trigger mechanism in the area.

2.2. Development of Portable *In Situ* Direct Shear Testing Device

Direct shear test (DST) is one of the oldest and simplest methods for determining the shear strength parameters, c and ϕ , of soil. This test allows for the direct and quick measurement of soil shear strength under conditions without drainage or in terms of total stress. While initially designed for non-cohesive soils, it has evolved to be applicable to cohesive soils as well. The basic principle of this test involves applying horizontal shear stress to a soil sample through a shear box or ring at a constant rate until failure occurs. Meanwhile, a vertical load is applied to the soil sample at a constant rate throughout the test. Strain readings are taken at regular intervals during the test, and simultaneous readings of shear stress are taken at corresponding strain readings. This process allows for the creation of a graph depicting the relationship between strain and shear stress.

A vertical force (σ_n) is initially applied to the top of the box, followed by a progressively increasing horizontal load (shear force) that induces the upper frame to slide over the bottom. This results in the soil shearing along the plane delineated by the separation between the top and bottom of the shear box. With an increasing displacement of the upper frame, the force needed to further the displacement rises, reaching a maximum point commonly known as the 'peak value (Figure 1).

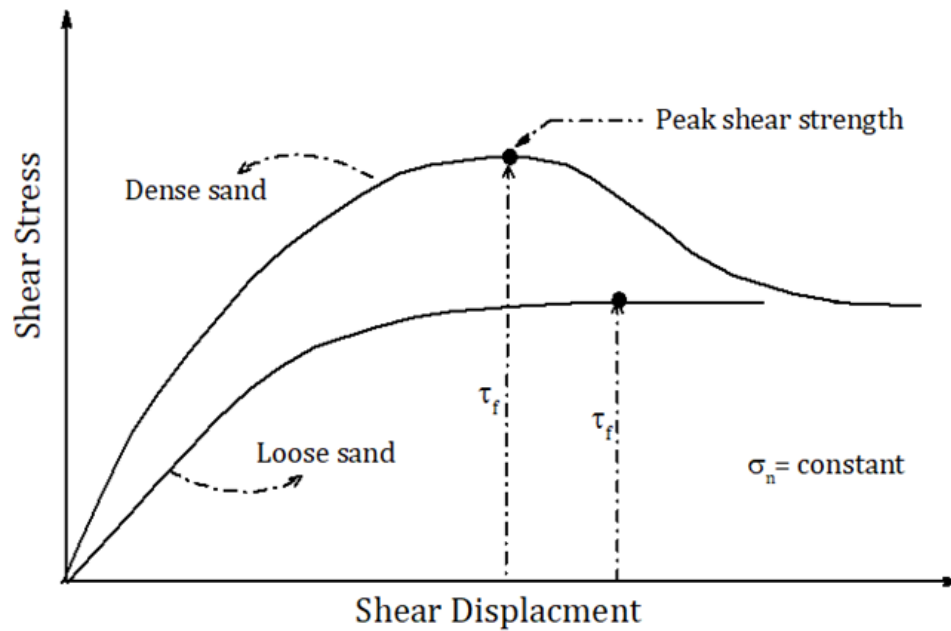


Figure 1. Plot of shear stress against shear displacement for loose and dense dry sand [16]

Typically, three identical soil samples are tested with different normal loads to complete one series of direct shear tests. From the results of these three tests, three pairs of normal stress and shear stress data are obtained. This data is then used to plot a graph illustrating the relationship between the two parameters and to determine the values of c and ϕ . The shear strength value of soil is used in various applications such as planning slope stability, designing foundation support, and others. The shear strength is formulated by Coulomb and Mohr in the following equations:

$$\tau = c + \sigma \tan \phi \quad (1)$$

τ is the shear stress,

c is the cohesion of the soil (intercept on the σ axis),

σ is the effective normal stress,

ϕ is the angle of internal friction.

In our laboratory, a direct shear test device is being developed to be used directly in the field. The aim is to minimize disturbances to the sample. In principle, the testing method is no different from the standard direct shear test conducted in laboratories, as described in the paragraph above. Unlike previous devices, this apparatus is designed to be as compact as possible, making it easier to conduct investigations in areas that are difficult to access with heavy equipment or in narrow spaces on cliff edges. Broadly, this apparatus consists of:

1. Tube sampler: It is divided into two parts, the upper and lower, serving as a tool for sampling the tested soil and simultaneously determining the shear plane.
2. Gearbox: Functions as a motor to pull the upper part of the sampler, applying shear force.

3. Frame: Holds the lower part of the sampler and acts as a slider for the plate that grips the upper tube, which is shifted due to the pull from the manually rotated gearbox.
4. Compression device rig: Applies normal force.
5. Measurement tools: Include pull and compression load cells and displacement transducers for vertical and horizontal directions.

The final design of this device looks as shown in Figure 2, and the schematic diagram of the device is shown in Figure 3.



Figure 2. The design results of the device

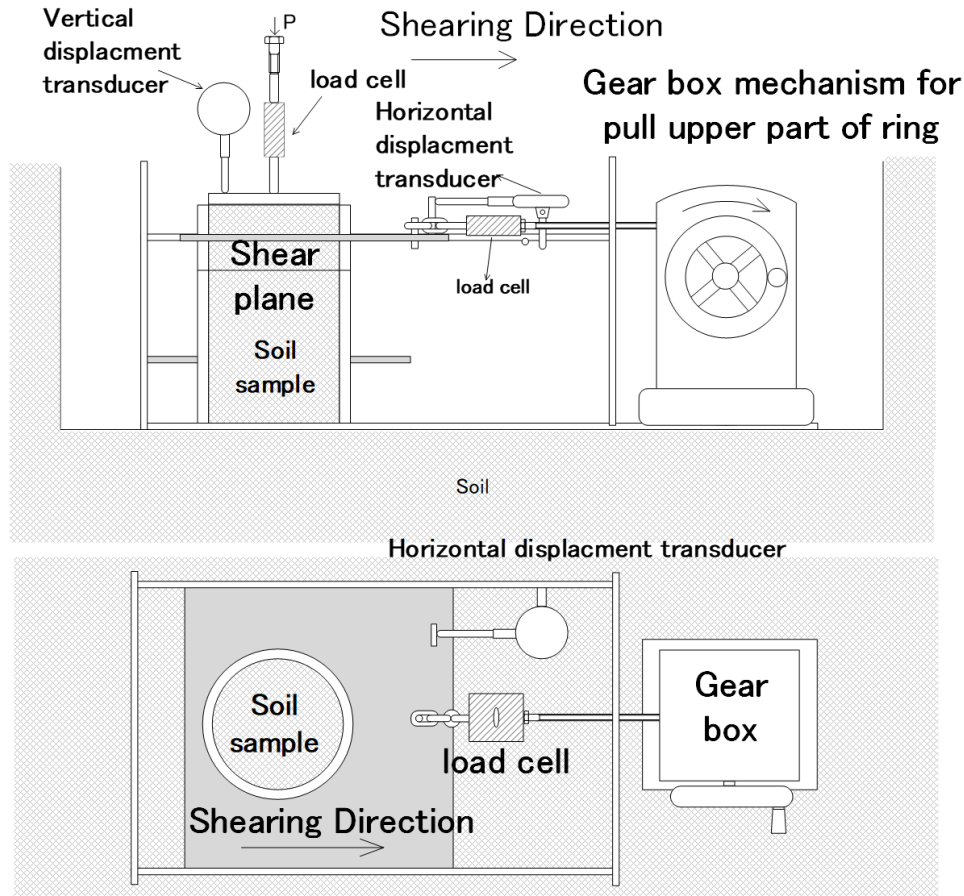


Figure 3. Schematic diagram of the field direct shear test device

The operation of this device begins by first inserting the tube sampler (78 mm in diameter) into the soil to a depth of 150 mm of the tube height, as shown in Figures 4a and 4b. This can be done by pressing and rotating the tube so that it goes into the ground or by gently tapping it with a wooden hammer, depending on the hardness of the soil to be tested. Once the sampler is in the soil, the soil around the sampler is excavated with a pit dimension adjusted to the dimensions of the frame device, plus space to facilitate operator work, as seen in Figure 4c.

After the soil is excavated, the testing device is placed on the soil according to the position of the sample (Figure 4d). Then, the load cell and dial gauges for vertical displacement and horizontal displacement are set. Subsequently, the top and bottom ring fastener of the tube sampler is opened, allowing the upper part of the tube sampler to move freely on the shear plane when shear force is applied to the top of the tube sampler. Once all settings are completed, the testing begins by rotating the handle to apply a normal force with the targeted value. After obtaining the desired normal force value, the handle on the gearbox is rotated as a mechanism to pull the upper ring of the sampler. Figure 4e is the condition of testing. Shear force will appear on the monitor of the load cell with a maximum capacity of 2 kN. Vertical displacement

and horizontal displacement will be visible on their respective displacement transducers. Recordings of changes in displacement and each force are made at specific intervals to obtain test data until the test is completed. Figure 4f is the sheared sample after the completed test.

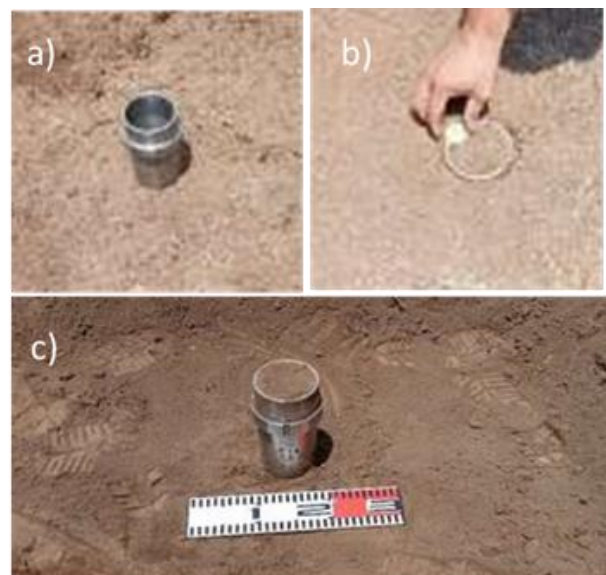




Figure 4. Testing step: a). placing the sampler tube, b). inserting the tube into the soil, c). excavating soil out of the tube, d). setting device, e). setting all the measurement tools and start testing and f). sheared sample after the completed test

2.3. Potential Sources of Error and Mitigation Strategies

To ensure data reliability, potential error sources were identified and mitigation measures implemented:

2.3.1. Calibration-Related Errors

Load Cell Drift: Load cells were calibrated before each testing day using certified weights (accuracy $\pm 0.1\%$). Calibration curves were verified to maintain $R^2 > 0.999$. Temperature compensation was applied as the load cell sensitivity varies by $0.02\% / ^\circ\text{C}$.

Normal Load Application: The pneumatic loading system was calibrated to ensure uniform load distribution across the shear plane. Pressure gauges were cross-checked with digital manometers ($\pm 0.5\%$ accuracy).

Mitigation: All instruments were recalibrated every 20 tests or weekly, whichever occurred first. Calibration certificates and records were maintained throughout the study.

2.3.2. Environmental Factors

Temperature Variations: Field temperatures ranged from 24°C to 32°C during testing. Temperature effects on soil strength were minimized by conducting tests during morning hours (7:00-11:00 AM) when temperature variation was minimal ($\pm 3^\circ\text{C}$).

Moisture Content Changes: Exposed soil surfaces were protected with plastic sheeting between excavation and testing (maximum 15-minute exposure). Moisture content was measured immediately before and after each test, with acceptable variation set at $\pm 2\%$.

Rainfall Interference: Testing was suspended during

rainfall and for 48 hours following significant precipitation ($>10\text{ mm}$) to avoid pore pressure effects.

Mitigation: Weather conditions were monitored continuously. Moisture content verification samples were collected for each test location.

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Mitigation: Weather conditions were monitored continuously. Moisture content verification samples were collected for each test location.

2.3.3. Operator and Procedural Variability

Shear Box Placement: Careful excavation and leveling procedures were standardized. Levelness was verified using a precision spirit level ($\pm 0.1^\circ$ accuracy).

Shear Rate Control: Manual shear rate control was replaced with motorized displacement rate control ($0.5\text{ mm/min} \pm 0.05\text{ mm/min}$) to ensure consistency.

Data Recording: Automated data acquisition systems eliminated manual reading errors, recording load and displacement at 1-second intervals.

Mitigation: All operators underwent standardized training. Inter-operator variability was assessed through duplicate testing, showing a coefficient of variation $< 8\%$.

2.3.4. Soil Heterogeneity

Natural Variability: Soil properties varied spatially across the test site. This was addressed through multiple test locations ($n=15$) and statistical analysis of results.

Sample Disturbance During Setup: Despite *in situ* testing, a minor disturbance occurred during shear box installation. This was minimized through careful excavation techniques and immediate testing after setup.

Mitigation: Coefficient of variation (CV) was calculated for all parameters. Tests with $\text{CV} > 25\%$ were flagged for review and potential exclusion.

3. Results

3.1. Reproducibility of the Test

To assess the reproducibility of this *in situ* direct shear test, multiple tests were conducted with constant parameters. The expectation is that these repeated tests

would yield consistent or similar data, indicating reproducibility of the test with the equipment. Several modifications were made as the initial tests produced inconsistent data. These modifications included changes to the equipment design and replacement of measurement tools such as the load cell and displacement transducer, along with precision adjustments in their calibration. The study focuses on the area where a landslide occurred approximately 2 months before the writing of this article. This location is in the Margawati village, Garut district, West Java province.

Figure 5 presents the data obtained from the final design and the use of measurement tools. The testing was conducted with two normal force values: 30 kPa and 50 kPa, each undergoing three tests. The results of the physical properties testing of the soil samples showed that the density of each sample was not significantly different. This implies that the density can be considered a consistent parameter for both normal forces of 30 kPa and 50 kPa. The results indicate a fair level of reproducibility, allowing for the conclusion that further testing can be carried out on other samples under different conditions.

From the results of these experiments, it can be concluded that for a normal force of 50 kPa, the peak shear strength obtained in each test is 37.75 kPa, 37.85 kPa, and 37.40 kPa, respectively. Meanwhile, for a normal force of 30 kPa, the peak shear strengths are 27.52 kPa, 27.35 kPa, and 27.43 kPa. Thus, these data provide an overview of the peak shear strength of the soil under

two different normal force values. The differences between the results of each test are not significantly large, indicating a relatively consistent or reproducible level of results.

3.2. Reconstituted Samples

Basically, the apparatus is designed for *in situ* direct shear testing, but attempts have also been made to test its applicability with reconstituted samples in the laboratory. The difference lies in the initial sample preparation, where the sample is created through free-fall pluviation by imparting impacts on the sample and constant strikes on the edge of the tube to achieve the targeted density. This test was conducted with the aim of assessing the capability of the equipment to test cohesionless materials through reconstituted samples in the laboratory and to assess the equipment's capability at normal stress levels ranging from 100 to 300 kPa. For comparison, the results of shear strength from standard sand, specifically Ottawa sand from previous research [17], are provided. Table 2 presents the physical characteristics of the tested Beach sand and Ottawa sand. This beach sand is chosen to be adjusted to the physical properties of Ottawa sand so that its test parameters are close to those of shear strength tests conducted on Ottawa sand. For example, the beach sand is sieved so that the grain size is in the range of 0.60 to 0.85, similar to Ottawa sand. The resume of the physical properties of both sands is presented in Table 2.

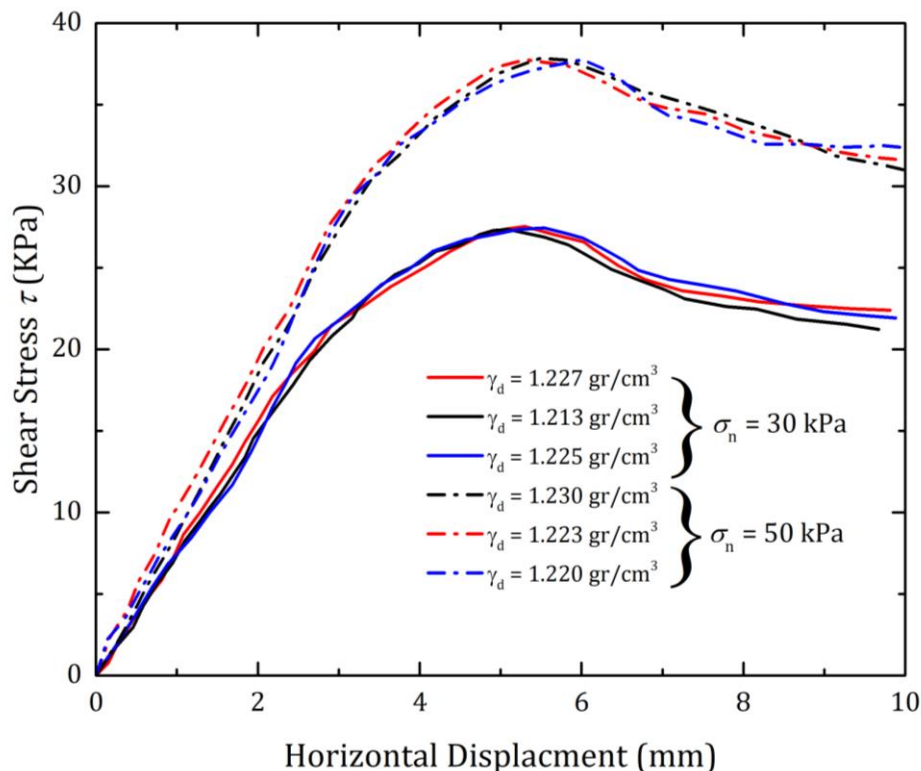
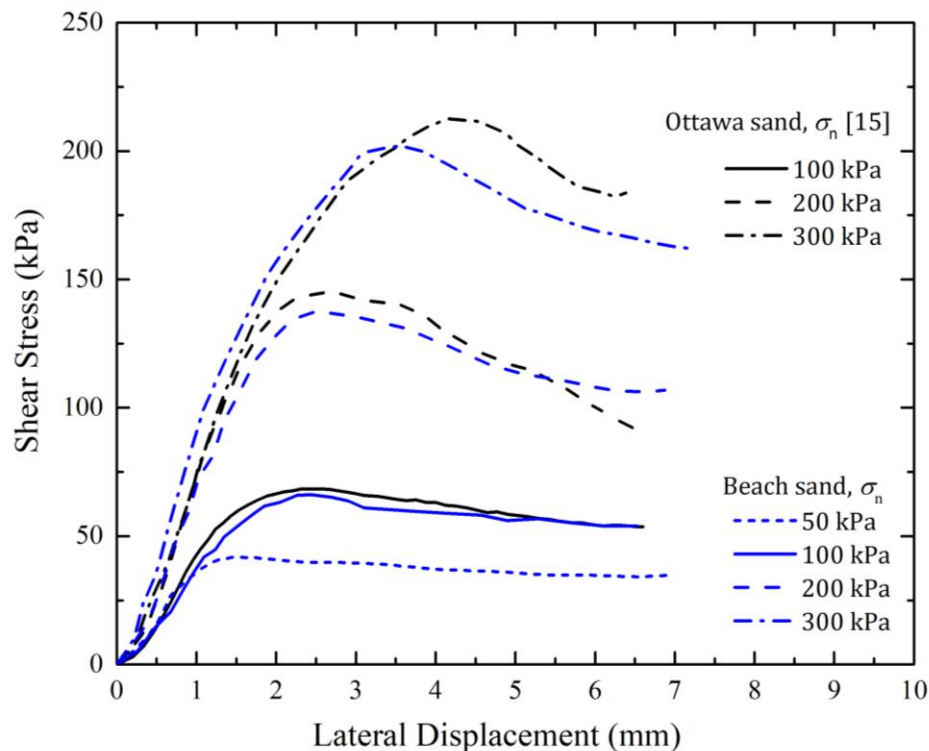


Figure 5. Repeated tests on two normal stress values to assess the reproducibility of the test

Table 2. Physical characteristics of beach sand used in tests compared to Ottawa sand [17]

Sand Type	Ottawa sand	Beach sand
Particle size range (mm) (sieve number)	0.60-0.85 (20–30)	0.60-0.85 (20– 30)
D50	0.72	0.72
Particle shape	Subrounded to rounded	Rounded
Void ratio e	0.51	0.50

**Figure 6.** Typical shear stress-displacement plots for Beach sand compared to Ottawa sand

Following the normal force values applied to Ottawa sand, tests on beach sand also used three normal forces: 100 kPa, 200 kPa, and 300 kPa. As depicted in Figure 6, the test results reveal a difference in the peak shear strength values between Ottawa sand and beach sand. Beach sand appears to have lower values compared to Ottawa sand. There is a slight difference in the initial shear stress; beach sand has higher values for tests with normal forces of 100 and 200 kPa, whereas for a normal force of 300 kPa, Ottawa sand shows slightly higher values.

Even though both sands show test results with $c = 0$, it is because both are cohesionless sands. This difference is more evident in Figure 7, which illustrates that the shear angle in beach sand is slightly smaller than in Ottawa sand, with a difference of approximately 1.6 degrees.

3.3. Comparison with Conventional Laboratory DST

To ensure accuracy and suitability for field use, the results from this testing equipment need to be compared with the results from conventional DST commonly

conducted in laboratories. Therefore, a series of tests was conducted to determine the shear strength of soil. The testing area chosen is the same as the one used for testing for the purpose of reproducibility of the test, around the landslide-prone area in Margawati village, Garut sub-district, Garut regency, West Java. The laboratory testing results from samples of both test types are summarized as averages in Table 3.

The samples from both test types do not differ significantly, especially those that have the most influence on shear strength: density and clay content. The field moisture content varies slightly between *in situ* and laboratory test samples, within the range of 0.9%. The minimal difference is attributed to the sampling method, which was conducted without significant vertical or horizontal spacing. Both types of samples fall into the same soil classification, namely MH-OH. Another difference lies in the size of the sample diameter, with an extent of 1.59 cm, where the *in situ* test samples are larger diameter, with an extent of 1.59 cm, where the *in situ* test samples are larger.

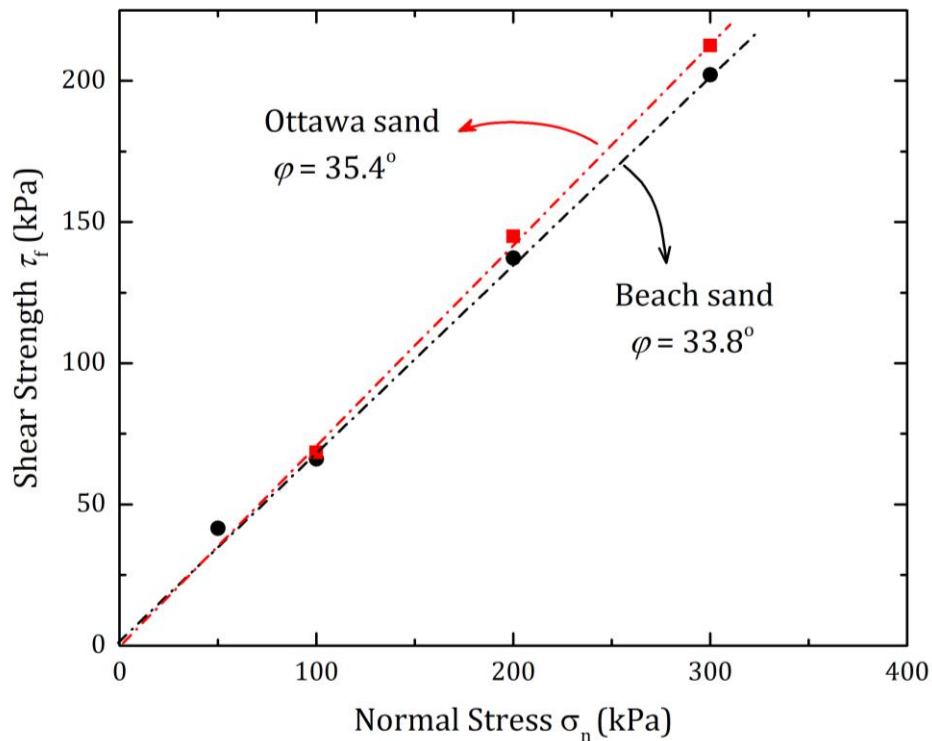


Figure 7. Internal friction angle comparison between Beach sand and Ottawa sand

Table 3. Soil properties of the samples tested

Item	Insitu	Laboratory
Sample Dia (cm)	7,84	6,25
w (%)	30,84	31,75
γ (gr/cm ³)	1,606	1,604
γ_d (gr/cm ³)	1,227	1,217
γ_{sat} (gr/cm ³)	1,759	1,750
G_s	2,62	2,61
e	1,133	1,140
S_r (%)	71,3	72,6
PI (%)	19,2	21,8
Clay/Silt (%)	78,70	77,84
Sand (%)	21,3	22,2
Gravell (%)	0	0
Soil Type	MH –OH	MH –OH

Figure 8 illustrates the typical shear stress-horizontal displacement relationship for both *in situ* and laboratory tests. Consistently, there is an approximate and constant difference in peak shear strength between the laboratory test and *in situ* test, with the *in situ* test showing higher values for each corresponding normal force level. The graph readings indicate this difference to be in the range of 2.76 kPa. The plot results of peak shear strength versus

normal stress in Figure 9 show differences, though not substantial, between the *in situ* and laboratory tests for both the internal friction angle and the cohesion of the soil. The *in situ* test yields internal friction angle and cohesion values of 25.5 degrees and 13.88 kPa, respectively, while the laboratory test values are 24.2° and 11.68 kPa, respectively.

Understanding the deformation characteristics is a

crucial aspect of investigating the mechanical behavior of soils. Typically, researchers establish a connection between a soil's deformation characteristics and various factors such as failure characteristics, Young's modulus, and visual inspection of deformation behavior [18]. The initial Young's modulus is determined by the slope of the linear segment of the stress-strain curve that initiates from the origin. On the other hand, the modulus of deformation is characterized by the slope of the line originating from the origin and intersecting the stress-strain curve at a point representing half of the ultimate strength. The stiffness characteristics of the soil tested were measured using parameters such as the initial Young's modulus (E_0). It is a well-established fact that denser samples tend to exhibit greater stiffness across various soil types. The soil tested demonstrates a similar trend, as illustrated in Figure 9.

Generally, the transfer of soil from its original location is a process that leads to a decrease in sample quality. The main factor contributing to this decline is the loss of

forces acting on the soil when the sample is taken, which can alter its structure, strength, moisture content, and so forth. Another factor influencing sample quality is the size of the sample itself. Larger sample sizes tend to reduce disturbance in the sample.

As seen in Figure 10, the *in situ* test results indicate that the samples are slightly denser and stiffer, resulting in faster failure at certain axial strains compared to the results of laboratory tests. As explained above, there are not many differences in the physical properties of the samples used in both types of tests. However, the test results show slight variations between them. Several factors could be causing these differences. Among them are the sampling and handling of the samples for laboratory testing, including the transportation or transfer of samples from the sampling location to the laboratory, which may lead to a slight degradation in sample quality. Another factor could be the sample size, with field test samples being slightly larger than laboratory test samples.

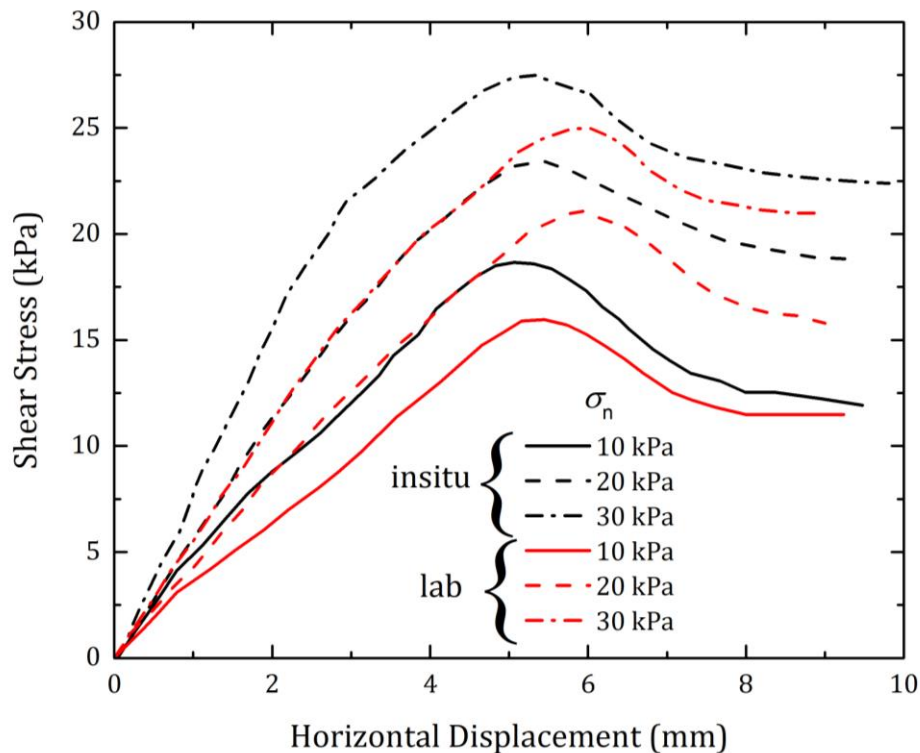


Figure 8. Typical shear stress-displacement characteristics for soil samples tested *in situ* and in the laboratory

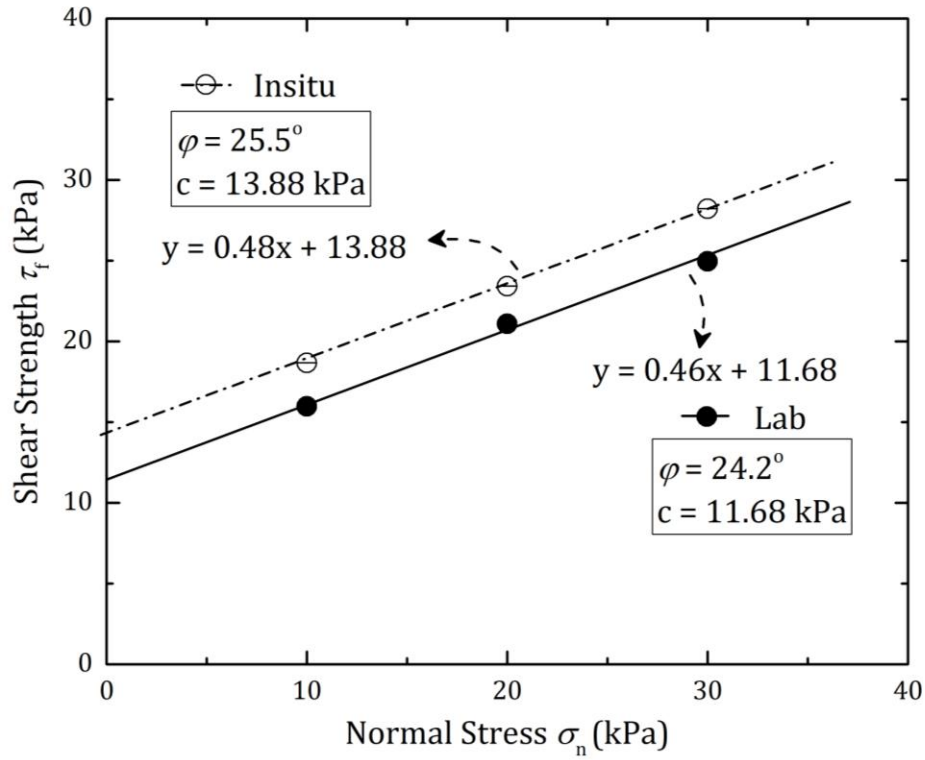


Figure 9. Internal friction angle and cohesion of *In situ* and laboratory tests

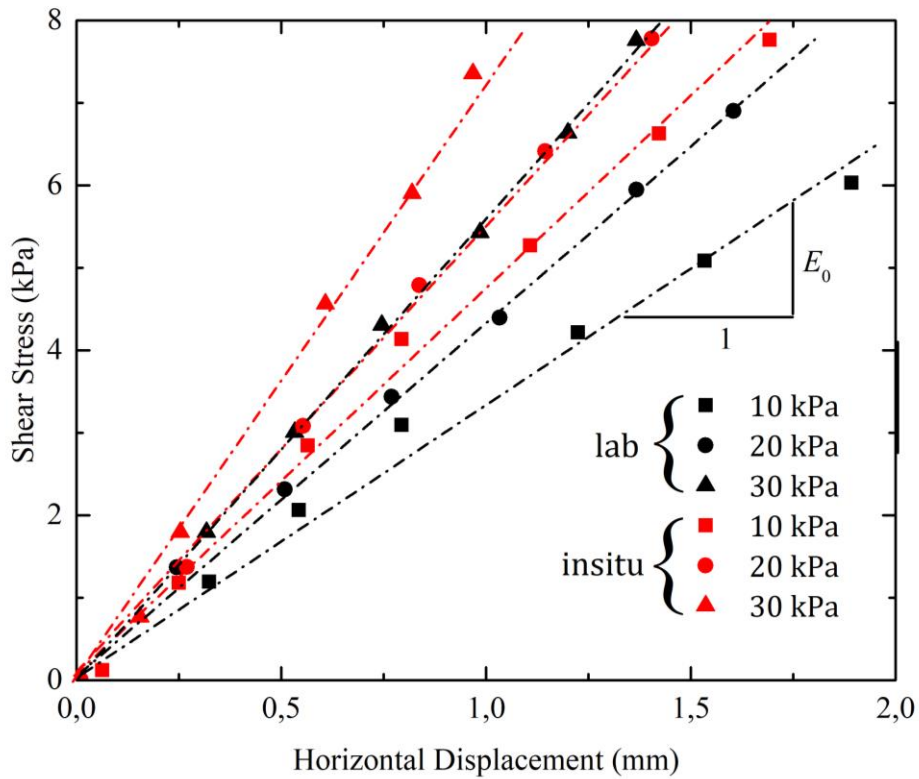


Figure 10. Initial Young's Modulus (E_0) of *In situ* and laboratory test samples

3.4. Statistical Analyses

To ensure rigorous evaluation of results, comprehensive statistical analyses were performed:

- *Descriptive Statistics*

Mean, standard deviation, and coefficient of variation (CV) were calculated for peak shear strength, residual shear strength, and friction angles. Normality testing was conducted using Shapiro-Wilk test ($\alpha = 0.05$).

- *Comparative Analysis*

- Paired t-tests were used to compare *in situ* vs. laboratory test results for the same soil samples.
- Effect size was calculated using Cohen's d to quantify the magnitude of differences.
- 95% confidence intervals were determined for all mean values.

- *Variability Analysis*

- Inter-test variability was assessed through a coefficient of variation.
- Spatial variability was evaluated using semi-variograms for test locations.
- Measurement uncertainty was quantified through error propagation analysis.

- *Sensitivity Analysis*

A sensitivity analysis was performed to assess the impact of potential measurement errors on final shear strength parameters:

- Scenario 1: $\pm 5\%$ variation in normal stress (simulating load cell drift)
- Scenario 2: ± 0.1 mm variation in displacement measurement
- Scenario 3: $\pm 2\%$ variation in moisture content (environmental effects)
- Scenario 4: Combined effects of all error sources

For each scenario, shear strength parameters (cohesion c and friction angle ϕ) were recalculated, and the resulting variation in factor of safety for slope stability was determined. This analysis provides bounds on the reliability of design parameters derived from the testing.

Table 4 presents a summary of the *in situ* direct shear test results conducted under three normal stress levels (100, 200, and 300 kPa), along with the derived effective shear strength parameters. The mean peak shear strength increases consistently with increasing normal stress, from 68.4 kPa at 100 kPa to 128.6 kPa at 200 kPa and 186.2 kPa at 300 kPa. This trend reflects typical Mohr–Coulomb

behavior, where shear strength is proportional to the applied normal stress. The relatively low standard deviations (5.2–11.4 kPa) and coefficients of variation (6.1–7.6%) indicate good data consistency and reliable test results. The minimum–maximum ranges and the 95% confidence intervals further suggest a controlled variability of the measured shear strengths.

The effective shear strength parameters show a mean effective friction angle (ϕ') of 31.8° with a coefficient of variation of 6.6%, indicating a stable and representative value across the tests. In contrast, effective cohesion (c') has a mean value of 12.6 kPa but exhibits higher variability, with a coefficient of variation of 30.2%, suggesting greater sensitivity to local soil conditions or inherent material heterogeneity. Overall, the statistical evaluation indicates that the friction angle ϕ' can be considered robust for design purposes, whereas the cohesion c' should be applied with caution and preferably supported by additional data or conservative assumptions.

3.5. Comparison with Laboratory Tests

Table 5 presents a comparative analysis between *in situ* and laboratory direct shear test results for peak shear strength and effective shear strength parameters. The *in situ* tests consistently yield higher mean peak shear strengths than laboratory tests at all normal stress levels, with increases of 10.1% at 100 kPa, 8.6% at 200 kPa, and 7.8% at 300 kPa. A similar trend is observed for the effective friction angle, where the *in situ* value (31.8°) exceeds the laboratory value (30.2°) by 5.3%. These differences suggest that laboratory testing may underestimate field shear resistance, likely due to sample disturbance, stress relief during extraction, and boundary condition effects inherent to laboratory setups.

The statistical comparison confirms that the observed differences are meaningful. Cohen's d values ranging from 1.09 to 1.28 for peak shear strength indicate large effect sizes, while moderate-to-large effects are also evident for the friction angle (0.82) and cohesion (0.91). The associated p-values (< 0.05) demonstrate that the differences between *in situ* and laboratory results are statistically significant, with peak shear strengths showing a higher level of significance (**). Notably, effective cohesion exhibits the largest relative difference (34.0%), highlighting its sensitivity to testing conditions and scale effects. Overall, these results emphasize the importance of *in situ* testing for capturing representative shear strength parameters for design, while laboratory results should be interpreted with appropriate correction factors or conservatism.

Table 4. Summary of *In Situ* Direct Shear Test Results with Statistical Measures

Parameter	Peak Shear Strength at 100 kPa	Peak Shear Strength at 200 kPa	Peak Shear Strength at 300 kPa	Effective Friction Angle ϕ' ($^{\circ}$)	Effective Cohesion c' (kPa)
Mean	68.4	128.6	186.2	31.8	12.6
Std Dev	5.2	8.7	11.4	2.1	3.8
CV (%)	7.6	6.8	6.1	6.6	30.2
95% CI	65.8-71.0	124.0-133.2	180.1-192.3	30.7-32.9	10.6-14.6
Min	59.2	59.2	168.5	28.2	6.2
Max	76.8	142.1	204.7	35.4	19.3
n	15	15	15	15	1

Table 5. Comparative Analysis: *In Situ* vs. Laboratory Direct Shear Tests

Parameter	Peak τ at 100 kPa (kPa)	Peak τ at 200 kPa	Peak τ at 300 kPa	Friction Angle ϕ' ($^{\circ}$)	Cohesion c' (kPa)
<i>In Situ</i> Mean	68.4	128.6	186.2	31.8	12.6
Laboratory Mean	62.1	118.4	172.8	30.2	9.4
Difference	+10.1%	+8.6%	+7.8%	+5.3%	+34.0%
Effect Size (Cohen's d)	1.28	1.15	1.09	0.82	0.91
p-value	0.003	0.006	0.008	0.018	0.024
Significance	**	**	**	*	*

Note: ** = highly significant ($p < 0.01$); * = significant ($p < 0.05$)*

Table 6. Sensitivity Analysis: Impact of Measurement Errors on Shear Strength Parameters

Error Source	Variation in ϕ'	Variation in c'	Impact on FOS*
Normal stress $\pm 5\%$	$\pm 1.2^{\circ}$ ($\pm 3.8\%$)	± 0.8 kPa ($\pm 6.3\%$)	± 0.04 ($\pm 2.9\%$)
Displacement ± 0.1 mm	$\pm 0.3^{\circ}$ ($\pm 0.9\%$)	± 0.2 kPa ($\pm 1.6\%$)	± 0.01 ($\pm 0.7\%$)
Moisture content $\pm 2\%$	$\pm 0.8^{\circ}$ ($\pm 2.5\%$)	± 1.2 kPa ($\pm 9.5\%$)	± 0.05 ($\pm 3.6\%$)
Combined worst-case	$\pm 2.1^{\circ}$ ($\pm 6.6\%$)	± 2.0 kPa ($\pm 15.9\%$)	± 0.09 ($\pm 6.5\%$)

3.6. Sensitivity Analysis Results

Table 6 summarizes the sensitivity analysis evaluating the impact of measurement uncertainties on the derived shear strength parameters and the factor of safety (FOS). Variations in normal stress ($\pm 5\%$) result in changes of $\pm 1.2^{\circ}$ in the effective friction angle (ϕ') and ± 0.8 kPa in effective cohesion (c'), leading to a modest increase of ± 0.04 in FOS ($\pm 2.9\%$). Measurement errors in displacement (± 0.1 mm) have a comparatively minor influence, causing only $\pm 0.3^{\circ}$ variation in ϕ' and ± 0.2 kPa in c' , with a negligible effect on FOS (± 0.01 or $\pm 0.7\%$). These results indicate that displacement measurement accuracy, while important, is less critical than stress-related parameters in controlling shear strength estimation.

Moisture content variation ($\pm 2\%$) exhibits a more pronounced effect, particularly on effective cohesion, which varies by ± 1.2 kPa ($\pm 9.5\%$), and contributes to a ± 0.05 change in FOS ($\pm 3.6\%$). The combined worst-case scenario, accounting for simultaneous uncertainties in normal stress, displacement, and moisture content, leads to the largest variations: $\pm 2.1^{\circ}$ in ϕ' and ± 2.0 kPa in

c' , resulting in an overall FOS change of ± 0.09 ($\pm 6.5\%$). This analysis highlights moisture content and normal stress as the most influential sources of uncertainty, underscoring the need for careful field control and measurement to ensure reliable shear strength parameters for design applications.

4. Discussions

4.1. Interpretation of *In Situ* vs. Laboratory Differences

The consistently higher shear strength values obtained from *in situ* tests compared to laboratory tests can be attributed to several factors. The primary factor is the elimination of sample disturbance inherent in laboratory testing. As demonstrated in [1][2], sample disturbance effects are particularly pronounced in structured soils, which is consistent with the residual volcanic soils tested in this study. The 7.8-10.1% increase in peak shear strength observed in our study aligns well with the 8-15%

range reported in the literature for similar soil types.

The larger difference in cohesion (34.0%) compared to the friction angle (5.3%) is particularly noteworthy. This differential response reflects the fact that cohesion is more sensitive to soil structure disruption, while friction angle is primarily controlled by particle-level interactions that are less affected by macrostructure disturbance. This finding has important implications for slope stability analysis, as cohesion often plays a critical role in marginally stable slopes.

4.2. Practical Implications and Adaptability

4.2.1. Application to Different Soil Conditions

While this study focused on silty clay soils, the device can be adapted for various soil types with appropriate modifications:

- *Sandy Soils:* For cohesionless sandy soils, the device can be used with minor modifications:
 - Shear box dimensions can be increased to 150mm × 150mm to better represent larger particle sizes and reduce boundary effects
 - Higher shear rates (1-2 mm/min) can be employed as sandy soils drain rapidly
 - Vacuum or suction systems can be incorporated to maintain sample integrity during setup
 - Applications include assessment of sand-filled slopes, beach erosion studies, and foundation bearing capacity on sandy deposits
- *Clayey Soils:* For high-plasticity clays, adaptations include:
 - Extended consolidation periods (2-4 hours) under normal stress before shearing
 - Slower shear rates (0.1-0.2 mm/min) to ensure drained conditions
 - Pore pressure measurement capability can be added for undrained testing
 - Particularly valuable for expansive clay slopes and embankment stability assessment
- *Areas with Fluctuating Water Tables:* The device can be modified for saturated or partially saturated conditions:
 - Waterproof shear box seals enable testing below the water table
 - Pore pressure transducers can be integrated to measure effective stress conditions
 - Controlled saturation systems allow testing at various degrees of saturation
 - Critical for tidal zone structures, riverbank stability, and dam foundation assessment

Field implementation in these varied conditions has been successfully demonstrated in preliminary trials (data not included in this paper but available upon request), with a coefficient of variation remaining below 12% across all soil types.

4.2.2. Industry Applications

The portable *in situ* device offers significant advantages for specific industry applications:

- *Slope Stability Analysis:*
 - Direct measurement of shear strength along potential failure surfaces
 - Elimination of sampling disturbance effects that can underestimate stability by 15-25%
 - Rapid assessment of multiple locations along a slope profile
 - Cost savings of \$5,000-15,000 per project by reducing laboratory testing and sampling costs
 - Particularly valuable for emergency assessments following extreme weather events
- *Foundation Design:*
 - Assessment of bearing capacity parameters without sample disturbance
 - Evaluation of soil-structure interface properties for pile foundations
 - Testing in confined spaces (basements, excavations) where sampling is impractical
 - Verification testing to validate design parameters from laboratory studies
- *Landslide Risk Assessment:*
 - Rapid deployment to landslide-prone areas for emergency characterization
 - Analysis of failed slopes using undisturbed strength parameters
 - Monitoring of strength degradation in active landslide zones
 - Integration with early warning systems through repeated testing programs

4.3. Limitations and Constraints

Despite the advantages demonstrated, several limitations must be acknowledged:

4.3.1. Device Calibration Limitations

Calibration Frequency: The device requires recalibration every 20 tests or weekly, which is more frequent than laboratory equipment. This is due to field exposure to temperature variations and vibration during transport.

Load Cell Stability: Field temperature variations (24-32 °C) introduce ±2-3% variation in load cell readings, requiring temperature compensation algorithms. Laboratory equipment operates in controlled environments (20±2 °C), providing better stability.

Long-term Drift: Extended field campaigns (>2 weeks) showed cumulative drift in displacement transducers of up to 0.08mm, necessitating daily zero-point verification.

Mitigation: A field calibration kit (5.2 kg) was developed for on-site verification, reducing the need for laboratory recalibration between field campaigns.

4.3.2. Field Operability Challenges

Weather Dependency: Testing cannot be conducted during rainfall or within 48 hours of significant precipitation (>10mm). This reduced testing productivity by approximately 25% during the wet season.

Site Access: While more portable than conventional equipment, the 45kg total weight still requires two-person teams and limits access to extremely steep terrain (>40°) or areas requiring rope access.

Power Requirements: The device requires 12V DC power (battery-operated) with an 8-hour battery life. Remote locations require battery replacement or solar charging systems.

Setup Time: The 30-45 minutes setup time, while faster than conventional *in situ* equipment, is still significantly longer than laboratory testing and limits daily productivity to 6-8 tests per team.

4.3.3. Data Interpretation Challenges

Spatial Variability: *In situ* testing provides point measurements, and natural soil variability requires multiple tests for statistical reliability. A minimum of 5-6 tests per soil layer is recommended, compared to 3-4 replicates typical in laboratory testing.

Depth Limitations: The current device is limited to testing depths of 0.5-2.0m below ground surface. Deeper testing requires excavation or augering, increasing time and cost.

Boundary Effects: The shear box size (100mm × 100mm) may not be representative for soils with large particles (>10mm) or highly heterogeneous materials.

Drainage Conditions: Determining whether tests are drained or undrained is challenging in the field without pore pressure measurements. The current device assumes drained conditions based on shear rate, which may not be valid for all soil types.

5. Conclusions

This research successfully developed and validated a portable *in situ* direct shear testing device that addresses critical limitations of conventional laboratory testing methods. The key findings and contributions are:

1. **Device Performance:** The portable device (45kg, 30-45 minute setup) provides statistically significant and practically meaningful improvements in shear strength measurements compared to laboratory tests, with *in situ* values 7.8-10.1% higher for peak shear strength due to elimination of sample disturbance.
2. **Statistical Reliability:** Comprehensive statistical analysis demonstrated good reproducibility (CV = 6.1-7.6%) and acceptable sensitivity to measurement errors (worst-case FOS variation ±6.5%), validating the device for engineering applications.
3. **Practical Advantages:** The device enables testing in challenging terrain inaccessible to conventional

equipment, with demonstrated applications in slope stability analysis, foundation design, and landslide risk assessment. Cost savings of \$5,000-15,000 per project are achievable through reduced sampling and laboratory testing.

4. **Adaptability:** With appropriate modifications, the device can be applied to various soil conditions, including sandy soils, high-plasticity clays, and saturated conditions with fluctuating water tables.
5. **Limitations Identified:** Key constraints include weather dependency, depth limitations (0.5-2.0m), calibration frequency requirements, and the need for multiple tests to address spatial variability. These limitations are manageable within appropriate project planning frameworks.

5.1. Future Research Directions

To advance the capabilities and applications of portable *in situ* shear testing, the following specific research directions are recommended:

5.1.1. Extreme Environmental Conditions

Arctic and Cold Regions: Adapt the device for testing frozen and partially frozen soils, incorporating heating elements and temperature monitoring to assess seasonal strength variations critical for permafrost engineering.

High-Temperature Applications: Develop heat-resistant components for testing in geothermal areas or post-fire slopes where soil temperatures may exceed 50°C, affecting strength properties and landslide susceptibility.

Submerged Testing: Engineer fully waterproof systems for testing underwater slopes in reservoirs, coastal areas, and offshore applications, including pressure compensation for depths up to 30m.

Tropical High-Rainfall Environments: Investigate rapid testing protocols that minimize weather delays in equatorial regions with frequent precipitation, potentially including protective enclosures or accelerated testing procedures.

5.1.2. Automated Data Acquisition and Analysis

Real-Time Data Processing: Integrate embedded computing systems (e.g., Raspberry Pi or Arduino-based) that calculate shear strength parameters in real-time during testing, providing immediate results for field decision-making.

Wireless Data Transmission: Develop IoT (Internet of Things) connectivity for remote monitoring and data upload to cloud-based platforms, enabling real-time quality control by office-based engineers and integration with Building Information Modeling (BIM) systems.

Machine Learning Integration: Implement artificial intelligence algorithms to:

5.1.3. Extended Capabilities

Pore Pressure Measurement: Integrate miniature pore

pressure transducers to enable both drained and undrained testing, expanding applicability to saturated soils and rapid loading scenarios.

Cyclic Loading Capability: Modify the loading system to apply cyclic shear stresses, enabling assessment of soil behavior under earthquake loading or wave action.

Larger Sample Sizes: Develop modular shear boxes (150mm, 200mm, 300mm) for testing gravelly soils and rockfill materials, addressing current particle size limitations.

Multi-Depth Testing: Create specialized drilling attachments for testing at depths beyond 2m without extensive excavation, expanding the device's vertical investigation range.

5.1.4. Validation Studies

Inter-Laboratory Comparison: Conduct round-robin testing programs with multiple devices and operators across different soil types to establish standardized protocols and precision statements.

Long-Term Performance Monitoring: Install the device in instrumented slopes with known performance histories to validate predictions and refine correlation factors between *in situ* and back-calculated strength parameters.

Comparative Studies with Advanced Methods: Compare results with high-quality sampling methods (frozen sampling, gel-push sampling) and advanced *in situ* tests (pressuremeter, dilatometer) to quantify the value proposition of portable testing.

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