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Design and Development of a Prototype Early Warning System for Landslide Detection Based on Mechanical Movement with an Automatic Ground Displacement Detector

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Abstract. This research aims to design a prototype of a landslide early warning device based on mechanical motion with an automatic displacement detector. The displacement of the soil pulls the rope and rotates the spool connected to the rotary encoder. The encoder pulse is processed by ESP32 into a linear displacement, displayed on a 16 × 2 I2C LCD, and used to activate the buzzer. The moisture sensor and MPU6050 function as supporting parameters. Seepage observations for 10 minutes produce a final value of 52 mm in loose soil, 28 mm in white or chalky soil, and 16 mm in clay. The system divides the prototype displacement range into Safe, Alert, Standby, and Caution from less than 1 mm to at least 9 mm. These thresholds have not yet become field hazard standards and still require calibration, documented repeated testing, and validation on actual slopes. The research methods include literature study, design, construction, programming, and testing on loose soil, clay, and white or chalky soil. The prototype uses a multi-level glass container measuring 85 cm × 35 cm × 60 cm with a media slope of 18.4°. The research results in a mechanical-electronic system designed to classify conditions based on shift values, ranging from safe, alert, standby, to caution. At the prototype scale, the warning range is set from shifts below 1 mm to at least 9 mm, with a continuously active buzzer at Warning III level. This threshold value is the prototype's operational threshold and still requires calibration and field testing before being used on actual slope conditions. This tool is expected to be an affordable alternative early warning system to help increase community awareness in landslide-prone areas.

Keywords: *Prototype Design, Landslide, Mechanical Motion, Rotary Encoder.*

A. INTRODUCTION

A landslide is the movement of a mass of soil, rock, or slope-forming material from a higher elevation to a lower one. This movement can be triggered by increased moisture content, changes in pore-water pressure, slope steepness, erosion, vibrations, and changes in land use. An evaluation of the landslide event in Banaran revealed that steep slopes, thick and loose weathered soil, land-use changes, and high rainfall acted in combination (Naryanto et al., 2019). Studies in Agam Regency and Silo District also identified rainfall, slope steepness, soil conditions, and ground movement as critical parameters for susceptibility assessment (Adfy & Marzuki, 2021; Susetyo et al., 2023). Given the multifaceted nature of the causes, monitoring only a single parameter risks yielding an incomplete interpretation. Slope simulations in Pagelaran further demonstrated that a rise in the groundwater table could reduce the slope's factor of safety (Kristyanto et al., 2020).

Early warning systems do not directly prevent landslides but instead detect changing conditions, enabling faster implementation of safety measures. National designs have incorporated moisture and vibration sensors (Susilo et al., 2011), moisture and tilt sensors with remote alert transmission (Setyawan et al., 2020), as well as displacement sensors, rain gauges, and telemetry systems (Sunardi et al., 2020). Device placement must still take into account susceptibility maps and elements at risk; UAV-based studies and multi-criteria analyses indicate that the quality of location data determines the accuracy of risk assessments (Fariz et al., 2023; Hamdani et al., 2025).

Domestic research indicates that ground displacement can be detected through various mechanisms. Mardhatillah and Wildian (2017) utilized springs, LEDs, and photodiodes; Diana and Wildian (2019) developed a spring-based detection system with SMS notifications, whereas Bilah (2018) utilized simple mechanical sensors to trigger sirens and SMS alerts. More quantitative measurements were achieved through fiber-optic extensometers (Bayuwati et al., 2017) and wire extensometers based on optical rotary encoders (Setiono et al., 2023).

Multi-sensor approaches leverage the relationship between groundwater conditions and changes in slope position. Parwati et al. (2018) combined hygrometers with piezoelectric sensors, while Artha et al. (2018) integrated MPU6050 sensors and moisture monitoring with an Android output. Similar integrations have been developed using web-based and IoT monitoring systems (Dasmasela et al., 2020; Utama et al., 2022; Mahardika et al., 2023). Hidayah et al. (2022) demonstrated that accelerometers and fiber optics could provide information on both the direction and magnitude of displacement during ground movement simulations.

Regarding communication, Awaludin and Dhewa (2018) emphasized the need for low-cost, reliable sensor nodes. Setyawan et al. (2020) used NodeMCU to transmit moisture data; Sunardi et al. (2020) implemented telemetry for displacement and rainfall monitoring; Priyadi et al. (2022) combined SMS with Progressive Web Apps; and Nurrokhnim et al. (2025) recorded displacement and moisture levels via telemetry. Long-range communication extends the reach of information but increases requirements for network infrastructure, power supply, data storage, and maintenance.

A significant gap remains for simple, locally deployed devices capable of displaying displacement magnitude directly while providing moisture and tilt context, without relying on computers or networks. This research addresses that gap through a system comprising a cable-spool-rotary encoder mechanism, ESP32 processing, an LCD display, and a multi-level buzzer alarm. Consequently, the output does not merely indicate the presence or absence of movement but presents displacement in millimeters as the basis for the prototype's operational status.

Unlike designs that rely solely on humidity or tilt angle as triggers, this study prioritizes linear displacement as the primary parameter. Humidity and tilt serve as contextual factors, while the LCD and buzzer provide local output. This configuration maintains a direct link between the detected phenomenon—ground movement—and the warning mechanism, while also preserving a relatively simple construction suitable for further development.

This study develops an early warning prototype featuring a primary detector composed of a cable, spool, and rotary encoder mechanism. Physical displacement of the soil mass is translated into encoder rotation; the ESP32 then converts the resulting pulses into linear displacement values and controls the display and alarm system. Humidity sensors and an MPU6050 sensor are utilized as supplementary parameters. The research objectives include designing the prototype, explaining the principle of converting mechanical motion into digital data, establishing automated warning levels, and analyzing test data obtained from soil samples in a laboratory setting.

B. LITERATURE REVIEW

1. Ground Displacement Monitoring

Surface displacement is a parameter that directly indicates mass movement. A wire extensometer connects two points via a cable and converts changes in length into displacement data. Setiono et al. (2023) demonstrated that optical rotary encoder pulses can be converted into linear measurements for monitoring translational landslides.

Similar approaches utilizing LVDTs, potentiometers, springs, and fiber optics highlight the importance of benchmarking against reference instruments, maintaining tension in the pulling element, and ensuring mechanical stability (Mardhatillah & Wildian, 2017; Bayuwati et al., 2017). Modern telemetry systems also prioritize displacement as a key data point requiring continuous recording (Nurrokhnim et al., 2025).

2. Moisture and Tilt Monitoring

Moisture data helps explain changes in soil conditions resulting from infiltration. Wahyuni and Wildian (2022) combined a linear potentiometer with a moisture sensor to distinguish between alert and danger states. Combinations of the MPU6050 sensor and moisture sensors have also been employed in Android, web, and IoT-based systems (Artha et al., 2018; Utama et al., 2022; Mahardika et al., 2023).

Nursuwars et al. (2019) incorporated a rain sensor to enhance the interpretation of ground movement. Given the MPU6050's susceptibility to drift, offset calibration and the fusion of accelerometer and gyroscope data are necessary before using tilt angles as a basis for decision-making (Mangkusasmito et al., 2020).

C. METHOD

The research employed a prototype design and testing methodology. The activities were conducted in Buha, Manado City, between March and July 2026. The research stages included a literature review, determination of functional requirements, preparation of tools and materials, construction of the container and circuitry, ESP32 programming, sensor zero-point calibration, testing of three types of soil media, and analysis of the results. The test media consisted of loose soil, clay, and white soil (or limestone).

Table 1. Prototype Design and Testing Parameters

No.	Parameter	Value/Condition
1	Test container	Tiered glass container; 85 cm × 35 cm × 60 cm
2	Media profile	Rear height: 50 cm; middle: 40 cm; front: 3 cm
3	Initial slope angle	18.4°
4	Detector distance	40 cm under initial conditions
5	Media	Loose soil, clay soil, and white/chalky soil
6	Planned repetitions	Three repetitions for each soil type
7	Artificial water discharge	2 L/min at constant opening
8	Seepage measurement interval	Every 1 minute for 10 minutes
9	Main parameter	Linear displacement measured by a rotary encoder
10	Supporting parameters	Soil moisture and changes in slope angle

The anchor post is installed in a soil mass expected to undergo movement, whereas the detector post is placed in a relatively stable area. Displacement of the anchor post pulls a cable, rotating the spool on the rotary encoder shaft. The encoder pulses are counted by an ESP32 to determine the displacement. The system's mechanical-electronic architecture is illustrated in Figure 1.

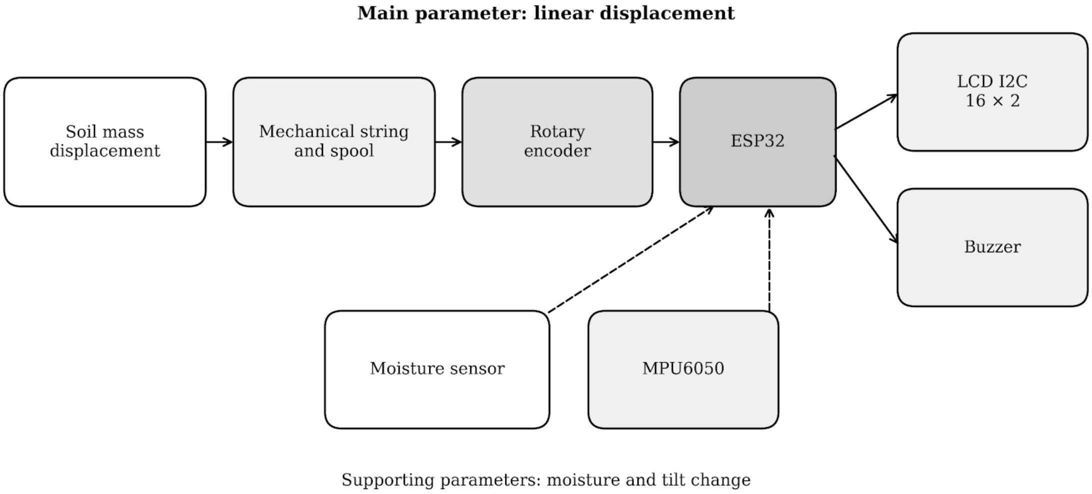


Figure 1. Mechanical-Electronic Architecture of the Landslide Early Warning Prototype

Table 2. Functions of Key System Components

No.	Component	Type	Function
1	Rotary encoder	Primary input	Converts spool rotation into pulses
2	Capacitive soil moisture sensor v1.2	Secondary input	Monitors changes in soil moisture
3	MPU6050	Secondary input	Reads changes in tilt/inclination
4	ESP32 Dev Kit	Processor	Calculates displacement and determines status
5	LCD I2C 16 × 2	Output	Displays values and alert levels
6	Buzzer	Output	Provides an audible alert

Linear displacement is calculated based on the number of encoder pulses, the number of effective pulses per revolution, and the spool diameter. The conversion equation used is: $s = (N/PPR) \times \pi D$ where s is the linear displacement of the cable (mm), N is the number of pulses since the zero point, PPR is the effective number of pulses per revolution, and D is the effective spool diameter (mm). The spool diameter, PPR, counting direction, and cable tension must be calibrated, as slippage, cable slack, or multi-layer winding can introduce bias.

Prior to testing, the media geometry and sensor positions were standardized, the cable was pre-tensioned, and the encoder reading was zeroed. Water was supplied at a constant flow rate of 2 L/min. Seepage values were recorded every minute for a duration of 10 minutes. Although the thesis design specified three replicates for each soil type, the source document did not provide the complete logs of the nine tests regarding displacement, moisture content, angle, and alarm activation time. Consequently, the analysis did not calculate the system's accuracy, precision, standard deviation, or success rate.

The test tank was constructed from transparent glass panels to allow for the observation of crack formation, failure planes, seepage, and soil movement patterns from the side of the container. The fabrication process involved cleaning the glass, marking and cutting it to size, joining the panels with silicone sealant, allowing the adhesive to cure, and verifying joint strength and checking for potential leaks before filling the container with soil.

Figure 2. Test Tank

The soil medium was shaped with a consistent profile for every test: a height of 50 cm at the rear, 40 cm in the middle, and 3 cm at the front, resulting in an initial slope of 18.4°. The test tank setup was designed to simulate slope conditions for testing a mechanical-motion-based landslide early warning system equipped with an automatic soil displacement detector. The tank was constructed primarily from transparent glass, with dimensions of 85 cm in length, 35 cm in width, and 60 cm in height. Glass was chosen to allow direct observation of soil movement from the side, ensuring that crack patterns, failure planes, and the direction of soil movement could be clearly seen. Additionally, the glass sections were joined using silicone sealant, creating a structure strong enough to withstand soil and water pressure during testing.

The dimensions of the test tank allowed for the creation of an 18.4° slope, ensuring consistent simulation of slope conditions across all tests. This dimensional uniformity was crucial to ensure that each type of soil medium started under identical conditions, thereby allowing for objective comparison of the test results.

D. RESULTS AND DISCUSSION

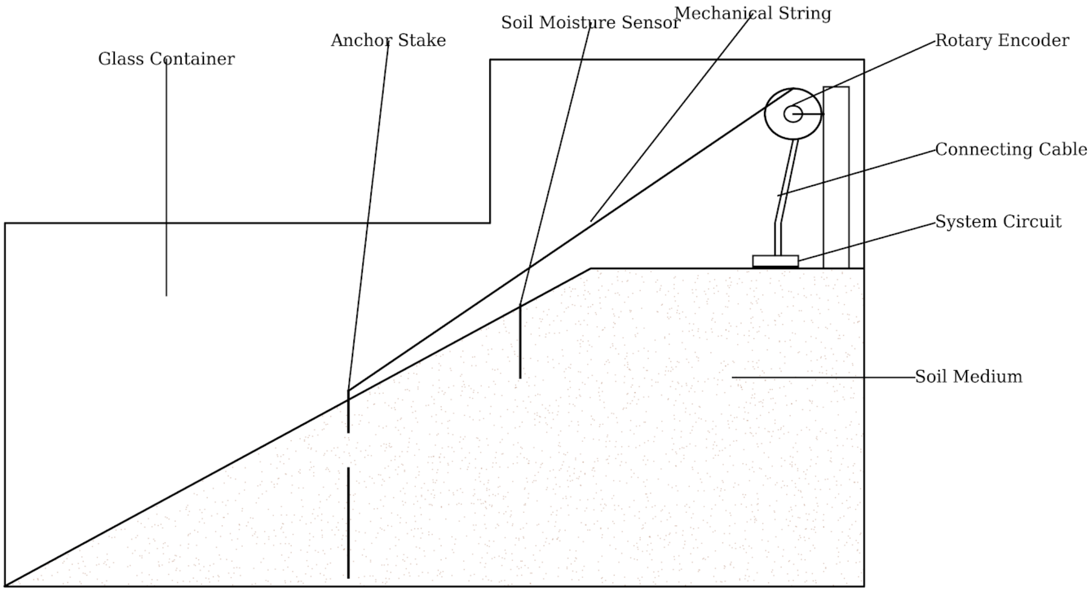
1. System Design Results

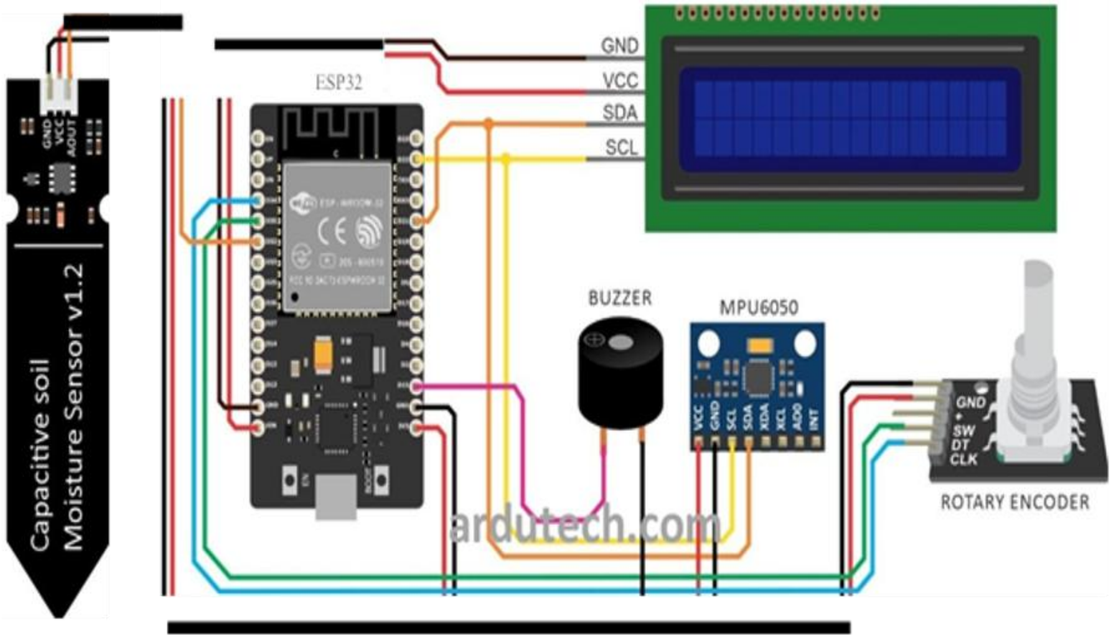
The research yielded a prototype of a terraced slope housed in an open, rectangular glass container. The glass enclosure facilitates the observation of cracks, seepage, and deformation of the medium. The system operates via a combined mechanical-electronic mechanism: soil displacement pulls a cable, an encoder generates pulses, an ESP32 calculates the distance, an LCD displays values and status, and a buzzer provides an alarm. This functional arrangement establishes displacement as the primary indicator of soil movement, while moisture and tilt data help explain the accompanying conditions.

This approach aligns with the use of encoder-based wire extensometers for monitoring translational displacement (Setiono et al., 2023) and fiber-optic extensometers on artificial slopes (Bayuwati et al., 2017). For field-scale deployment, a spring-loaded winding mechanism and a waterproof housing should be incorporated to maintain constant cable tension and ensure readings remain unaffected by moisture. Telemetry logging can be employed to continuously record the history of displacement and moisture levels (Nurrokhnim et al., 2025). Additionally, the tilt sensor must be mounted on a fixture that moves in unison with the medium, rather than on the stationary control box.

Figure 3. Stages of Cutting, Joining, and Filling the Test Tank

Visual inspection results indicate that the connected panels form a tiered container capable of holding media and allowing water flow during the simulation. The transparency of the glass facilitates direct observation; however, conclusions regarding structural strength remain limited to the conditions of the prototype test. For applications involving larger soil volumes or higher lateral pressures, it is necessary to verify the glass thickness and joint quality, as well as to add protective framing at the container corners.





2. **Water Discharge and Seepage Patterns**

Artificial watering was administered at a flow rate of Q = V/t. Loose soil received 4 L over 2 minutes; white or calcareous soil, 6 L over 3 minutes; and clay soil, 8 L over 4 minutes. All three conditions resulted in the same flow rate: 2 L/minute. Uniformity in flow rate was required to ensure that any differences in response could be attributed to the characteristics of the medium rather than variations in the watering rate.

Table 3. Water Seepage Data in Three Types of Soil Media

Time (Minutes)	Loose Soil (mm)	Clay (mm)	White Soil/Chalk (mm)
1	5	2	3
2	11	4	6
3	18	5	9
4	24	7	12
5	30	8	15
6	35	10	18
7	40	12	21
8	44	13	23
9	48	15	26
10	52	16	28

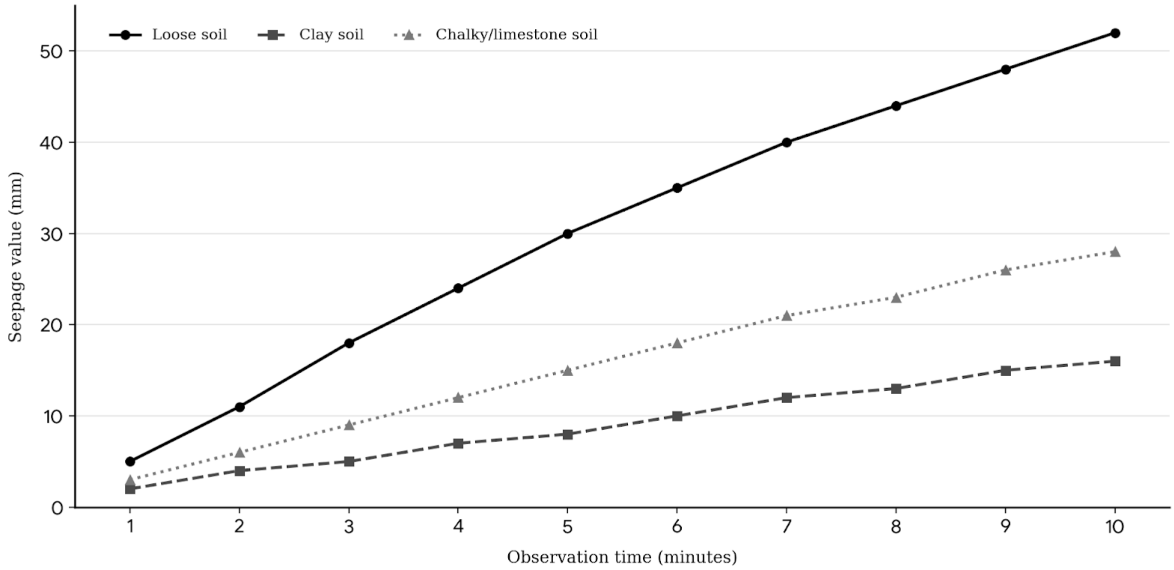


Figure 3. Progression of Water Seepage Over 10 Minutes Across Three Test Media

At the 10-minute mark, seepage values reached 52 mm for loose soil, 28 mm for white soil (limestone-rich), and 16 mm for clay. The average rates of increase from the first to the tenth minute were approximately 5.22 mm/min, 2.78 mm/min, and 1.56 mm/min, respectively. Loose soil exhibited the fastest water penetration, whereas the fine particles of clay slowed infiltration into the subsurface.

Seepage values cannot be directly equated to the level of landslide risk. Rapid seepage can accelerate the increase in soil mass weight, yet slow infiltration in clay can lead to surface ponding and the formation of a slip plane upon saturation. Therefore, interpretation must integrate factors such as displacement, moisture content, slope inclination, and the mechanical properties of the medium. This multi-parameter approach aligns with studies on landslide causes and the development of moisture-vibration sensors in Indonesia (Naryanto et al., 2019; Adfy & Marzuki, 2021; Susilo et al., 2011).

3. Prototype Warning Level

Warning levels are determined primarily based on linear displacement. The terminology in the operational table aligns with the conclusions of the thesis: "Waspada" (Caution) applies to displacements of 1 mm to less than 4 mm; "Siaga" (Alert) to 4 mm to less than 7 mm; and "Awas" (Warning) to 7 mm and above. Each level triggers an LCD display and a buzzer sound pattern of increasing intensity.

Table 4. Warning Stages Based on Ground Displacement

Displacement (mm)	Stage	Condition	Buzzer Response
0–<1	Safe	No significant displacement	Buzzer off
1–<2	Alert I	Minor initial displacement	Short beep
2–<3	Alert II	Increasing displacement	Slow periodic beep
3–<4	Alert III	Displacement becoming visible	Periodic beep
4–<5	Standby I	Continued displacement	Moderate interval
5–<6	Standby II	Greater increase	Faster beep
6–<7	Standby III	Approaching danger limit	Rapid beep
7–<8	Warning I	Danger at prototype scale	Very rapid beep
8–<9	Warning II	Displacement continues	Almost continuous

≥9	Warning III	Highest testing level	Continuous beep

The 1–9 mm range represents the prototype's operational threshold rather than a standard value for slope safety. Field-specific values must be determined through calibration, repeated testing, geotechnical analysis, and validation at sites representative of actual conditions. The system should ideally maintain the highest level reached until a manual inspection and reset are performed, or implement hysteresis and a minimum duration to prevent status oscillation caused by vibration and pulse noise.

4. Evaluation and Limitations

The design's strength lies in its easily traceable mechanical linkage: ground movement pulls the cable, the cable rotates the spool, and the encoder generates digital data. However, the mechanical path is susceptible to cable slack, elongation, friction, slippage, or changes in effective diameter due to multi-layer winding. A single-layer grooved spool, low-elongation cable, tensioning mechanism, and water protection are required to minimize errors. Testing of encoder-based and fiber-optic extensometers indicates that sensor outputs must be compared against reference displacements and tested under conditions representative of actual slopes (Setiono et al., 2023; Bayuwati et al., 2017).

While available data demonstrate the system architecture, conversion equations, seepage data, and status logic, they do not yet present paired reference and sensor measurements for each trial run. Consequently, a quantitative statement regarding the device's accuracy or effectiveness cannot yet be made. Further testing must report absolute and relative errors, mean values, standard deviations, response times, false alarms, and detection failures. Prior to field deployment, the system also requires a waterproof enclosure, backup power, data logging capabilities, remote communication, and maintenance procedures. These requirements are evident in the development of telemetry, web applications, and IoT systems for landslide warnings (Sunardi et al., 2020; Priyadi et al., 2022; Dasmasela et al., 2020).

E. CONCLUSION

The research resulted in the design of a landslide early warning prototype based on a mechanical-electronic system. A tiered glass container measuring 85 cm × 35 cm × 60 cm served as the simulation medium. Soil displacement was transmitted via a cable and spool to a rotary encoder; an ESP32 microcontroller then converted the pulses into linear displacement, displayed the data on an LCD, and controlled a buzzer. A capacitive moisture sensor and an MPU6050 sensor served as supplementary monitoring components.

Observations of seepage over a 10-minute period revealed displacements of 52 mm for loose soil, 28 mm for white soil (limestone-rich), and 16 mm for clay. While these differences indicate varying infiltration responses, they are insufficient to determine landslide susceptibility without data on displacement and the mechanical condition of the slope. The warning logic categorizes displacement levels into Safe, Alert, Standby, and Warning, ranging from less than 1 mm to a minimum of 9 mm.

These thresholds cannot yet serve as field standards. Future development should prioritize calibrating the encoder against a reference measuring instrument, fully recording three trials for each medium, analyzing error rates and alarm consistency, accurately measuring rainfall, and validating the system on actual slopes.

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