

Innovative Transformation of Analog to Digital Direct Shear Test Tool Based on Microcontroller with Wireless Data Acquisition System

Maskur Efendi^{1✉}, Eko Setyawan²

^{1,2} Department of Civil Engineering & Planning, Faculty of Engineering, Universitas Negeri Malang, Indonesia

✉ Corresponding Author : Maskur Efendi (e-mail: maskur.efendi@um.ac.id)

Article Information	ABSTRACT
Article History Received : December 05, 2024 Revised : December 20, 2024 Published : January 06, 2025	Direct Shear Test (DST) is an important method for measuring soil shear strength in civil engineering applications. However, analog DST tools have limitations, such as low accuracy, low efficiency, and the need for manual data processing. This study aims to convert analog DST tools into digital ones using Arduino UNO R4 WiFi-based microcontroller technology and a wireless data acquisition system. This innovation replaces analog dial indicators with digital dial indicators to record shear force and horizontal displacement data automatically and in real-time. This system is designed to generate automatic test reports in the form of tables, graphs, and soil parameters, such as cohesion and angle of internal friction. The results show an accuracy rate of up to 90% compared to test results with commercial digital DST, better operational efficiency with only one operator, and a 30% reduction in testing time compared to using analog DST. With an implementation cost of less than 10% of commercial digital DST, this solution offers affordable modern testing technology for laboratories with limited budgets. This article discusses the technical design, hardware implementation, software development, and performance analysis of the resulting tool.
Keywords: <i>Direct Shear Test; Laboratory Equipment Digitalization; Microcontroller; Soil mechanics laboratory; Wireless data acquisition.</i>	

INTRODUCTION

In civil engineering work, the stability and performance of a structure are closely related to the mechanical behavior of the soil beneath it. The mechanical properties of the soil significantly affect the design and safety of civil engineering structures. The soil on which a structure will be built must have the quality and ability to withstand the load of the structure above it. Soil quality not only determines the bearing capacity but also determines the stability of the structure. Soil testing has been widely accepted as a method of determining soil quality for various applications, one of which is in the construction sector. By testing the soil, it can assess its suitability for the project and obtain solid data, which can then be used to make the right decisions and plan construction according to the test data. In building a construction, it is important to pay attention to technical matters, such as soil testing in a soil mechanics laboratory.

The soil mechanics laboratory is an integral part of civil engineering research and learning, especially for analyzing soil parameters such as shear strength, bearing capacity, and slope stability. Soil shear strength parameters are needed for analysis in calculating the bearing capacity of the soil for foundations, planning retaining walls, determining the level of slope stability, thrust on retaining walls, and so on (Hardiyatmo, 2012). Soil shear strength, often determined through laboratory-based Direct Shear Test (DST), is a key parameter in assessing soil stability and designing structures such as retaining walls, slopes, and foundations. The purpose of DST testing

is to obtain soil parameters to calculate; 1) soil bearing capacity, 2) soil pressure on retaining walls, and 3) soil slope stability (Wesley, 2017). DST is a method used to measure soil shear strength under certain conditions. In this sample test, the soil is placed in a test box and given horizontal stress gradually until shear failure occurs. The results of this test provide the value of the shear force failure and other parameters that are important for structural planning, such as soil bearing capacity and slope stability (Craig, 1991).

DST testing requires special equipment made by the manufacturer to meet soil testing standards. The parameters measured by this tool are the magnitude of the shear force that occurs in the soil sample so that it experiences failure shear and obtains the failure shear value. The type of tool based on the measurement method is divided into analog and digital models. The quality of the instrument, the technology used and the method of operation greatly affect the price of the instrument, the level of accuracy of the test results and the ease of operation. Conventional DST equipment with analog dial indicators to measure shear force and horizontal deformation has the following limitations: low measurement accuracy due to manual reading errors, measurement data must be recorded manually in written form, the need for two operators to manage data collection and equipment operation simultaneously, and time-consuming manual data processing to produce test results.

These shortcomings hinder its application in laboratories with limited budgets. High-performance commercial digital DST systems overcome these problems but are very expensive for many laboratories, often reaching hundreds of millions of rupiah. This condition is a challenge for laboratories with limited budgets. Meanwhile, more affordable conventional DST equipment has limitations in accuracy, efficiency and ease of operation. Thus, an affordable solution is needed that maintains the functionality and accuracy of the digital system.

This study overcomes these limitations by upgrading existing analog DST equipment with digital dial indicators and wireless data acquisition capabilities. This improved system aims to bridge the gap between analog systems and high-cost digital alternatives, enabling affordable yet efficient soil testing for academic and professional laboratories. This study introduces a modified DST system that incorporates a digital dial indicator, wireless data acquisition, and automated report generation. By utilizing widely available microcontroller technology, this innovation offers a scalable and cost-effective alternative to high-end digital DST systems. This study will design and build a device that will be added (add-on tools) to the analog model DST soil test tool. With the addition of the device, the performance of the tool can be improved so that it can have advantages including: higher measurement result accuracy, direct measurement result data is automatically recorded in digital data form, the tool can be used by 1 (one) person to operate the tool, and direct measurement data is processed into a test result report using the DST-UM application.

Soil mechanics laboratory users who already have or will buy an analog DST measuring tool can utilize the innovative device so that the tool's performance increases to approach the advantages of a digital DST tool. After using this additional device, the DST tool has the advantage of automatically reading measurement data recorded as digital data, and directly processing measurement data into a test result report using the DST-UM application that has been programmed to analyze measurement data. This study aims to develop an analog DST tool into a low-cost digital tool, using microcontroller technology and wireless data acquisition. This innovation not only improves accuracy and efficiency, but also provides a solution for civil engineering laboratories to access modern testing technology.

Soil shear strength is the main parameter that determines the bearing capacity of the soil, the pressure on the retaining wall, and the stability of the slope. The condition of the collapse of a material occurs due to the combination of critical conditions of normal stress and shear stress (Mohr, 1910). The value of shear strength is formulated by Coloumb and Mohr in the equation (Hardiyatmo, 2012):

$$\tau = c + \sigma \operatorname{tg} \phi \quad (1)$$

with;

τ = soil shear strength (kg/m²)

c = soil cohesion (kg/m²)

σ = normal stress (kg/m²)

ϕ = angle of internal friction (degrees)

DST is a standard method used to determine the shear strength of soil. The main parameters measured are cohesion (c) and angle of internal friction (ϕ) (Das, 1995). This process involves applying normal and shear stresses to a soil sample until failure shear occurs. The test is carried out by applying a normal load to the soil sample in a shear box, then applying a shear force until the soil fails. DST tools generally consist of (Soedarmo & Purnomo, 2001): shear box: where the soil sample is tested, proving ring: measures the applied shear force, and dial indicator: measures horizontal and vertical deformation.

Technological developments allow analog components to be replaced with digital ones to improve accuracy and efficiency (Buehler & Stojanovic, 2020). Digitization allows data to be acquired automatically, recorded in digital format, and processed using software, thereby reducing the potential for manual errors (Hernandez & Sánchez, 2016). The application of digital measuring instruments, such as digital dial indicators, has significantly improved the accuracy and efficiency of geotechnical testing. Digital systems offer real-time data logging and compatibility with data acquisition systems, allowing for automated generation of results. Despite these advances, affordability remains a challenge, especially for laboratories with limited budgets.

A microcontroller is a chip in the form of an IC (Integrated Circuit) that functions as a controller or controller of an electronic circuit and generally stores embedded programs (Budiharto, 2005). Arduino® UNO R4 WiFi is a very popular microcontroller platform for various programming and electronics applications. Arduino is easy to use for hardware and software integration (Sarma & Singh, 2014). The UNO R4 WiFi model allows wireless data acquisition and transmission, making it suitable for laboratory testing applications. Microcontroller technology has had a significant impact on the automation of laboratory testing processes. Arduino UNO R4 WiFi, as one of the microcontrollers used in this study, has the ability to receive input from digital sensors, process data, and send it wirelessly to a receiving device for further processing (Arduino, 2021).

Flexible Configuration: Microcontroller-based data acquisition devices, such as those described by Hercog and Gergič, offer flexibility in configuration, allowing for customized input/output settings without altering the firmware. This adaptability is crucial for tailoring the device to specific testing requirements (Hercog & Bojan, 2014). **Integration with Software:** The use of LabVIEW drivers facilitates the development of data acquisition and signal processing algorithms, enabling a seamless interface between the hardware and software components of the shear test tool (Hercog & Bojan, 2014).

Wireless Communication: The integration of wireless data transmission systems, as demonstrated in high-speed test rotating tables, allows for the contactless transfer of data from the testing apparatus to mobile electronic devices. This feature enhances the portability and convenience of the testing process (Gang, et al., 2018). **Portable Solutions:** Portable tools with wireless measured value transmission, such as those developed by Fluhrer et al., enable the remote monitoring and control of testing operations, reducing the need for physical presence at the testing site (Fluhrer, Rieger, & Kugler, 2012).

Precision and Stability: The incorporation of automatic data acquisition systems in direct shear test devices, as highlighted by Guo et al., ensures high measurement precision and stability. This is achieved through the use of strain control and precise stress measurement techniques (Guo, et al., 2014). **Versatility in Testing Conditions:** Devices like the dual-purpose direct shear tester by Liu and Zang offer the ability to conduct tests both in situ and indoors, accommodating various soil conditions and sample types. This versatility is essential for comprehensive soil strength analysis (Liu & Zang, 2008).

Digital Shear Stress Sensors: The development of digital shear stress sensors, as described by Park et al., demonstrates the effectiveness of digital devices in measuring soil shear properties. These sensors provide accurate data storage and retrieval, enhancing the reliability of test results (Park, et al., 2008). **Innovative Apparatus for Coarse-Grained Soils:** Cheng-gong's apparatus addresses technical defects in traditional shear testing methods, ensuring consistent shear area and

stress distribution. This innovation is particularly beneficial for testing large, coarse-grained soil samples (Cheng-gong, 2008).

The purpose of this study is to transform an analog direct shear test into a digital system by integrating microcontroller technology and wireless data acquisition. This innovation aims to improve the precision, efficiency, and usability of shear testing, which is very important in geotechnical engineering. This study will examine the key components, advantages, and challenges associated with this transformation, including improved real-time data acquisition, accuracy, and ease, as well as implementation cost.

RESEARCH METHODS

System Design and Component Integration

The proposed system enhances existing analog DST equipment by replacing analog dial indicators with digital dial indicator as sensors and incorporating wireless data acquisition. Key components include:

- 1) Dial Indicators: Mitutoyo digital dial indicators 575-121 for measuring shear force and 543-781 for measuring horizontal displacement.
- 2) Microcontroller: Arduino UNO R4 WiFi, programmed to receive data input from digital dial indicators, process it, and send the data to a computer via wireless technology.
- 3) SPC Connection Cable: Mitutoyo 905409 connects the digital dial indicator which has a data out interface feature to the microcontroller.
- 4) Software: PHP and C++ based desktop application was developed to record deformation data from digital dial indicators, process it into tables and graphs, and analyze the data to generate test results in cohesion and angle of internal friction.

Hardware Assembly

This innovation is done by replacing the analog dial indicator on the DST tool with a Mitutoyo digital dial indicators, type 575-121 for shear force measurement and type 543-781 for horizontal displacement measurement. This digital dial indicator is connected to the Arduino UNO R4 WiFi microcontroller via Mitutoyo 905409 SPC cables, which functions as a processing unit and sends data wirelessly to a computer using WiFi. The tool components and connections are illustrated in **Figure 1**.

Software Development

The DST-UM application was developed using PHP and C++ to provide functionalities for:

- 1) Real-time data monitoring dan recording.
- 2) Automated calculation of shear stress and normal stress.
- 3) Create a table of the relationship between horizontal displacement and shear stress.
- 4) Create a graph of the relationship between normal stress and failure shear stress from 3 samples.
- 5) Analyze data to generate test results in cohesion and angle of internal friction.

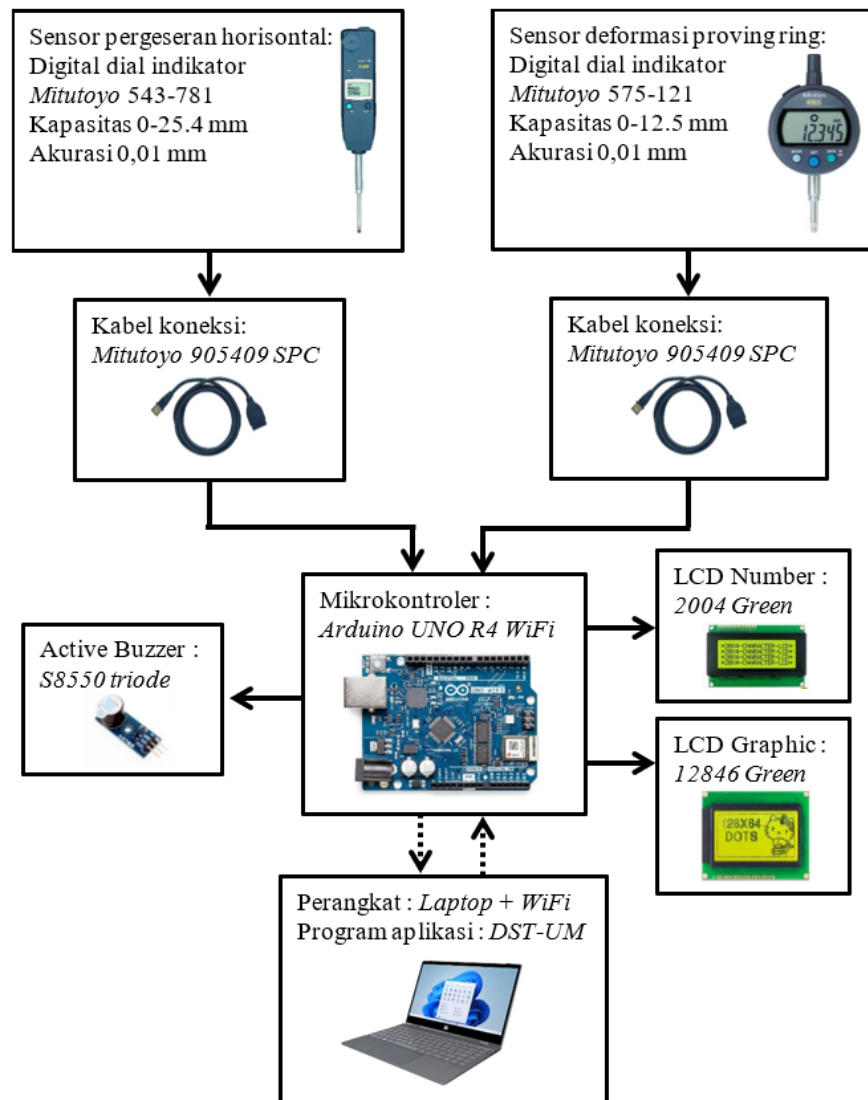


Figure 1. Tool Components and Connection Diagram

Data Acquisition and Processing

The procedure for operating the direct shear test equipment is the same as the general testing standard, the only difference is in the data acquisition. The shear force and horizontal displacement data read on the digital dial indicators are sent by Arduino R4 wifi wirelessly to specially designed application software (DST-UM). This software processes the data to produce test reports in the form of tables, graphs, and parameter values, such as cohesion (c) and angle of internal friction (ϕ). The numeric LCD is used to monitor the horizontal displacement and shear stress values, and the graphic LCD is used to monitor the horizontal displacement -shear stress relationship graph resulting from the application program analysis.

Experimental Testing

Three soil samples with varying normal loads were tested to evaluate the system's performance. Key metrics, including accuracy, repeatability, and operational efficiency, were compared with those from the commercial digital DST.

Performance Evaluation

The innovative DST tool was tested using three soil samples with different normal loads. The performance of the innovative DST tool was compared with analog and commercial digital

DST. The parameters measured included measurement result accuracy, operational efficiency, test result reporting and implementation costs.



Figure 2. Tool Prototype

RESULTS AND DISCUSSION

The upgraded DST system demonstrated the following improvements:

Level of Accuracy

The integration of a digital dial indicator eliminates human error in reading and recording measurements, providing precise measurements of horizontal displacement and shear force. The system achieves a resolution of 0.01 mm for horizontal displacement and 0.01 kgf for shear force. Three soil samples with varying normal loads were tested using innovation DST and commercial digital DST. The DST test results on 3 samples at normal stress and failure shear stress values is shown in **Table 1**.

Table 1. Comparison of DST Test Results

Sample Number	Normal Stress (kg/cm ²)	Failure Shear Stress (kg/cm ²)	
		Innovation DST	Commercial Digital DST
1	0,158	0,18	0,191
2	0,316	0,22	0,238
3	0,474	0,29	0,314

Table 1 shows the results of DST tests on 3 samples using Innovation and digital DST tools. The test uses the same normal stress which produce different shear stress values on both tools. The test results show that the shear stress that occurs has a different value and the difference is still below 10%. The test result graph relationship between normal stress and failure shear stress at **Table 1** is shown in the **Figure 3** and **Figure 4**. **Figure 3** show graph relationship between normal stress and failure shear stress using Innovation DST, and **Figure 4** show graph relationship between normal stress and failure shear stress using Commercial Digital DST. The parameter values of cohesion (c) and angle of internal friction (ϕ) in using both tools can be analyzed using graphs in **Figure 3** and **Figure 4** that have been made.

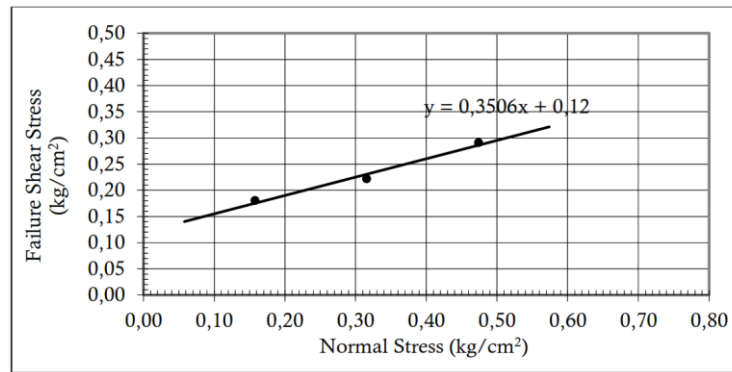


Figure 3. Test Result Graph Using Innovation DST

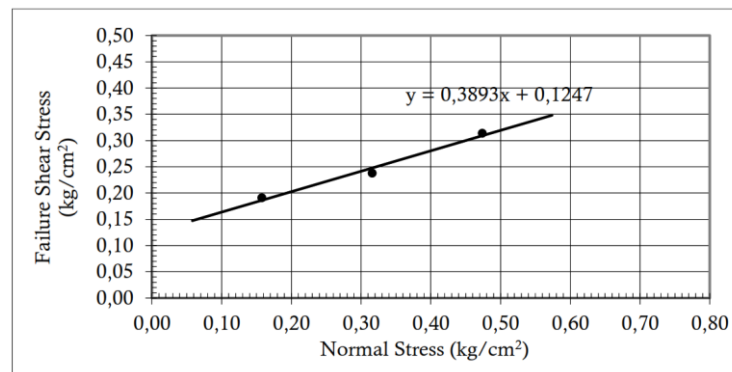


Figure 4. Test Result Graph Using Commercial Digital DST

The test result parameter values for cohesion (c) and internal friction angle (ϕ) from the analysis results are shown in **Table 2**. With differences in cohesion and the angle of internal friction, the innovative DST achieves an accuracy of up to 90% compared to commercial digital DST.

Table 2. Comparison of Test Result Parameter Values

Parameter	unit	Innovation DST	Commercial Digital DST
cohesion (c)	kg/cm ²	0,12	0,125
angle of internal friction (ϕ)	degree	19,32	21,27

Operational Efficiency

The integration of the microcontroller enabled real-time data logging, reducing the need for manual interventions. Testing can be performed by one operator without the need for manual recording. The improved DST equipment requires only one operator, compared to the conventional two-person operation, reducing personal needs demands. From **Table 3**, it can be seen the difference in testing time with 3 samples using analog DST and innovation DST. Each requires a testing time of 14 minutes 14 seconds and 9 minutes 10 seconds, the difference in testing time is about 35.60% of the time of 14 minutes 14 seconds. Real-time data acquisition and processing further reduces testing time by up to 30% compared to analog DST, allowing for faster turnaround for multiple samples.

Table 3. Comparison of Test Times

Sample Number	Test Time	
	Analog DST	Innovation DST
1	12 minute 32 second	8 minute 20 second
2	14 minute 47 second	9 minute 12 second
3	15 minute 23 second	9 minute 58 second
average	14 minute 14 second	9 minute 10 second

Automatic Reporting

Automatic processing of test data allows direct generation of test reports, including tables, graphs and test parameter values. The DST-UM application generates test reports immediately upon completion of the test. The reports include: a table of horizontal displacement and shear stress values, graphs illustrating the relationship between normal stress dan shear stress on the 3 tested samples, analyze the test parameter values of soil in cohesion (c) and angle of internal friction (ϕ).

Cost-Effectiveness

This innovation utilizes components such as the Mitutoyo digital dial indicator and Arduino UNO R4 WiFi which are economical compared to procuring commercial digital Direct Shear Test equipment. The innovative DST tool requires an implementation cost of around IDR 16,588,850, much cheaper than commercial digital DST tools which can cost up to IDR 200,000,000 - IDR 400,000,000. The total cost of upgrading the analog DST equipment to digital is less than 10% of the price of a new digital DST system. This makes the proposed solution highly accessible for laboratories with limited budgets.

Limitations and Challenges

Although the innovation of digital-based DST offers many advantages, there are still some limitations and challenges in its implementation. The accuracy of the instrument can be reduced when used on certain types of soil, such as cohesive or coarse-grained soil, requiring additional calibration. In addition, laboratories that do not have adequate technological infrastructure, such as a stable WiFi network, may have difficulty adopting this instrument. Electronic components, such as digital dial indicators and microcontrollers, are also susceptible to damage due to less than ideal environments, such as high humidity or exposure to dust. Maintenance and repair of this instrument require specialized technical expertise, which can be a challenge for laboratories with limited human resources. The dependence on software can also be a barrier, especially if there is a technical problem that affects data processing. In addition, users who are used to analog systems may need time to adapt and learn this new technology. Although the cost of this instrument is lower than commercial digital systems, the initial investment in high-quality components remains a challenge for laboratories with limited budgets. These constraints indicate the need for further development to make this instrument easier to use, more durable, and more affordable.

CONCLUSION

Comparative analysis indicated that the performance of the upgraded system matched that of high-cost digital DST equipment, validating the efficacy of the proposed modifications. This study successfully demonstrated the performance enhancement of analog DST equipment through the integration of digital measurement sensors and wireless data acquisition. The improved system offers significant improvements in accuracy, operational efficiency, and immediate data processing to produce test result reports, at a much lower cost than commercial digital DST systems. This tool offers an economical and practical solution for soil mechanics laboratories, especially in institutions with limited budgets. This innovation reduces the cost of purchasing new equipment while improving the quality of test results.

The results of this innovation have the potential to be widely applied to other soil mechanics testing equipment and can be the basis for further development in laboratories with limited resources.

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