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Real-Time Data for Monitoring Rainfall-Induced Landslide using IoT System

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ABSTRACT

Rainfall-induced landslides present a significant hazard to vulnerable communities, particularly in regions prone to intense or prolonged precipitation. Conventional landslide monitoring systems often lack the capability to provide timely and accurate early warnings, limiting their effectiveness in risk mitigation. This study proposes an integrated real-time rainfall-slope monitoring framework for landslide predictions that combines Internet of Things (IoT)-based sensor networks using Arduino Nano ESP32 with the Blynk application. Three phases of work were conducted, to fulfil the objectives of study which are 1) to investigate the geotechnical properties of soil from selected slope, 2) to develop a rainfall-slope monitoring system using Arduino Nano ESP32 with Blynk application, and 3) to assess the rainfall-slope monitoring system on a lab-scale slope model under controlled conditions. The system continuously monitors slope movement and environmental parameters such as soil moisture and temperature. The system was calibrated using these parameters, with critical values such as optimum moisture content and shear strength used as thresholds. The observation of surface runoff also takes into account things such as measuring the rate of infiltration. The system has successfully measured changes in slope properties such as soil moisture levels, which increased significantly with higher volumes of artificial rainwater varied by time in seconds (1000 ml to 5000 ml under durations of 20, 40, and 60 seconds). Additionally, slope angles decreased from 45.0° to 44.5°, due to the soil saturation increment. The system effectively detected changes in each parameter within a 60-second observation window per condition. Alerts were triggered when moisture exceeded 17.5% and tilt surpassed 10 mm. The study demonstrated that calibrated thresholds based on actual soil behavior significantly improve the responsiveness and reliability of early warning systems, especially for rainfall-induced landslides.

1. Introduction

Rainfall-induced landslides occur when heavy or extended rainfall stimulates the movement of rock and soil on sloping terrain. This phenomenon is more common in areas with steep terrain, weak or poorly compacted soil formations, and periods of heavy precipitation. When there is a heavy rain

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for a long period, the soil becomes saturated and loses shear strength, making it more prone to sliding. Additionally, as precipitation percolates into the soil, pore water pressure rises, and the frictional resistance between soil particles decreases [1, 2]. These activities can have a cumulative effect that alters the stability of the slope, creating instability and the possibility of landslides occurring.

An area's susceptibility to landslides caused by rainfall is influenced by several factors. Topography is important because areas with steep slopes are more prone to landslides by nature, especially when combined with erosive tendencies [3, 4]. The composition, stability, and compaction of the soil all play a major role in determining the possibility of landslides. Such occurrences are common in the Himalayan region because of its distinct topography and monsoonal rainfall patterns [5]. These kinds of landslides are common in Malaysia, especially during the monsoon season because of the country's tropical environment and heavy rainfalls of up to 700 mm each month. The increased precipitation levels can potentially saturate the soil, lowering its mechanical characteristics and, as a result, decreasing slope stability [4]. Intense and prolonged rainfall is a primary trigger for landslides as it increases pore water pressure within the soil, reducing shear strength and leading to slope failures [6]. The degree and duration of rainfall during the monsoon season are closely related to the initiation of landslides.

Reducing the risks connected to landslides caused by rain requires a variety of approaches. Early warning systems (EWS) that always monitor slope stability, soil moisture, and rainfall can send out vital notifications that allow for prompt evacuations of high-risk locations [7]. An essential function of land use planning is to highlight the need of avoiding building on steep slopes and putting erosion control measures in place. Additionally, by lowering surface runoff and fostering soil cohesiveness, preservation such as maintenance on slopes can also improve soil stability.

In the context of the Landslide Early Warning System using IoT, the deployment of sensors in landslide-prone areas is an essential component of this proactive monitoring approach. These sensors, including soil moisture, rain drop, water level, temperature, and humidity sensors, will be placed to collect data on slope movements, deformation, and other elements that affect slope stability and induce landslides. The use of IoT technology enables the seamless integration of various sensors, allowing for real-time data collection and transmission [8].

Rainfall-induced landslides threaten communities, infrastructure, and the environment, especially in regions with steep terrain, weak soils, and heavy precipitation. Traditional monitoring systems often fail to provide timely and accurate warnings, resulting in inadequate preparedness and response. Thus, an advanced system is needed for continuous observation of environmental factors that trigger landslides. Significant parameters include soil moisture, slope angle, surface runoff, temperature and humidity. Slope angles were measured to assess the impact of rainfall on slope stability, moisture sensors assess soil water content, temperature and humidity sensors detect changes in the physical characteristics of water and soil [6].

Existing systems lack real-time data integration and prompt threat communication. The proposed Landslide Early Warning System uses IoT technology to integrate various sensors for real-time data collection and transmission. Therefore in-corporation with Physical Sensors, Arduino and Blynk, an integrated systems are being developed to monitor the possibility of landslides to occur in real time. This system enhances response accuracy and timeliness, addressing the shortcomings of traditional methods and reducing natural disaster risks for communities in landslide-prone areas [9].

The aim of this study is to study the impact of rainfall on slope using IoT- based system with aims to create safer communities by providing accurate information to reduce the impact of landslides. The objectives are 1) to investigate the geotechnical properties of soil from selected slope, 2) to develop a rainfall-slope monitoring system using Arduino Nano ESP32 with Blynk application using selected sensors, and 3) to assess the rainfall-slope monitoring system on lab scale slope model.

2. Methodology

This study encompasses three pivotal phases essential for its completion. Phase 1 will be focused on soil geotechnical analysis, emphasizing mechanical and physical testing of the soil without altering its inherent properties and saturations. Phase 2 is dedicated to IoT development, involving tasks such as operating the sensors and consolidating all generated output into Blynk Application. During this phase, the collected data will be stored in a cloud-based system and displayed in a graph. Finally, Phase 3 integrates the outcomes of both Phase 1 and Phase 2, incorporating additional testing on a laboratory model that will be physically fabricated in the lab. The model will be testing on different rain intensities (1000 ml, 3000 ml, and 5000 ml) under different duration (20 second, 40 second, and 60 second). The flowchart for each phase t is shown in Figure 1 and Geotechnical properties analysis will be later further discussed in Results and Discussion section.

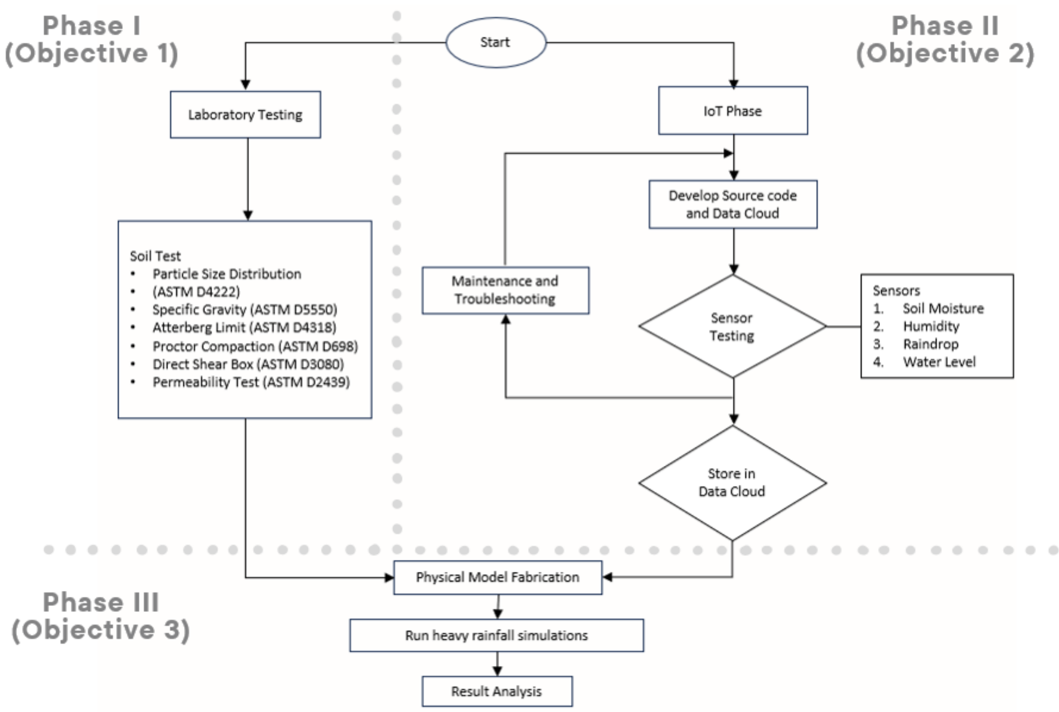
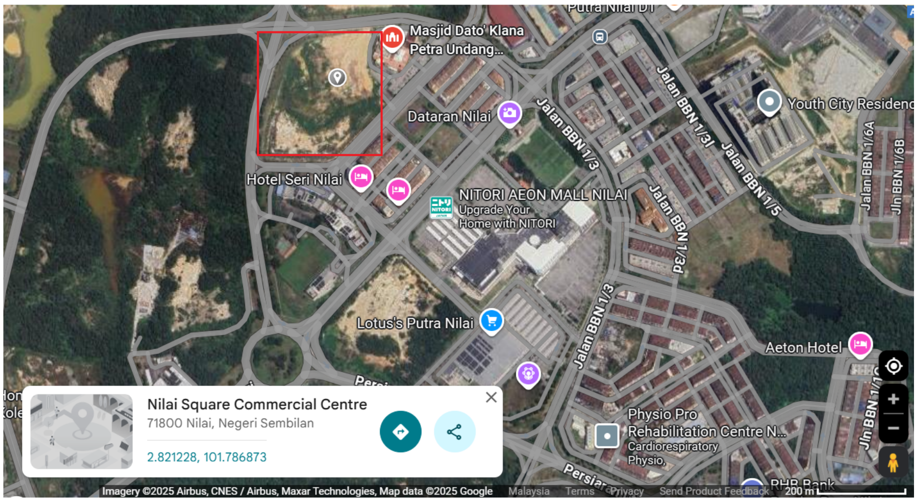


Fig. 1. Flow chart for the study

2.1 Location and Site Sampling

Nilai is situated in a region characterized by varied topography, including hills and valleys, which are inherently susceptible to landslides. The area's geological composition, consisting of weathered rock and soil layers, contributes to slope instability, especially during heavy rainfall. The presence of weak rock formations, such as shale and mudstone, further exacerbates the risk of landslides [10]. These geological and topographical features make Nilai an excellent case study location for examining the underlying causes of landslides and developing predictive models for slope failures.

Soil sample was collected at Bandar Baru Nilai, 71800 Nilai, Negeri Sembilan. The coordinate of the location is 2.821228E, 101.786873W. The geotechnical properties analysis of the soil sample is conducted at Soil Laboratory, Universiti Putra Malaysia (UPM), Malaysia.



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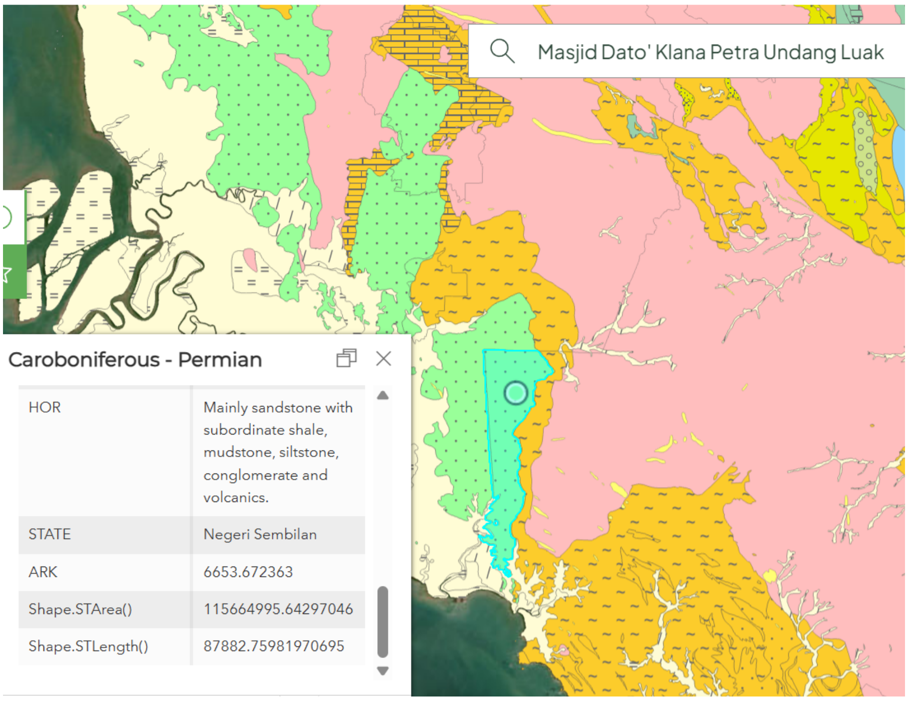


(c)

Fig. 2. a) Sampling location (Google Map, 2025), b) collecting process of disturbed samples at hilly area and c) geological map of Bandar Baru Nilai, Negri Sembilan, Malaysia.

2.2 Geotechnical Experimental

This section will discuss a geotechnical experimental conduct in soil laboratory to determine the physical and mechanical properties of studied soil. The referred standard for each test is shown in Table 1.

Table 1
Geotechnical properties test and the respective standards

Properties	Standard
Particle Size Distribution	[11]
Atterberg Limit (LL, PL)	[12]
Linear Shrinkage Limits, LS	[13]
Specific Gravity, G_s	[14]
Compaction	[15]
Permeability, k	[16]
Shear Strength	[17]

2.2.1 Physical Properties

The physical properties such as particle size distribution, Atterberg limit test and specific gravity were carried out for soil samples. For soil samples taken, sieve analysis is an essential technique for describing the distribution of particle sizes. This method yields a thorough material's gradation by the quantitative determination of mass across multiple size categories and the methodical segregation of particles. This test was conducted according to ASTM D 422-63 by using Endecotts EFL 2000 Sieve Shaker machine (Figure 2a). The resulting data set includes retained masses, percentages going through each sieve, and sieve analyses performed consecutively. This provides all the information required to ascertain the test sample's particle size distribution to determine the physical properties of the soil taken from the site. the liquid, plastic, and shrinkage limits of fine-grained soils, the Atterberg limits test is utilized. The Atterberg limits test was carried out based on the ASTM D 4318. This test was conducted by using the Casagrande apparatus as shown in Figure 2b. Specific gravity or known as pycnometer test (Figure 2c) stands as a fundamental and dimensionless property crucial to the understanding of soils materials. As the ratio of material density to water density, specific gravity plays a pivotal role in calculating essential soil parameters, including density, void ratio, and saturation. This test is carried out based on the ASTM D854-14.

(a) (b) (c)

Fig. 3. a) Sieve shaker apparatus for sieve analysis, b) Casagrande apparatus for liquid limit test and c) Pycnometer apparatus for specific gravity test

2.2.2 Soil Compaction Test

Compaction is a mechanical method designed to minimize the air spaces between soil particles by bringing them closer together. This results in densely packed soil with higher unit weight and density compared to less compacted soils. In construction, soil compaction is crucial because it provides working platforms. This testing follows the ASTM D698 standard, which outlines the methods for determining the compaction characteristics of soil in a laboratory using standard effort. The purpose of this test is to establish a relationship between the moisture content and the dry density of the soil to find the optimum moisture content for the soil.

Fig. 4. Standard Proctor test

2.2.3 Mechanical Properties Tests

Mechanical properties of soil were determined using Direct Shear Box apparatus to determine shear strength behaviour of soil and Falling Head Permeability test.

a) Direct Shear Box Test
The direct shear test entails placing a soil specimen in a shear box apparatus, applying a predetermined normal stress, and creating wetting with draining conditions for the specimen. The specimen is then consolidated under the applied normal stress. The test is conducted based on ASTM D 3080 – Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. In this test, two types of specimens, one dry and the other wet, are compared to determine the shear strength of each soil material. Shear strength is characterized as the maximum resistance a material can endure when subjected to shearing forces. The test is conducted using Soil Direct Shear Testing Machine Model ST-DS5A.

b) Falling Head Permeability Test
This test method is to determine the coefficient of permeability for laminar water flow through fine soils. This method is particularly suitable for assessing the permeability of fine-grained soils, such as those commonly encountered in natural deposits, embankments, or base courses beneath pavements. The falling-head permeability test is ideal for situations where a constant-head method is impractical or ineffective. It involves measuring the rate of water flow through a soil specimen under a falling hydraulic head, allowing for the determination of the soil's permeability coefficient (Figure 3a). This test is carried out based on ASTM D5856.

(a) (b)

Fig. 5. Mechanical properties tests a) Direct Shear Box and b) Falling Head Permeability tests

2.3 Internet of Things (IoT) Works Program

In this section, a brief explanation for each part of IoT system used in this study was discussion begin with the microcontroller board ESP32, Arduino IDE application, Blynk platform and related sensors to observe selected geotechnical parameters.

2.3.1 Microcontroller Board ESP32

ESP32 is a low-cost, low-power system-on-a-chip microcontroller featuring built-in Wi-Fi and dual-mode Bluetooth (Figure 6). The ESP32 is a multipurpose microcontroller with many IoT applications. Peer-to-peer (P2P) connectivity, which allows devices to communicate directly with one another, data processing capabilities ranging from simple sensor inputs to sophisticated calculations using real-time operating systems (RTOS) or non-OS software development kits (SDK), networking capabilities for establishing connections with Wi-Fi routers, and the capacity to operate as a web server, providing access to HTML or other development language-based pages, are among its primary features. Because of this, the ESP32 is appropriate for a wide range of IoT applications that need web server, data processing, and connection features.

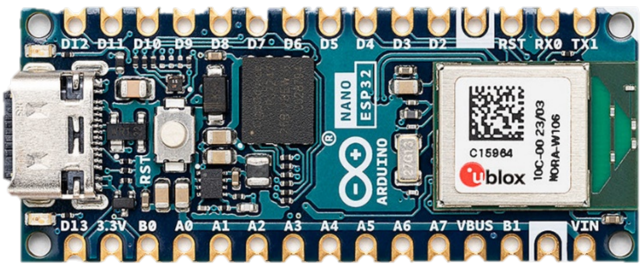


Fig. 6. Microcontroller ESP 32 (espressif.com)

2.3.2 Arduino IDE Application

The Arduino Integrated Development Environment (IDE) is a powerful tool that provides an easy-to-use platform for coding, compiling, and uploading programs to Arduino-compatible microcontroller boards. It supports a variety of libraries and hardware, making it versatile for a range of projects. In your case, you are utilizing the Arduino IDE to interface with various sensors to monitor parameters like soil moisture, slope angle, water level, humidity, and temperature.

2.3.3 Blynk Platform

Blynk is a comprehensive software suite facilitating the development, deployment, and remote management of connected electronic devices, suitable for both personal IoT projects and large-scale commercial products. It empowers users to connect hardware to the cloud, create mobile applications, analyze real-time and historical data, and remotely control devices. There are several packages that come with Blynk application such as Blynk Console, Blynk Apps., Blynk Edgent and Blynk Cloud.

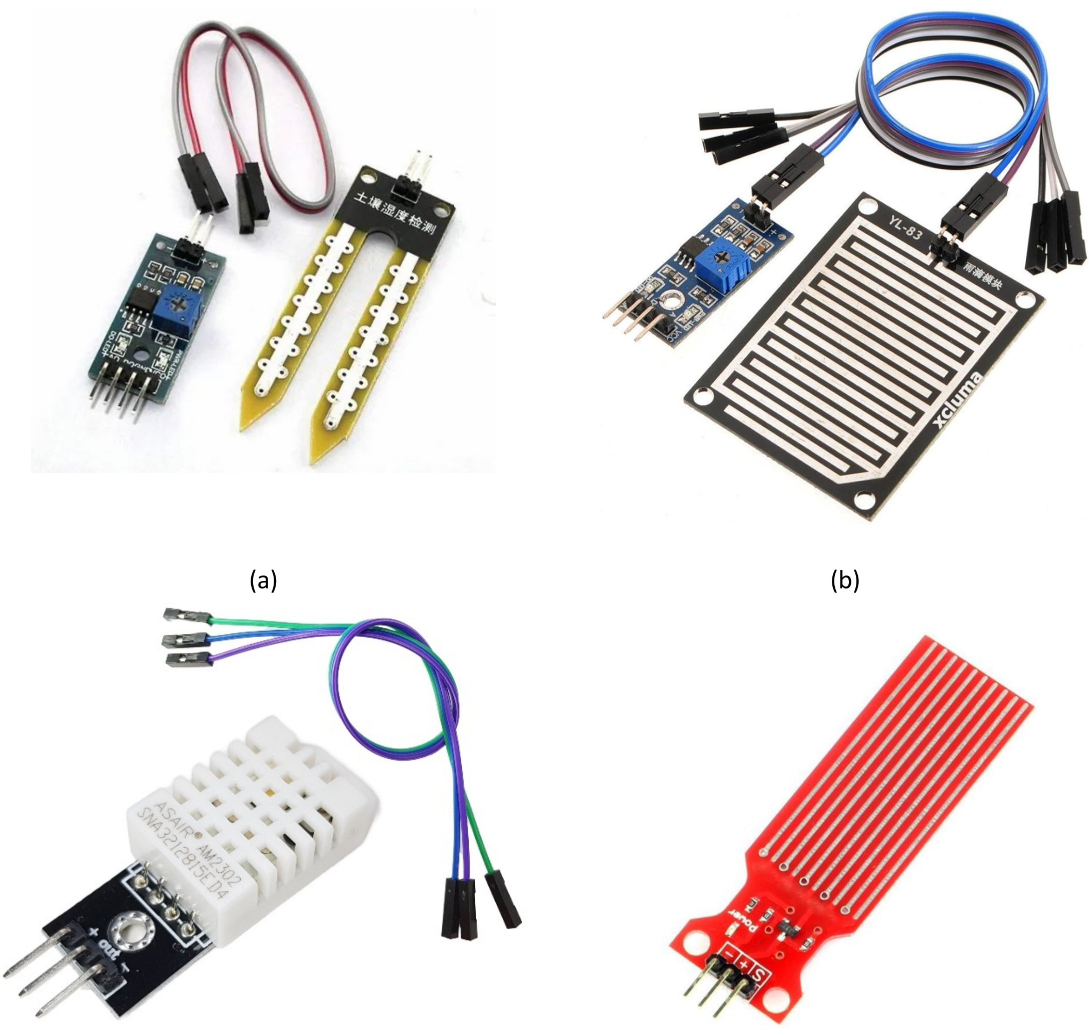
2.3.4 Sensors

a) Soil Moisture Sensor
The relationship between soil moisture and slope stability can be an important aspect in landslide monitoring systems, contributing to the overall resilience of sensitive locations. A soil moisture sensor is an important tool for detecting and monitoring soil moisture levels (Figure 7a). These sensors can detect variations in soil moisture content, particularly in landslide-prone locations, and can offer timely alerts as well as important information for landslide prediction and mitigation.

b) Raindrop Sensor
A raindrop sensor is a specialized device that detects and measures rainfall intensity (Figure 7b). It has conductive traces that respond to raindrops, transforming the conductivity change into a signal. Furthermore, raindrop sensors are useful for tracking landslides since they can measure the intensity of rainfall and correlate it with soil moisture content. This ability aids in determining the likelihood of landslides brought on by prolonged periods of precipitation.

c) Temperature and Humidity Sensor
Temperature and humidity sensors are critical for landslide monitoring, particularly when combined with other sensors (Figure 7c). These sensors measure two critical parameters: temperature and humidity, providing significant information about soil conditions. Temperature sensors assist in monitoring the soil's ambient temperature, contributing to a better understanding of the thermal dynamics that influence slope stability.

d) Water Level Sensor
Water level sensors can be used as part of a comprehensive landslide monitoring system to detect soil saturation levels (Figure 7d). Elevated soil water levels due to heavy rains may exacerbate landslides. A more precise evaluation of the risk of landslides can be made by combining data from water level sensors with information from other environmental factors, such as soil moisture levels and data from raindrop sensors.



(a) (b) (c) (d)

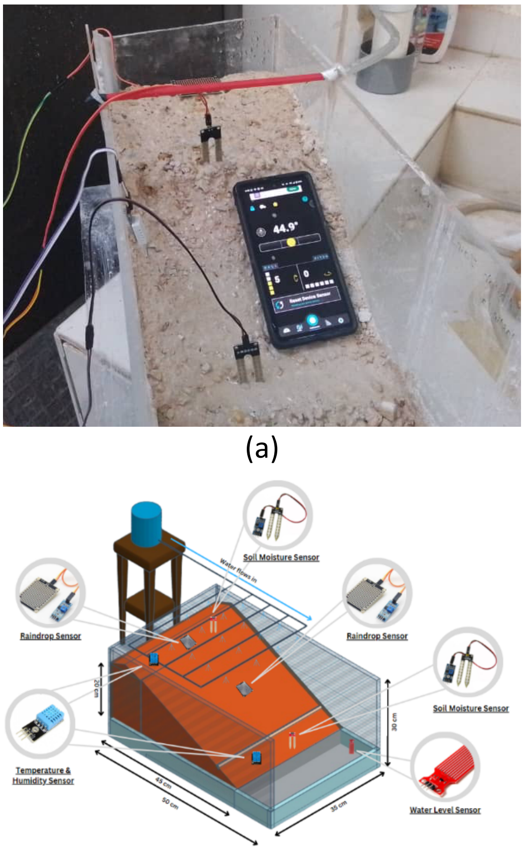
Fig. 7. Sensors used in this study a) soil moisture sensor, b) raindrop sensor, c) temperature and humidity sensor, and d) water level sensor

This study integrates Blynk, an IoT platform for remote monitoring and control of devices via the internet. The Blynk template ID, template name, and authentication token connects the ESP32 microcontroller to the Blynk server. Wi-Fi credentials are provided for network connectivity. Two soil moisture sensors connected to analog pins 35 and 34 measure soil water content. A DHT22 sensor on digital pin 33 measures humidity and temperature. A Blynk timer periodically reads these sensors and sends the data to the Blynk server. The “sendSensor” function reads values from the soil moisture sensors, converts them to percentages, and reads the DHT22 sensor for temperature and humidity. These readings are sent to the Blynk server using “BlynkvirtualWrite” and printed to the serial monitor for local monitoring. The setup function initializes serial communication, connects to Blynk, starts the DHT22 sensor, and sets the timer interval for data transmission. The loop function ensures continuous operation of Blynk and the timer. This system provides real time slope monitoring system.

Fig. 8. Example of Arduino code integrated with ESP32 microcontroller

2.4 Soil Slope Model Setup

This study expected to reflect the conditions of soil slope after different rainfall intensities under certain durations. The small prototype model was made as in Figure 3.14 to simulate and observe the effects on slope stability after it being subjected to rain. The soil moisture sensors were put in 2 places to gain data insight and investigate the difference between uphill and downhill on a slope. Figure 3.15 is the dimension and sensors placement on the slope model.



(a)

(b)

Fig. 8. The soil slope a) lab scale physical model and b) Model Design using Tinkercad

3. Results

3.1 Soil Geotechnical Properties

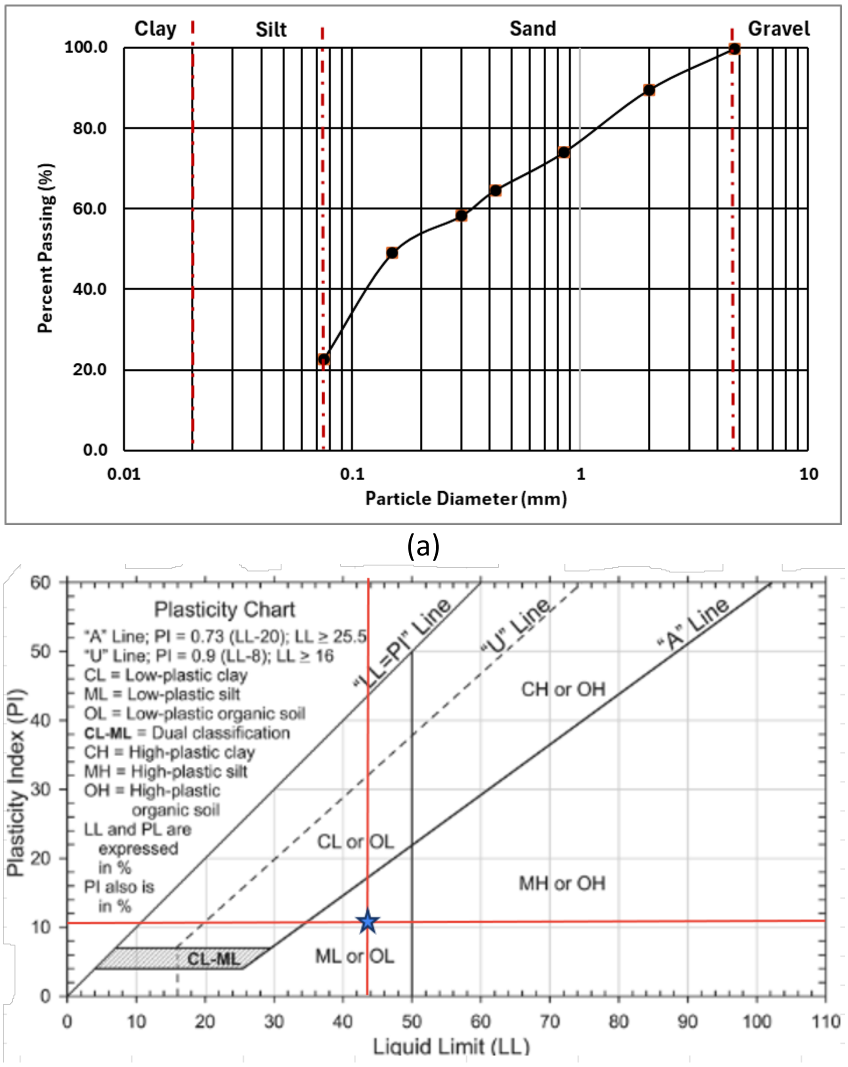
This section discusses the results obtained from the soil geotechnical properties experiments as tabulated in Table 1. Each of properties for the sample studied are discussed in the next sub section.

Table 1
The soil physical properties value

Soil Parameters	Unit	Values
Grain Size Distribution		
Gravel	%	0.2
Sand	%	77.1
Fines (Silt; Clay)	%	22.7
Specific Gravity	-	2.79
Plastic Limit, PL	%	34.03
Liquid Limit, LL	%	44.74
Plasticity Index, PI	%	10.71
Linear Shrinkage, LS	%	2.1
Initial Moisture Content	%	17.46
Compaction		
Opt. Moisture Content	%	14.3
Max. Dry Density	kg/m^3	1638
Soil Strength		
Cohesion, c	kPa	12.2
Internal Friction Angle, ϕ	°	21.1
Permeability, k	m/s	4.47×10^{-5}

3.1.1 Soil Physical Properties

Soil physical properties for the studied sample covered for particle size distribution, specific gravity and Atterberg limits with linear shrinkage determination. The results are summarized in Table 1. From particle size distribution curve as shown in Figure 9a, it was indicated the composition of studied soil primarily consist of sand and fines which are 77.1% and 22.7% with a negligible amount of gravel which is 0.2%. The specific gravity of sample is 2.79 showing the value in the range of silty sand and inorganic soil and the Atterberg limits values which are Liquid Limit and Plastic Limit, 44.74% and 34.03%, respectively. This finding led to the plasticity index value equals to 10.71%. Referring to the plasticity chart (Figure 9b) and Unified Soil Classification System (USCS), the soil type is categorized as ML – low silt and silty sand (SM), sand silt mixtures.



(b)

Fig. 9. a) Particle size distribution curve of studied soil sample, and b) Plasticity Index chart

3.1.2 Compaction Parameters

Soil compaction testing is critical as it determines the soil's maximum dry density and optimum moisture content. The maximum dry density indicates the highest density that soil can achieve under standard compaction efforts, while the optimum moisture content is the water content at which the soil reaches this maximum density. Proper soil compaction enhances the soil's load-bearing capacity and reduces settlement issues, crucial for the stability and longevity of engineering structures [18]. The lab results indicated a peak dry density of approximately 1638 kg/m³ at an optimum moisture content of around 14.3% (Figure 10).

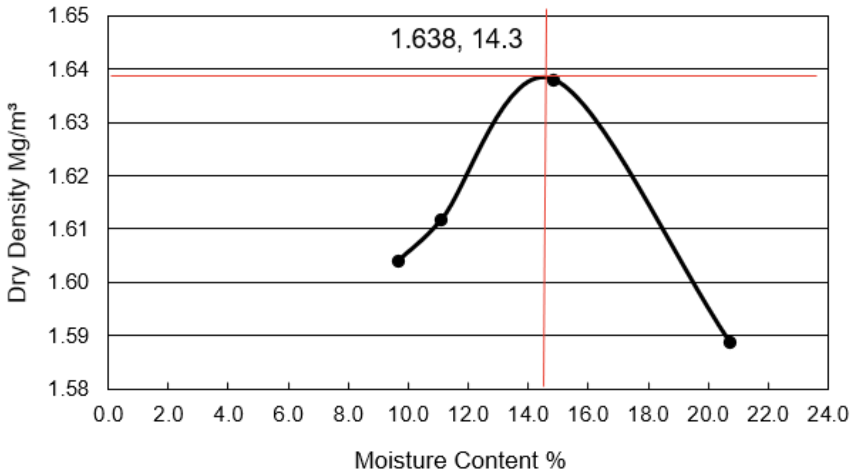


Fig. 10. Compaction curve of studied soil sample

3.1.3 Soil Mechanical Properties

The direct shear box test determines the shear strength parameters of soil, such as cohesion and internal friction angle, crucial for analyzing and designing foundations, slopes, and other soil-structure interactions. From the curve of shear stress versus normal stress (Figure 11), the internal friction angle, ϕ was around 21.2 degrees, and the cohesion, *c*, was approximately 12.2 kPa under saturated conditions.

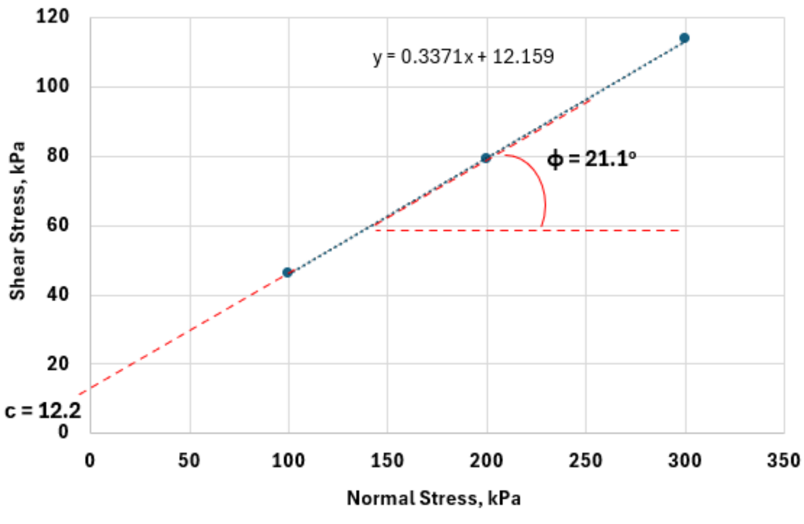


Fig. 11. Shear stress versus normal stress curves of studied soil sample

3.2 Analysis on Sensors Output of Soil Slope Model

The analysis of soil moisture readings and water runoff data provides significant insights into the behavior of soil under varying conditions of water application. Figures 12 and 13 illustrate these parameters, respectively, offering a detailed view of how soil moisture and water runoff change with different volumes of water and durations.

In Figure 12, the soil moisture readings for two locations, top of berm (Soil Moisture 1) and bottom of berm (Soil Moisture 2), are shown under various water application volumes (1000 ml, 3000 ml, and 5000 ml) and durations (20, 40, and 60 seconds). The data indicates that soil moisture percentages increased with the increments of the volume of water applied and the duration of application. For instance, after 20 seconds of water application, soil moisture is relatively low but shows a consistent increase as more water is added. At 60 seconds, the soil moisture readings are significantly higher, especially at the 5000 ml application, demonstrating a notable increase in soil moisture content reading. This trend is observed for both locations, although the location at bottom of berm consistently shows slightly higher moisture levels due to gravitational water flow.

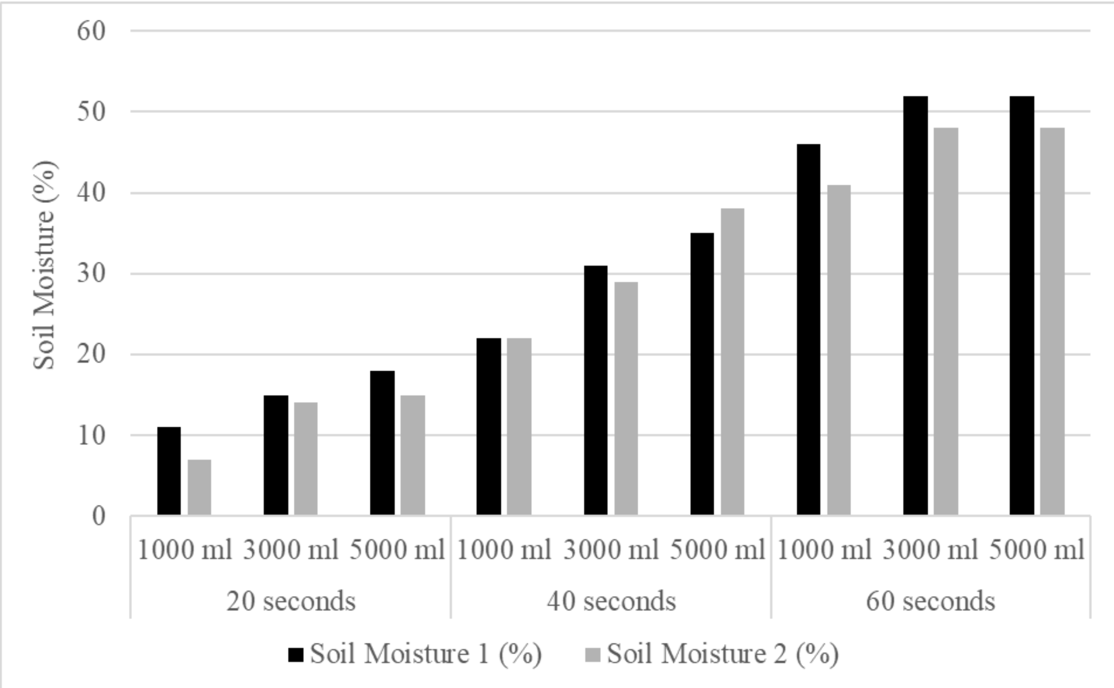


Fig. 12. Sensor's data reading on Soil Moisture 1 (Top of Berm) and Soil Moisture 2 (Bottom of Berm)

In terms of classification, the soil moisture remains relatively stable at lower volumes (1000 ml) and shorter durations (20 seconds). However, as the volume and duration of water application increase, there is a consistent rise in soil moisture levels, reaching high levels at the highest volume (5000 ml) and longest duration (60 seconds). Figure 13 illustrates the water runoff and infiltration for the same conditions. The data shows that water runoff increases with the volume of water applied, with a significant portion of the water infiltrating the soil at higher volumes and longer durations. For instance, at 5000 ml of water application for 60 seconds, the runoff volume is substantial, but there is also a considerable amount of water that infiltrates the soil. This indicates that while a large volume of water leads to increased runoff, it also promotes deeper soil infiltration, which is crucial for understanding water retention and soil saturation.

The classification of water runoff and infiltration shows that at lower volumes (1000 ml) and shorter durations (20 seconds), the infiltration is low, with most water contributing to runoff. With moderate volumes (3000 ml) and longer durations (40 seconds), there is a balanced distribution between runoff and infiltration. At the highest volume (5000 ml) and longest duration (60 seconds), runoff is high, but infiltration is also significant, indicating a high soil absorption capacity under prolonged water application. These findings highlight the importance of monitoring soil moisture and water runoff, especially in regions prone to rainfall-induced landslides.

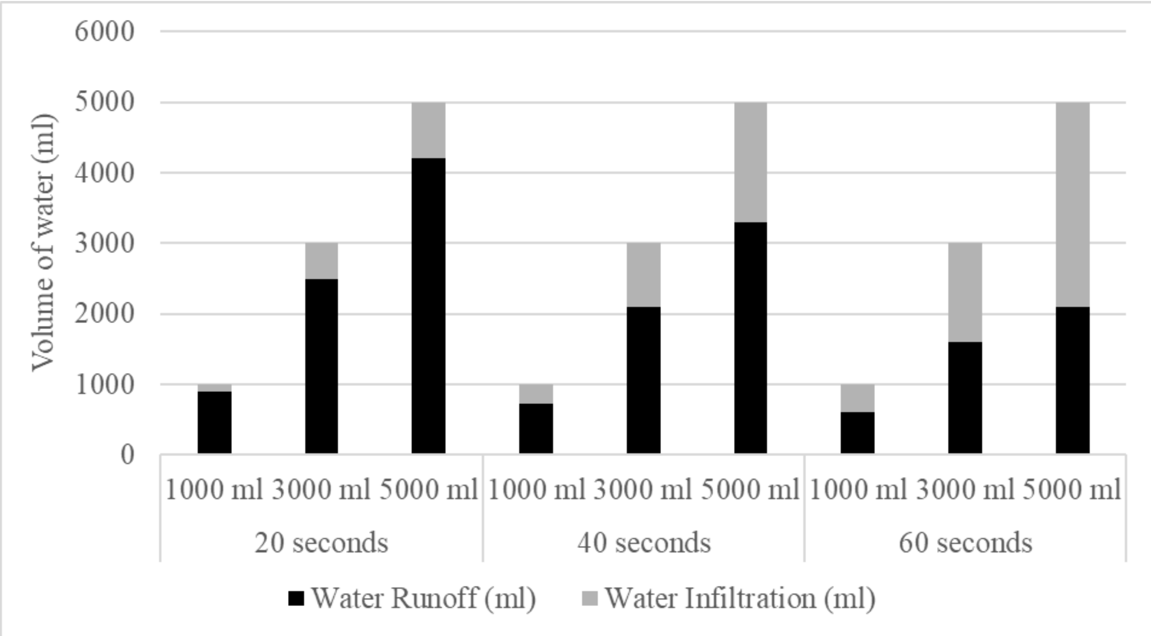


Fig. 13. Volume of water runoff and water infiltration of studied soil slope – lab scale

Table 2
Impact of variation precipitation on slope angle

Volume (ml)	Slope Gradient (°)	
	Before Raining Simulation	After Raining Simulation
Rain Duration = 20 seconds		
1000	45.0°	45.0°
3000	45.0°	45.0°
5000	45.0°	44.9°
Rain Duration = 40 seconds		
1000	45.0°	45.0°
3000	45.0°	44.9°
5000	45.0°	44.7°
Rain Duration = 60 seconds		
1000	45.0°	44.8°
3000	45.0°	44.8°
5000	45.0°	44.5°

As shown in Table 2, at a lower volume of 1000 ml, the slope angle remains relatively stable across all durations (20, 40, and 60 seconds). Specifically, at 20 seconds, the slope angle is unchanged at 45.0° before and after the simulation. This stability is maintained at 40 and 60 seconds, with only a minimal change to 44.8° after 60 seconds. These observations suggest that at lower water volumes, the soil structure retains its integrity, and the impact of water application on the slope angle is negligible. This stability indicates that most of the water likely contributes to surface runoff rather than infiltrating the soil, maintaining the soil's initial angle and moisture content.

Therefore, the slope angle, surface runoff volume, and soil moisture before and after rainfall simulation offers valuable insights into the behavior of soil moisture and water infiltration under different conditions. The stability at lower volumes contrasts with the increased infiltration and decreased soil stability at higher volumes, highlighting the need for careful monitoring and management of soil moisture in regions susceptible to heavy rainfall and landslides.

Continuous monitoring using IoT platforms like Blynk as shown in Figure 14 can provide real-time data, enabling early warning systems to mitigate risks associated with soil saturation and landslides. This real-time approach is crucial for effectives risk management in areas with heavy rainfall and steep terrains.

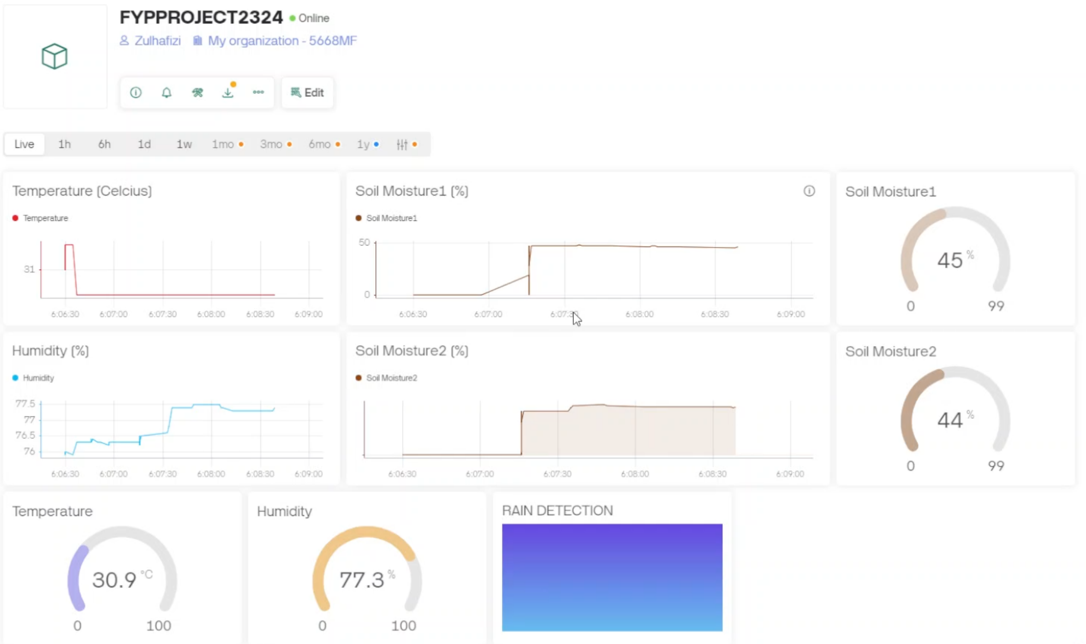


Fig. 14. Real time monitoring on sensors using Blynk

The monitoring system recorded sensor responses under simulated rainfall conditions. Moisture sensor readings remained below the optimum moisture content (OMC) of 15% during light rainwater, indicating stable conditions. As water input increased, the readings surpassed 17%, equivalent to the natural field moisture content, triggering an alert in the Blynk application. This indicates that moisture content beyond the OMC significantly affects slope stability, confirming the soil's sensitivity to water infiltration. The consistency between the sensor thresholds and laboratory test values demonstrates that integrating soil geotechnical properties with real-time IoT monitoring provides a reliable basis for early warning. The combination of both sensors working together allows the system to cross check multiple danger signs. For instance, high moisture content alone may not cause a warning if the slope remains stable. But when moisture rises and increases values in humidity are also detected, the system becomes more certain that a landslide is likely to occur. The Blynk app displays these sensor values live, allowing users to monitor the slope remotely and receive automatic notifications if danger levels are reached.

Table 3 compiles the sensor response and system actions under different rainfall conditions, the experiment simulated different rainfall conditions (dry, light, moderate, heavy, and extreme) to observe the response of temperature, soil moisture, and humidity using the Arduino-based monitoring system. Each condition was maintained and observed for 60 seconds to monitor how the soil model reacted within a short but consistent time frame.

Table 3
Recommended sensor thresholds based on laboratory data

Rainfall Condition	Temperature (°C)	Soil Moisture (%)	Humidity (%)	System Status/ Action
Dry	30-34	8-12	50-60	Normal readings – No Alert
Light rainfall	28-30	13-15 (near OMC value)	60-70	Moisture warning (Monitor slope condition)
Moderate rainfall	26-28	16-18 (field MC)	70-80	High moisture detected (Alert via Blynk App.)
Heavy rainfall	24-26	>18	80-95	Critical alert (High risk of slope movement)
Extreme/ continuous rain	22-24	>20	>95	Landslide likely (Combined alert triggered)

Under dry conditions, the temperature ranged between 30–34°C, with soil moisture remaining low (8–12%), and minimal tilt movement (0–1 mm). Humidity was also low, between 50–60%. These readings indicated a stable slope, and no alert sign was triggered, confirming safe conditions. During light rainfall, temperature slightly dropped to 28–30°C, and soil moisture approached the optimum moisture content (13–15%) and humidity rose to 60 - 70%. Although the slope remained stable, the system issued a moisture warning via the Blynk app to indicate early water infiltration. Under moderate rainfall, temperature decreased further (26–28°C), and soil moisture increased to around 17.5%, reaching the natural field moisture content and humidity increased to 70–80%. These values suggested that the slope began to soften, and the system triggered an alert, highlighting increased risk due to accumulated water. In the case of heavy rainfall, the temperature dropped to 24–26°C, soil moisture exceeded 17.5%, and humidity ranged between 80–95%, showing high saturation levels. The system responded with a high-risk warning, indicating potential slope failure based on both sensor thresholds being exceeded. Under extreme or continuous rainfall, saturation occurred (moisture >20%), temperature fell to 22–24°C, and humidity reached above 95%. These combined conditions showed that the slope was critically unstable. The system triggered a combined alert, warning that a landslide was highly likely to be occurred.

Overall, the system demonstrated the ability to detect early warning signs through real-time sensor data. The 60-second observation period for each rainfall stage allowed the sensors to react quickly and reflect actual slope behavior. This real-time monitoring approach is effective in identifying slope instability and issuing timely alerts, especially in response to changing environmental conditions. These results show that the Arduino-Blynk system, when calibrated using real geotechnical data, can successfully provide early warnings related to rainfall-induced slope failure. The system helps detect signs of slope instability earlier than visual observation alone. By combining sensor technology with lab-based understanding of soil behavior, this monitoring system adds a practical and efficient tool for reducing the risks of landslides, especially in areas with frequent heavy rain.

4. Conclusions

This study aimed to investigate the impact of rainfall on slope stability through the development of an IoT-based monitoring system, with the goal of enhancing community safety by providing timely and accurate information on landslide risks.

The geotechnical properties of the studied soil can be concluded as sandy silt with significant sand and fine content, determined from particle size distribution analysis and supported by the findings from Atterberg limits and specific gravity. The optimum moisture content and maximum dry density of compacted soils suggest that the soil's load-bearing capacity and compaction characteristics are sensitive to its moisture content. Mechanical properties of soil, focusing on valuable insights of the shear strength parameters and soil permeability emphasized the impact of soil composition, moisture content, and sample preparation on soil performance.

Despite some limitations, including differences between controlled lab conditions and real-world scenarios, as well as the qualitative nature of some sensor readings, the study successfully demonstrated the potential of IoT technology in landslide monitoring. The integration of sensors for soil moisture, humidity, and water penetration provided a comprehensive approach to slope analysis.

The investigation of soil moisture and water runoff under varying conditions of artificial rainwater application further underscores the importance of understanding soil behavior in relation to water infiltration and stability. Increased rainwater volumes and durations lead to higher soil moisture levels and reduced slope angles, suggesting a greater risk of slope failure under heavy rainfall conditions.

Overall, the findings of this study support the development of an IoT-based landslide monitoring system. By offering real-time data and early warnings, this system has the potential to significantly reduce the risks associated with rainfall-induced landslides.

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References
[1] Xu, Linrong, Aliyu Bamaiyi Usman, Al-Amin Danladi Bello, and Li Yongwei. 2023. “Rainfall-Induced Transportation Embankment Failure: A Review.” *Open Geosciences* 15, no. 1: 20220558. https://doi.org/10.1515/geo-2022-0558.
[2] Zhang, Zonglin, Runqiang Zeng, Xingmin Meng, Shufen Zhao, Shixin Wang, Jianhua Ma, and Hong Wang. 2023. “Effects of Changes in Soil Properties Caused by Progressive Infiltration of Rainwater on Rainfall-Induced Landslides.” *Catena* 233: 107475. https://doi.org/10.1016/j.catena.2023.107475.
[3] Dou, Hongqiang, Rui Wang, Hao Wang, and Wenbin Jian. 2023. “Rainfall Early Warning Threshold and Its Spatial Distribution of Rainfall-Induced Landslides in China.” *Rock Mechanics Bulletin* 2, no. 3: 100056. https://doi.org/10.1016/j.rockmb.2023.100056.
[4] Batumulai, Pavithran, Nor Shahidah Mohd Nazer, Norbert Simon, Norasiah Sulaiman, Mohd Rozi Umor, and Mohamad Anuri Ghazali. 2023. “Soil Detachment Rate of a Rainfall-Induced Landslide Soil.” *Water* 15, no. 12: 2149. https://doi.org/10.3390/w15122149.
[5] Dikshit, Abhirup, Raju Sarkar, Biswajeet Pradhan, Samuele Segoni, and Abdullah M. Alamri. 2020. “Rainfall-Induced Landslide Studies in Indian Himalayan Region: A Critical Review.” *Applied Sciences* 10, no. 7: 2466. https://doi.org/10.3390/app10072466.
[6] Lee, Yonghee, Weon-Hack Choi, and Seok-Chul Kim. 2019. “Slope Monitoring System for Nuclear Power Plants.” *Nuclear Engineering and Design* 347: 86–94. https://doi.org/10.1016/j.nucengdes.2019.03.019.
[7] Tohari, Adrin. 2018. “Study of Rainfall-Induced Landslide: A Review.” In *IOP Conference Series: Earth and Environmental Science*, vol. 118, 012036. IOP Publishing. https://doi.org/10.1088/1755-1315/118/1/012036.

[8] Khan, Amina, Sumeet Gupta, and Sachin Kumar Gupta. 2020. "Multi-Hazard Disaster Studies: Monitoring, Detection, Recovery, and Management, Based on Emerging Technologies and Optimal Techniques." *International Journal of Disaster Risk Reduction* 47: 101642. https://doi.org/10.1016/j.ijdrr.2020.101642.

[9] Nong, Muhammad Aiman Hakimi Bin Mohd, Noorhanaliza Binti Berahan, Lilysuriazna Raya, and Mohammed Hazim Alkawaz. 2023. "Solar Powered Landslide Detection Using Global System Mobile (GSM) Communication." In *2023 IEEE 14th Control and System Graduate Research Colloquium (ICSGRC)*, 139–43. IEEE. https://doi.org/10.1109/icsgrc57744.2023.10215420.

[10] Roslee, Rodeano, and Felix Tongkul. 2018. "Engineering Geological Study on the Slope Failure along the Kimanis to Keningau Highway, Sabah, Malaysia." *Geological Behavior* 2, no. 2: 1–9. http://doi.org/10.26480/gbr.02.2018.01.09.

[11] ASTM International. 1963. *ASTM D422-63: Standard Test Method for Particle-Size Analysis of Soils.* https://doi.org/10.1520/D0422-63R07.

[12] ASTM International. 2017. *ASTM D4318-17: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.* https://doi.org/10.1520/D4318-00.

[13] ASTM International. 2018. *ASTM D4943-18: Standard Test Method for Shrinkage Factors of Cohesive Soils by the Water Submersion Method.* https://doi.org/10.1520/D4943-18.

[14] ASTM International. 2014. *ASTM D854-14: Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer.* https://doi.org/10.1520/D0854-14.

[15] ASTM International. 2012. *ASTM D698-12: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 [600 kN-m/m^3]).* https://doi.org/10.1520/D0698-12R21.

[16] ASTM International. 2002. *ASTM D5856-95: Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter.* In *Annual Book of ASTM Standards, Section 4, Vol. 04.08, Soil and Rock; Building Stones.* Philadelphia: ASTM. https://doi.org/10.1520/D5856-95.

[17] ASTM International. 2004. *ASTM D3080-04: Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions.* https://doi.org/10.1520/D3080-04.

[18] Bowles, Joseph E., and Yingzhong Guo. 1996. *Foundation Analysis and Design.* 5th ed. New York: McGraw-Hill.