Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1212

Development of an electromagnetic induction-controlled free fall penetrometer for undrained shear strength measurement

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ABSTRACT: Accurate estimation of undrained shear strength (S_u) is crucial for geotechnical design in soft clay deposits, particularly in coastal and offshore environments. While traditional laboratory tests are time-consuming and prone to sample disturbance, in-situ free fall penetrometer (FFP) tests offer a rapid alternative. However, existing FFP methods often rely on complex accelerometer data processing and expensive equipment. This study focuses on developing an innovative FFP apparatus that achieves and maintains a constant, pre-defined penetration velocity using electromagnetic induction. The newly developed apparatus ensures a consistent terminal velocity throughout the penetration process, and an ultrasonic sensor is integrated for accurate, real-time measurement of penetration depth, leading to enhancing the reliability and repeatability of the test. Experiments were conducted on both undisturbed and remolded marine clay samples, and the results were compared with those from Unconsolidated Undrained (UU) triaxial tests and laboratory vane shear tests. Based on the experimental data, an empirical formula is proposed to predict the S_u as a function of penetration depth. Most notably, this study demonstrates that the enhanced fall cone test, with its controlled penetration velocity, retains the simplicity and cost-effectiveness of the traditional method while significantly improving accuracy and reliability, thereby expanding its potential for both laboratory research and practical field applications.

KEYWORDS: Undrained shear strength, Free fall penetrometer, Electromagnetic Induction.

1 INTRODUCTION

The rapid and accurate estimation of undrained shear strength (S_u) has become increasingly critical with the growing demand for offshore infrastructure. This need is particularly acute along the southwestern coast of Korea, where numerous offshore wind farms are planned on extremely soft, silty marine clays formed under distinctive geomorphological conditions. Safe, economical, and reliable foundation design in such deposits requires robust assessment of both strength and deformation characteristics.

S_u is commonly evaluated using in-situ and laboratory tests. Representative in-situ methods include the field vane test (FVT) and the cone penetration test (CPT). The FVT infers S_u from the torque required to rotate a cruciform vane inserted into the soil; although simple and deployable on site, it is sensitive to disturbance and often exhibits limited precision and repeatability. CPT provides continuous depth profiles by measuring the resistance to a cone pushed into the ground, but S_u estimates are indirect and can be strongly influenced by soil type and in-situ conditions. In the laboratory, the unconsolidated–undrained (UU) triaxial test on "undisturbed" samples obtained with Shelby tubes is widely used, yet sampling, transport, and preparation introduce disturbance and cost, and the workflow is time-consuming and operator-dependent.

To address these limitations, alternative techniques such as the free-fall penetrometer (FFP) and the fall cone test have been investigated (Chow and Airey, 2014; Sivakumar et al., 2015; Stark et al., 2016; O'Kelly et al., 2018). While FFPs enable rapid, field-based assessment, interpretation of accelerometer records is non-trivial, and instrumentation can be costly. Fall cone tests are simple and inexpensive but have a limited S_u range and can suffer from consistency issues. Importantly, both methods rely solely on gravity-driven penetration, which can impose excessive impact energy and high strain rates in very soft clays, potentially disturbing the material and biasing S_u upward unless significant corrections are applied.

This study develops a new device that controls the drop velocity of a penetrometer using electromagnetic induction. By prescribing the penetration energy and maintaining a constant terminal velocity throughout penetration, the system reduces impact-related disturbance and mitigates strain-rate effects. An integrated time-of-flight (ToF) laser distance sensor measures penetration depth in real time, enabling reliable interpretation of soil resistance. The proposed approach aims to improve both the accuracy and repeatability of S_u estimation in soft clay over a wide range of water contents, offering a practical alternative to existing gravity-based methods. The paper presents the device design and operating principles, outlines the test program, and evaluates performance relative to established methods, followed by discussion and conclusions.

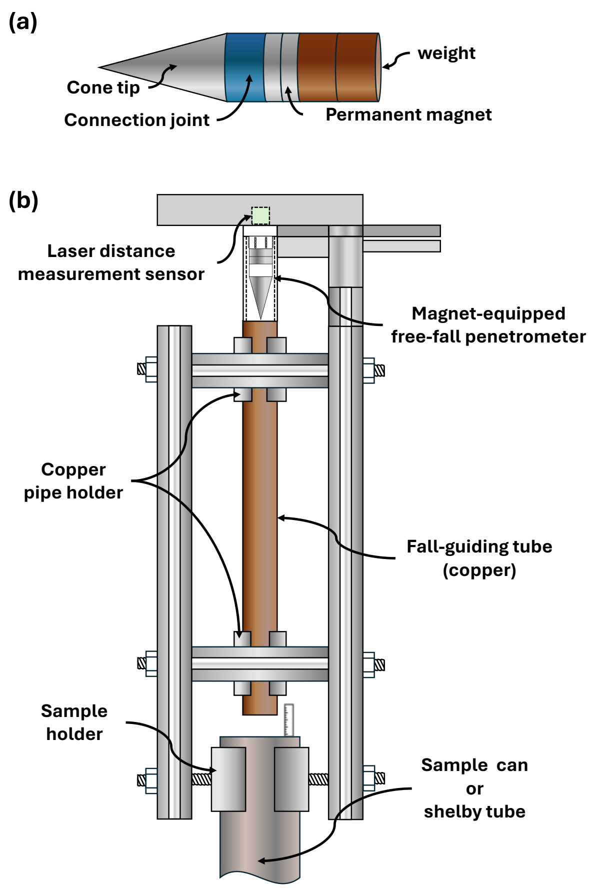

Figure 1. Schematic diagram of the undrained shear strength testing device developed in this study: (a) penetrometer assembly; (b) overview of the system.

2 PRINSIPLE OF THE PROPOSED SYSTEM

As illustrated in Figure 1, the proposed device is a magnet equipped free fall penetrometer that controls and maintains the pre-impact falling velocity by means of magnetic breaking. The penetrometer assembly in Figure 1(a) comprises a steel cone tip with a 30° apex angle rigidly connected to a neodymium permanent magnet, with detachable brass weights mounted above the magnet. The magnet and weights are replaceable, allowing adjustment of the total mass and, through the magnet conductor interaction, the effective braking constant so that the penetration energy can be prescribed under a target velocity condition. The overall body diameter is 30 mm. A schematic of the test configuration is provided in Figure 1(b).

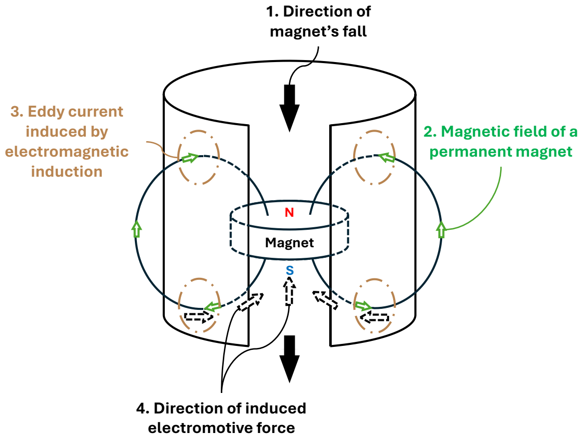

Figure 2. Conceptual diagram of eddy current generation due to electromagnetic induction.

During testing, the penetrometer assembly fell freely inside a conductive copper guide tube. As illustrated in Figure 2, the magnet traversing the tube induces eddy currents in the wall; in accordance with Lenz's law, the resulting magnetic field opposes the motion and produces a retarding force(Donoso, 2005). In the moderate-speed regime, this braking force increases approximately linearly with velocity (Levin et al., 2006), and the descent asymptotically approaches a constant terminal velocity(v_t). The guide tube is 600 mm in length with an outer diameter of 44 mm and an inner diameter of 32 mm, providing sufficient radial clearance for smooth guidance while maintaining effective electromagnetic coupling (Lee and Park, 2023). The tube length is selected so that the penetrometer approaches v_t before soil contact, thereby ensuring reproducible initial penetration conditions.

Table 1. Test cases.

Case ID	# of magnet	# of weight	Total weight (g)	Velocity (m/s)	Penetration energy (mJ)
2-0	2	0	224.1	0.064	0.45
2-1	2	1	354.1	0.101	1.82
4-2	4	2	589.3	0.113	3.78
4-3	4	3	719.3	0.137	6.74
5-4	5	4	901.9	0.160	11.55
2-4	2	4	466.6	0.240	13.44
1-4	1	4	691.5	0.398	54.83

By prescribing the terminal velocity rather than relying solely on gravity, the system directly limits the kinetic energy at impact and the initial shear-strain rate, minimizing soil disturbance and reducing the tendency to overestimate undrained shear strength (S_u) often reported for gravity driven devices in very soft clays. The adjustable brass weights enable fine control of the mass velocity combination for site specific conditions, while magnetic braking maintains the set velocity throughout the free-fall phase irrespective of minor ambient variations.

After penetration commences, an integrated time-of-flight (ToF) laser distance sensor (VL53L1X) records penetration depth in real time. Coupling the depth time history with the pre-calibrated terminal velocity enables depth resolved interpretation of resistance and consistent comparison with established methods. This controlled approach enhances the reliability and repeatability of testing and supports accurate estimation of S_u in soft, sensitive marine clays without extensive post-test corrections.

Table 2. Material properties of tested material.

Index properties	Kaolin clay	Testing method
Specific gravity, G_s	2.53	ASTM D854
Liquid limit, *LL* (%)	35.4	BS-1377 (1990)
Plastic limit, *PL* (%)	23.6	ASTM D4318
Unified soil classification system	CL	USCS

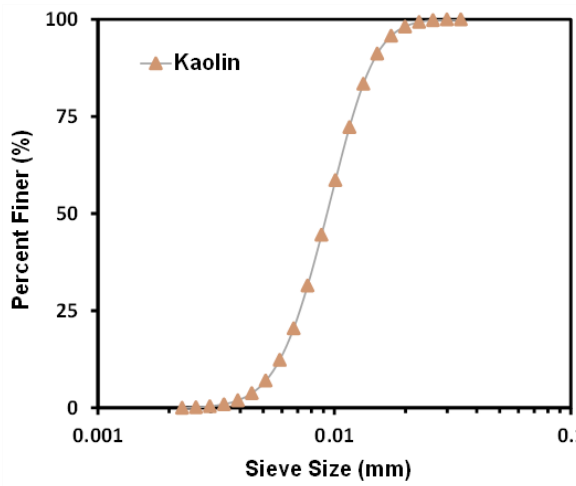

Figure 3. Particle distribution curves of the material.

3 EXPERIMENTAL PROGRAM

In this study, a series of tests were conducted using the proposed magnet equipped free fall penetrometer to evaluate the undrained shear strength (S_u) of kaolin clay under various penetration energies. First, the number of magnets and brass weights was adjusted, and the drop velocity was measured. For a fixed number of magnets, increasing the brass weight produced an approximately linear increase in velocity; the measured velocities were then used to define multiple penetration energy levels. The penetration energy for each configuration was calculated using Equation (1) and summarized in Table 1. In Equation (1), m represents the mass of the penetrometer (kg), and v denotes the drop velocity (m/s); the penetration energy is defined as the kinetic energy of the falling body.

$$Penetration\ energy = \frac{1}{2}mv^2 \tag{1}$$

Kaolin clay supplied by Lakwoo Company (South Korea) was used for the experiments. The basic index properties of the clay are summarized in Table 2, and the particle size distribution is shown in Figure 3. To span a range of S_u values, specimen water contents were adjusted from near the liquid limit (LL; very low S_u) to near the plastic limit (PL; relatively higher S_u). Specifically, specimens were prepared at water contents of 21.3%, 24.8%, 27.4%, and 30.3%, thereby covering the PL–LL interval and representing different undrained shear strengths.

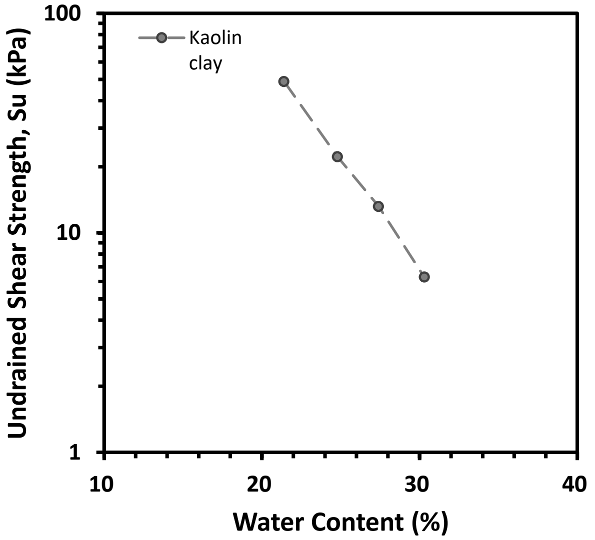

Figure 4. Relationship between water content and undrained shear strength.

The kaolin clay was mixed thoroughly to the target water content and sealed in a zipper bag. After 24 hours of conditioning to achieve uniform moisture distribution, the samples were transferred into fall cone molds and reconstituted. The surface was carefully leveled, and the penetration tests were conducted by releasing the penetrometer from the guide tube, as illustrated in Figure 1(b). For each drop, the penetration depth was recorded, and S_u was evaluated under the different penetration-energy conditions.

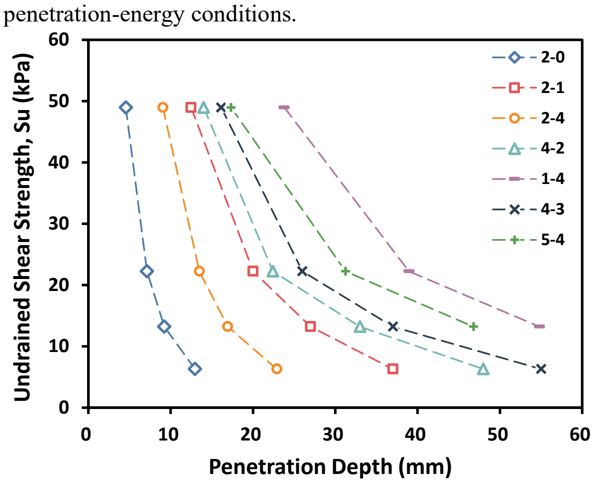

Figure 5. Undrained shear strength versus penetration depth for different test conditions. Number in the legend indicates the Case ID in Table 1.

4 RESULTS AND DISSCUSSION

To determine the reference undrained shear strength (S_u) of reconstituted kaolin samples prepared at four target water contents (21.3%, 24.8%, 27.4%, and 30.3%), both unconfined compression tests (UCS) and unconsolidated undrained triaxial tests (UU tests) were conducted. For each case, the average S_u obtained from UCS and UU tests was used as the representative reference value. As shown in Figure 4, S_u decreased with increasing water content due to reduced interparticle bonding and cohesion (Koumoto and Houlsby, 2001).

Test specimens with four different water contents (i.e., 21.3%, 24.8%, 27.4%, and 30.3%) were prepared, and free fall penetration tests were performed. Figure 5 shows the variation of S_u, determined using Figure 1, according to penetration depth under the varying penetration energies in Table 1. The results (Figure 5) showed that the penetration depth decreased as S_u increased at a given penetration energy. This inverse relationship indicates that clays with higher shear strength provide greater resistance to cone intrusion under the same impact energy (Sivakumar et al., 2015). While traditional fall cone tests also exhibit this exponential reduction of penetration depth with increasing S_u, they tend to lose reliability in high strength ranges due to excessive sensitivity to small variations in depth (Hansbo, 1957). However, in this study, by increasing the penetration energy using the proposed device, this sensitivity was reduced, thereby improving measurement reliability across a broader S_u range.

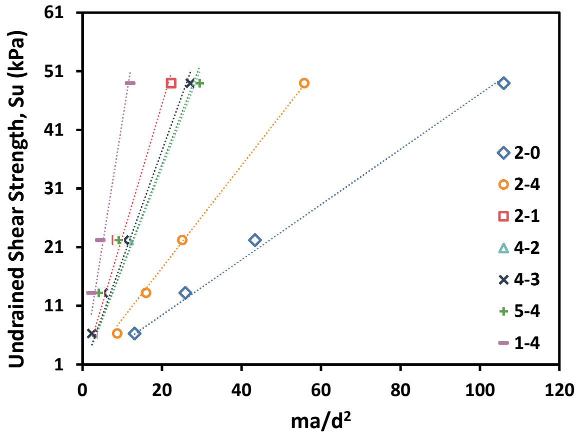

Figure 6. Relationship between undrained shear strength and normalized energy term for various test cases.

Based on these findings, the experimental data were applied to the empirical estimation formula commonly used in fall cone and free-fall penetration tests (Equation (2)):

$$S_u = K\frac{m \cdot a}{d^2} \tag{2}$$

where m is the mass of the penetrometer (g), a is the gravitational acceleration (9.81 m/s²), d is the penetration depth, and K is an empirical correction factor influenced by penetrometer geometry, soil properties, and shear strain rate(Llano-Serna and Contreras, 2020). Figure 6 plots S_u a function of the normalized energy term ma/d^2 for each test condition, and simple linear regression was applied to estimate the empirical correction factor K in Equation (2). As the penetration energy increased, the K values also increased. This is interpreted because of higher initial shear rates and the associated rate-dependent strengthening of the clay, which leads to a larger regression slope (K). In other words, higher shear rates yield larger nominal S_u, and the correction factor K that accounts for rate effects increases accordingly. In all cases, the coefficients of determination were R^2 >0.98, indicating strong linearity and high reliability. The K values obtained in this study ranged from 0.47 (minimum, Case ID 2-0) to 4.24 (maximum, Case ID 1-4).

5 CONCLUSIONS

This study developed and validated a magnet-equipped free-fall penetrometer that prescribes and maintains a constant terminal velocity via electromagnetic induction and records depth in real time with a time-of-flight laser distance sensor. Tests on reconstituted kaolin at four water contents confirmed two robust trends for soft clays: S_u decreases with increasing water content, and at a given energy penetration depth decreases with increasing S_u. The measurements conform to the customary energy depth form, $S_u = K(ma/d^2)$, with $R^2 > 0.97$ for all cases, demonstrating strong linearity and high reliability.

In terms of implications, the rate-controlled approach reduces impact and strain rate related disturbance and extends the usable S_u range beyond that of conventional fall cone methods. As a contribution to the body of knowledge in soil mechanics and geotechnical engineering, the work establishes a practical framework for velocity controlled FFP testing and provides a simple calibration pathway via *K* that links strength to a normalized energy depth term, enabling rapid and repeatable Su estimation in soft marine clays.

6 ACKNOWLEDGEMENTS

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT). (RS-2023-00221719).

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